GEOTECHNICAL SITE INVESTIGATION OF VEGETATED SLOPES

by

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Dedicated to the memory of
my loving parents

Wendy Nova Wint
1942-1996

and

Jeffrey Wint
1930-2000

Certificate of originality

This is to certify that I am responsible for the work submitted in this thesis, that the content is my own except where specified in the acknowledgements and that neither the thesis nor the original work contained therein has been submitted to this or any other institution for a higher degree

Signature..

Joanne Wint

Abstract

Geotechnical site investigation of vegetated slopes

Vegetation on a slope has been shown to affect the geotechnical and hydrogeological properties of that slope, and thus may contribute to slope stability. However, vegetation is rarely quantified or taken into account during geotechnical site investigation and subsequent design. This is in part is due to an awareness of the variability associated with vegetation, but is also due to a lack of understanding of how the vegetation may contribute to slope stability, what parameters may be quantified to characterise the contribution and the optimum techniques for obtaining said data. The interaction of vegetation with its environment is both complex and dynamic, varying on a seasonal and annual basis, and as such an assessment of the contribution to slope stability must be considered over the long term. Therefore, a framework for the geotechnical site investigation of vegetated slopes has been developed by completion of a cross disciplinary study; conducted to identify the relevant parameters and techniques available to quantify the parameters required for slope stability analysis, incorporating the contribution of vegetation to slope stability.

Fieldwork was undertaken to evaluate the appropriateness of the techniques available to quantify the vegetation and its contribution to shear resistance. The heterogeneity and variability of the soil and roots means that the *in situ* shear box and root pull out tests should be considered as index tests which impacts on the relevance of the data obtained. Laboratory work conducted revealed the soil root composite analysis is affected by sample disturbance induced during sampling, while individual root analysis is affected by the storage of the samples i.e. dehydration of the roots. Finally, following evaluation and assessment of the relevant parameters and techniques, a tiered approach for the geotechnical site investigation of a vegetated slope was developed, which optimises the determination of parameters for characterising a vegetated slope.

Keywords: Vegetation, Slope Stability, Geotechnical Site Investigation.

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1 Introduction

'A journey of a thousand miles begins with a single step.'
Lao-tzu (604 BC - 531 BC). The Way of Lao-tzu

Vegetation on a slope affects the geotechnical properties of that slope; however, vegetation is rarely quantified or taken into account during geotechnical site investigation and subsequent design. A site investigation is the process by which geotechnical and hydrogeological parameters required for a slope stability analysis are obtained. A site investigation is usually necessary on existing slopes, either engineered or natural, that are showing initial signs of instability or where failure has occurred and back analysis is required, or as part of an asset management strategy. Alternatively, site investigation is required when construction occurs in the vicinity of a slope, and the affect of the planned construction on the slope must be assessed. In such circumstances the existing vegetation at the time of the investigation is of little consequence, or is given cursory attention in situations where the removal of trees and hedges could lead to heave of water content sensitive clay soils. However, many of these cases would benefit from the incorporation of a vegetation investigation, to assess any contribution from existing or planned vegetation cover.

The integrity of embankments and cuttings are essential for the safe efficient operation of railway, highway and canal infrastructure, and hence the understanding, management and longevity of these assets are of concern to the owners and operators of transport links (Perry *et al.* 2003a). A survey of motorway cuttings and embankments in England and Wales conducted by Perry (1989) reported that of 570 km of motorway surveyed, accumulated lengths of over 17 km of embankment and 5.5 km of cutting slope had failed. Perry (1989) concluded that the total length at risk of failure is the sum of slopes of more severe geometry and the length of slope observed with cracking, therefore, three times as many slopes are likely to fail in the future than have failed so far if no preventative measures are taken. However, this may be an overestimation as the contribution of vegetation on some of these slopes may enhance their stability. Therefore, asset management assessment of slopes would benefit from a holistic approach that considered the contribution of vegetation along with the geotechnical appraisal.

The use of vegetation as a reinforcing medium is not new technology, during the 17th and 18th Centuries French settlers along the Bay of Fundy (Canada) used sticks to reinforce mud dikes, and dikes incorporating tree branches have been used in China for at least 1,000 years (Elias *et al.* 2001). More recently, the observation of landslides after forest clear cutting (Burroughs and Thomas 1977; Montgomery *et al.* 2000; Ziemer 1981a; Ziemer and Swanston 1977) has encouraged researchers including Kitamura and Namba (1981) Watson (1990) and Abe and Ziemer (1991a) to attempt to quantify the reinforcing effects of certain vegetation on slope stability.

The effect of vegetation on the hydrogeological properties was brought to the attention of the UK civil engineering community by Biddle (1985) and its application to slope stability was reported by Greenway (1987). The use of vegetation within civil engineering was summarised by Coppin and Richards (1990) who detailed examples of 'bioengineering' techniques for the remediation of unstable slopes. However, a procedure for the geotechnical investigation of vegetated slopes has not been developed, instead focus has been placed on discrete research methods to demonstrate the increased shear resistance of a root reinforced soil (Abe and Iwamoto 1986a; Norris and Greenwood 2000; Tobias 1994; Waldron and Dakessian 1981; Wu and Watson 1998) or the influence of vegetation on pore water pressures (Blight 2003; Tarantino *et al.* 2002; Wilkinson 2000) or expansive clay soils (Bukhari 1998; Cameron 2001) rather than the characterisation of a vegetated slope to establish the overall contribution of vegetation to slope stability.

Various disciplines have researched the interaction between soil and vegetation for different reasons; foresters have focused on the stability of forest stands either on slopes or flat ground and their resistance to wind throw (Anderson *et al.* 1989a; Moore and Quine 2000; Nicoll *et al.* 1995; Niklas 1998; Ruel 2000). Agronomists and botanists have focused on the ability of plants to adapt to their environment (Chiatante *et al.* 2003; Coutts and Nicoll 1991; 1993; Haque *et al.* 2001; Nicoll and Ray 1996) or alter their environment with the uptake, exudation or fixation of nutrients and water (Durrant *et al.* 1973; Högberg *et al.* 2002; Mulder *et al.* 2002; Tsutsumi *et al.* 2003). Hydrologists have studied and modelled the effect of vegetation on the hydrological cycle in the immediate environment of certain crops and ecosystems (Hultine *et al.* 2003; Stothoff *et al.* 1999), while ecologists have studied population dynamics and the interaction of species within their environment (Archer *et al.* 2002; Schmid 2002) and various researchers have focused on the ability of roots to minimise erosion (Amarasinghe 1996; Miura *et al.* 2003; Sharma *et al.* 1991; Shields and Gray 1992; Wynn *et al.* 2004). Whereas, geotechnical engineers have focused on the shrink swell damage caused to structures from tree species, with a high water demand, planted too close to buildings or buildings being constructed on land cleared of vegetation or direct damage to structures from roots (Biddle 1985; 2001; Crilly 1996; N.H.B.C. 1988).

To conduct a geotechnical investigation of a vegetated slope it is necessary for geotechnical engineers to appreciate the effects of vegetation and have an awareness of appropriate techniques employed by other disciplines that may be incorporated into a geotechnical investigation framework. Research projects investigating the influence of vegetation have employed various techniques to assess the contribution of vegetation to slope stability (Greenwood *et al.* 2001; MacNeil *et al.* 2001), and a field protocol for the evaluation of vegetated slopes was compiled by Cammeraat *et al.* (2002), as part of the ECOSLOPES project to harmonise the data collected from the different key sites selected for the project (Section 1.2). However, the protocol is a compilation of techniques, contributed by the various ECOSLOPES partners that may be employed to assess various aspects of a slope and vegetation rather than a framework for the geotechnical assessment of a vegetated slope. Therefore, there is a requirement for the development of a framework for the geotechnical site investigation of a vegetated slope, which may be employed to ascertain the contribution of vegetation to slope stability.

1.1 AIM AND OBJECTIVES

The aim of the investigation:

- To develop a framework for the geotechnical site investigation of vegetated slopes

The objectives:

- To determine the effect of vegetation on slope stability and establish the parameters required for slope stability analysis
- To ascertain the most suitable techniques and procedures for the geotechnical assessment of a vegetated slope

- To evaluate field and laboratory techniques employed to quantify the contribution of vegetation to slope stability

1.2 CONTEXT

The research project described herein formed part of a research project undertaken by Nottingham Trent University with the ECOSLOPES project. The research was commissioned and funded by the EU as part of the European 5th framework. ECOSLOPES is a multidisciplinary project, which intended to unite engineers, geomorphologists and foresters, with the aim of producing techniques and tools to improve slope stability and erosion. The ECOSLOPES project is driven by a need to improve tree and slope stability and safety within Europe, using effective, sustainable and inexpensive techniques, thus enhancing forest production and beauty in rural and urban areas (Stokes *et al.* 2000). The PhD research post was formed and funded by the ECOSLOPES project and much of the field testing used within the PhD research was undertaken on field sites selected for the ECOSLOPES project. The individual research projects such as this PhD are envisaged to compliment and enhance the ECOSLOPES project, with further understanding of vegetation and soil slope interaction, beyond the remit of the original project.

Table 1.1 ECOSLOPES field study sites

Site	No.	Location	Grid ref	General Description	Problem
Key sites	1	M25, England	51° 65'N 0° 16'E	Motorway embankment Constructed from London Clay	Shallow landslips
	1a	M11, England	51° 62'N 0° 06'E	Motorway cutting Constructed from London Clay	Shallow landslips
	2	Trivento, Italy	41° 71'N 14° 55'E	Natural marl hill slopes with earthquake triggered landslide complex	Shallow landslips
	3	Vaujany, France	45° 15'N 6° 07'E	Forested rock slopes of the French Alps	Rock fall
	4	Thessaloniki, Greece	40° 15'N 23° 37' E	Forested hill slopes subject to wildfires	Erosion
Additional sites	5	Ben Nevis, Scotland	56° 51'N 4° 57' W	Forestry Commission plantation on natural hill slopes	Wind throw
	6	Valencia, Spain	39° 42'N 0° 42' W,	Research station located on natural hill slope used to study impact of fires	Erosion
	7	Almudaina, Spain	38° 78'N 0° 20' W	Natural, marl hill slopes, historically terraced	Shallow landslips

Four key sites were selected for the ECOSLOPES project (Table 1.1) to represent distinctive slope types found in Europe, including Mediterranean hill sides which have suffered wild fires and subsequent erosion (Halkidiki, Greece) or have a history of landslips triggered by either seismic events or excess pore water pressure (Trivento, Italy), Alpine mountain sides which suffer rock falls and avalanches (Vaujany, France) and a motorway cutting and embankment prone to shallow landslips (M11 and M25, England). Three additional sites, two in Spain, (Almudaina and Valencia) and one in Scotland (near Fort William) were selected to link in ongoing research with the ECOSLOPES project and provide sites for additional testing if required.

The ECOSLOPES project facilitated the opportunity to observe and undertake some *in situ* testing and allowed first hand experience to be gained in site characterisation. Site works were undertaken on each site by a multidisciplinary team facilitating familiarisation with a wide range of investigation techniques and site characterisation procedures, employed by the various disciplines (geomorphologists, pedologists, botanists, foresters and geotechnical engineers). The literature review was conducted parallel to the fieldwork, as most fieldwork comprised single visits to the continental sites within the first 12 months of the PhD programme.

1.3 GENERAL OUTLINE

The characterisation of a vegetated slope can theoretically draw upon techniques from a wide range of disciplines, and as such the initial subject area is large. Therefore, in order to discern the most appropriate techniques to characterise a vegetated slope for geotechnical slope stability design, it is first necessary to identify the parameters that may be input into slope stability analysis. From which, it is possible to distinguish the most appropriate techniques available to measure the required parameters. The key aspects to consider when characterising a vegetated slope are the ground, vegetation and the water. Therefore, geotechnical, botanical and hydrogeological parameters and investigation techniques have been the focus of this study.

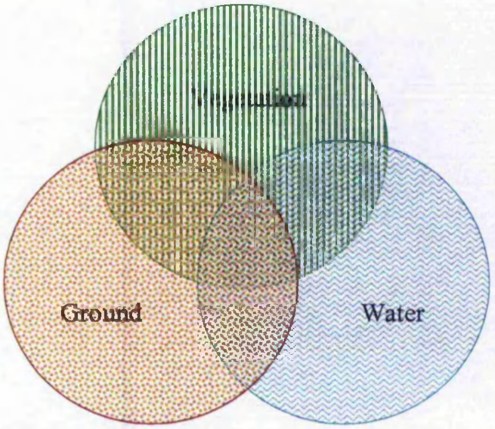


Figure 1.1 Interaction between vegetation and its environment

Generally, geotechnical and hydrogeological parameters are recorded and used to ascertain the stability of a slope. The incorporation of vegetation into a refined slope design analysis is more complex than the simple addition of a set of vegetation parameters, due to the interaction between the three phases (Figure 1.1), plus the interaction of vegetation with other vegetation, fauna and the atmosphere.

Therefore, a framework for the geotechnical assessment of a vegetated slope should not only include the determination of geotechnical, botanical and hydrogeological parameters, but must also include comparative analysis to ascertain to what extent the vegetation has modified or been influenced by its environment. To this end the literature review has identified the parameters associated with the three key phases and the techniques available to quantify these parameters. In addition, field and laboratory investigations have been conducted to evaluate certain techniques, and assess the relevance of the results obtained, to determine the suitability of both the techniques and the results for design analysis, with a view to developing a framework for the geotechnical investigation of vegetated slopes.

1.4 THESIS STRUCTURE

The interaction between vegetation, soil and the atmosphere requires a multidisciplinary approach to evaluate the contribution of vegetation to slope stability. Therefore, a comprehensive literature review was undertaken to ascertain the effect of vegetation on the soil properties and establish the parameters required for slope stability analysis, and also discern the most suitable techniques, from the various disciplines, that may be employed within a framework to enable the geotechnical assessment of vegetated slopes.

The thesis is divided into ten chapters and the literature review extends from Chapter 2 to Chapter 5. Chapter 2 outlines the factors influencing the root system growth and development and survival strategies of vegetation along with the mechanical, hydrological and chemical effect vegetation may have on the soil and the subsequent contribution to slope stability, and its limitations. Chapter 2 also introduces the principles of slope stability and outlines the development of models employed for slope stability analysis to incorporate the effect of vegetation.

Chapter 3 reviews the geotechnical parameters used within slope stability analysis and outlines the various techniques that may be employed within a geotechnical ground investigation, to retrieve soil samples and ascertain the soil parameters, with regard to the vegetation covering the slope.

Chapter 4 outlines the vegetative parameters that may be included within a slope stability analysis and reviews the various investigation techniques employed to ascertain the distribution of vegetation, root architecture and the mechanical contribution of root reinforcement.

Chapter 5 summarises the placement of vegetation in the hydrological cycle and the effect of hydrogeological processes on slope stability. The input, output, storage and transfer mechanisms within the water balance system are outlined, along with the various techniques for assessing the hydrogeological parameters and the effect vegetation may have on the hydrogeology.

Techniques employed and observed during the preliminary fieldwork are discussed in Chapter 6, along with analysis of the results obtained and evaluation of the procedures followed. Lessons learnt from the preliminary fieldwork are discussed and modifications to the procedures and apparatus that were taken forward to the main field investigation are discussed. Similarly, the techniques employed and observed during the main field trial are outlined and discussed in Chapter 7, along with an evaluation of the procedures followed and the quality of the results obtained and their suitability for slope stability analysis. The various laboratory techniques employed to characterise soil, roots and root reinforced soil are discussed in Chapter 8.

The parameters required to characterise a vegetated slope and conduct a slope stability analysis of a vegetated slope are summarised in Chapter 9, along with the development of the framework for the geotechnical investigation of a vegetated slope. The conclusions from the research and recommendations for further work arising from the research findings are discussed in Chapter 10.

The Effect of Vegetation and Slope Stability

2

'What we are concerned with here is
the fundamental interconnectedness of all things.'
Douglas Adams (1952-2001). Dirk Gently's Holistic Detective Agency

Plants have been shown to enhance soil stability and inhibit shallow downward mass movement by the mechanical reinforcement of their roots and through the removal of soil water via transpiration (Burroughs and Thomas 1977; Gray and Sotir 1995; Marriott *et al.* 2001; Waldron 1977; Waldron and Dakessian 1982; Ziemer 1981b). However, the quantification of this enhancement is not altogether straightforward as external factors may augment or diminish the beneficial or detrimental effects of vegetation and so alter their zone of influence. In order to successfully quantify the contribution of vegetation to slope stability it is necessary to conduct an effective investigation, to characterise a vegetated slope. In order to design an effective site investigation, conceptual designs must be carried out at the earliest possible stage so that all the relevant, and only the relevant, parameters are obtained (Simons *et al.* 2002). Conceptual designs consider all the possible engineering solutions, which may be adopted to deal with a specific project, so that the required geotechnical parameters are obtained. Therefore, to conduct an effective investigation of a vegetated slope it is necessary to establish what effect vegetation may have on the local environment in order to determine which are the most significant parameters and also the best methods to obtain the data.

However, vegetation is also influenced by its environment, soil fertility, seasonal variability, herbivore activity, and so on, so it is also important to have an understanding of root development, form and function. Therefore, the following chapter discusses the effect of vegetation on its local environment outlining the effect vegetation has on mechanical, hydrological and chemical parameters; and discusses the influence the environment can have on the type of vegetation growing on a site and root development. The principles of slope instability and the use of bioengineering techniques employed to improve slope stability are also outlined in an attempt to put the contribution of vegetation into context. Although the input of data into a model may be the final stage of the characterisation procedure, the choice of model ultimately determines the most relevant parameters to be ascertained during the investigation stage. Therefore, the development of slope stability analysis and the inclusion of vegetation parameters are summarized.

2.1 EFFECT OF VEGETATION

Plants alter their environment in many ways both above and below the soil. Above soil alterations include interception of rainfall and the generation of a microclimate, by partitioning solar energy, reducing airflow and thus affecting humidity and local temperature (Tindall and Kunkel 1999). A study conducted by Hashimoto and Suzuki (2004) following clear cutting of a forest reported an increase in the average and maximum soil temperature with little change to the minimum temperature. Below ground the presence of roots can affect infiltration by changing the permeability and bulk density of the soil (Hiller and MacNeil 2001).

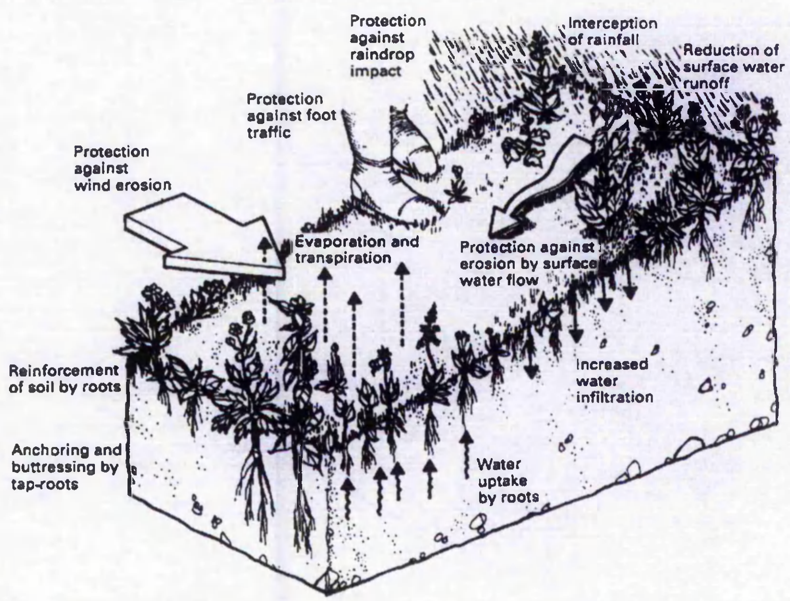


Figure 2.1 Some influences of vegetation on the soil (Coppin and Richards 1990)

The significant effects of vegetation on slope stability are generally considered to be mechanical and hydrological, illustrated in Figure 2.1 (Coppin and Richards 1990). In addition, roots chemically alter the soil by the extraction of solutes, water and nutrients, necessary to sustain life and also contribute to the soil chemistry through exudation of polysaccharides and decomposition post mortem. Polysaccharide and polyurinide gums are excreted from epidermal and cortical cells to advance the root growth; these exudates along with microbial decomposition are responsible for binding small aggregates into large stable aggregates (Tindall and Kunkel 1999) and may alter the texture of the soil. The ability of vegetation to alter its environment, thrive or perish is dependent on a number of factors, including the amount and type of vegetation, ecology, geology, geomorphology, topography, hydrogeology and climate.

2.2 MECHANICAL EFFECTS OF VEGETATION

Vegetation can mechanically enhance the strength and competence of the soil in which it is growing and, therefore, contributes to its stability. Roots embedded in the soil form a composite material consisting of fibres of relatively high tensile strength and adhesion, within a matrix of lower tensile strength. This may be compared to a reinforced soil system, where a slope is stabilised by the inclusion of metallic, synthetic or natural material (Wu 1995). Stress transfer between the soil and the reinforcement material occurs continuously along the reinforcement by two mechanisms, namely friction and passive resistance.

Roots of between 1 and 12 mm diameter physically restrain soil particles from movement induced by gravity, raindrop impact, surface runoff and wind (Coppin and Richards 1990). Upper layers of soil may be reinforced by grass roots in this way, while lateral roots of trees can extend beyond the drip zone of the canopy and interweave, holding soil blocks together (Burroughs and Thomas 1977). The network of intertwined lateral roots at shallow depth forms a mat with a significant degree of in plane strength (Coppin and Richards 1990) and tensile strength which can stabilise a slope against shallow slides and creep (O'Loughlin and Watson 1981; Zhou *et al.* 1998).

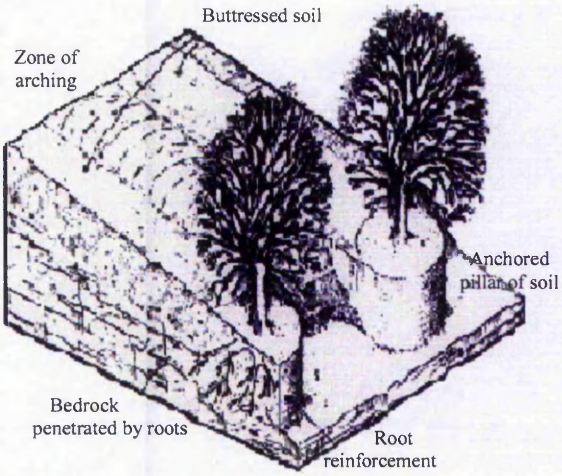


Figure 2.2 Physical effects of vegetation on slope stability (after Coppin and Richards 1990)

Tree roots that penetrate deeper than the surface binding achieved by grasses may be likened to the function assumed by geotextiles (Wilkinson 2000). Taproots and large sinker roots may act as anchors, while the entire root system of a large tree can form a block that has a buttressing effect, and if a number of trees are spaced in close proximity arching can occur (Figure 2.2).

2.2.1 Reinforcement

The principle of reinforced soil is that an introduced material provides a tensile restraining force that reduces the lateral stress required to maintain the equilibrium of a loaded soil unit (Mitchell and Jardine 2002). As the soil element compresses under vertical stress it tends to strain laterally, and a tensile stress is generated in the reinforcement, resisting the outward movement and giving rise to lower horizontal stresses than the same soil element under the same vertical load but without reinforcement. Therefore, the tensile force in the reinforcing element depends on there being lateral strain (Mitchell and Jardine 2002).

British Standard (BS 8006: 1995) states that for soil reinforcement to be effective it should interact with the soil to absorb the stresses and strains, which would otherwise cause the unreinforced soil to fail. The mechanism by which this interaction occurs is dependent on both the soil properties and the reinforcement characteristics. Mitchell and Jardine (2002) note the important variables for reinforced soil are form, surface properties, dimensions, strength, longitudinal stiffness (EI) and bending stiffness (EA).

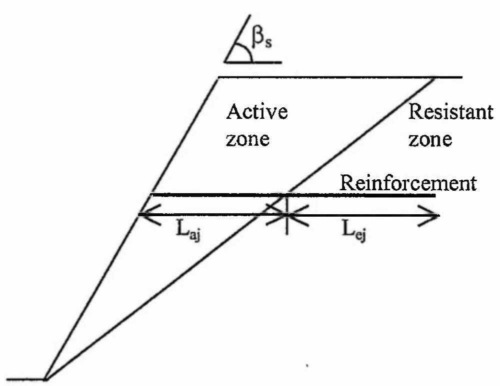


Figure 2.3 Reinforcing mechanisms in slopes (BS 8006: 1995)

The subsequent bond strength is generated by friction, adhesion or bearing stresses between the soil and the reinforcement, and facilitates steeper slope geometry when sufficient reinforcement is embedded into the resistant zone (Figure 2.3). The embedment length and spacing of the reinforcement is designed to minimise failure in manufactured reinforced slopes. The reinforcement is embedded into the stable part of the slope and spans potential failure surface to reinforce the active part.

Initial studies into root reinforcement and its potential were carried out in the 1960s after harvested forested slopes began to fail. Tsukamoto and Kusakabe (1984) developed a simple classification for forested slopes in Japan, considering key factors such as morphology and proximity to the critical slip surface (Figure 2.4).

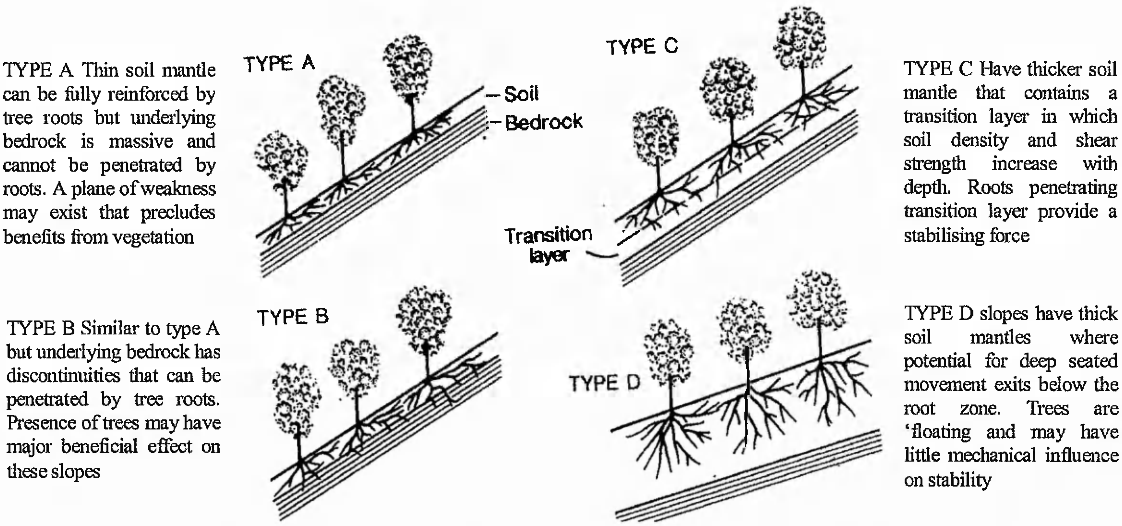


Figure 2.4 Slope classification scheme based on root reinforcement and anchoring (Tsukamoto and Kusakabe 1984)

The increased shear resistance of root-reinforced soil was investigated using the laboratory shear box by several researchers (Kassif and Kopelovitz 1968; Operstein and Frydman 2000; Waldron 1977). Waldron (1977) carried out laboratory shear box tests to measure the amount of reinforcement gained in root-permeated soils compared to fallow soil. Waldron and Dakessian (1982) followed up this research with direct shear tests on twelve different species comprising grass, legumes and trees. They found that after 7 months the grasses increased the shear resistance by 3 fold at 0.3 m depth, as did the oak roots after three years, and Alfa alfa by 4 fold after a year at 0.45 m depth.

Radoslaw and Čermák (2003) conducted drained triaxial tests on fibre reinforced sand containing randomly orientated synthetic fibres, and reported that an increase in failure stress can be as much as 70% at a fibre concentration of 2%. *In situ* shear tests on soil-root systems have been performed on soil blocks with and without roots, enclosed in a rigid frame (Abe and Iwamoto 1986b; Endo 1980; Norris and Greenwood 2003; O'Loughlin and Watson 1981; van Beek *et al.* 2005; Ziemer 1981b).

Wu (1976) developed a theoretical model for predicting the increase in shear strength due to basal roots perpendicular to the shear plane (Equations 2.1 and 2.2). The model considers roots as individual elements initially crossing a slip plane perpendicularly and assumes the ultimate strength of the materials is mobilised along the failure plane. The reinforced shear resistance (ΔS) increases rapidly by stretching before the root slips (Wu 1976).

$$\Delta S = a_r T_n (\sin\beta + \cos\beta \tan\phi) \quad \textbf{(2.1)}$$

$$T_n = (4\tau' / EZ / D)^{1/2} \quad \textbf{(2.2)}$$

Where:

ΔS	=	Reinforced shear resistance
T_n	=	Max tensile stress in root
a_r	=	Cross sectional area of root
τ'	=	Max tangential friction between root and soil
E	=	Young's modulus
Z	=	Shear zone width
D	=	Diameter of root
β	=	Angle of root deformation

The component of tension tangential to the shear zone directly resists shear while the normal component increases the confining pressure on the shear plane (Wu 1976). Therefore, the amount of tangential friction is the most significant factor contributing to ΔS, because the root can stretch rather than slip (Figure 2.5). Reinforced shear resistance also increases slowly after the slippage, with the rate of increase related to the tangential friction between the root and soil (τ), and the earth pressure generated on the roots.

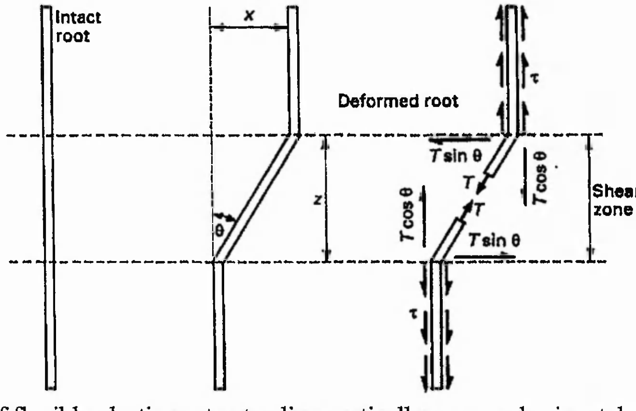


Figure 2.5 Model of flexible elastic root extending vertically across a horizontal shear zone (Wu 1976)

Operstein, and Frydman (2002) comment that stability analysis of root-reinforced slopes must consider the roots as individual elements, and take account of their properties, as well as their interaction with the surrounding soil. Therefore, the level of reinforcement achieved is a function of root density, tensile strength, length/diameter ratio, alignment and orientation relative to the principle strains (Hiller and MacNeil 2001).

Gray and Leiser (1982) considered the case of a root inclined with respect to the slip plane and Wu *et al.* (1988) have proposed other models to consider different angles of pull out of the root and take into account passive soil, these include the cable model and the pile model. Frydman and Operstein (2001) used the finite difference code FLAC to simulate root reinforcement and reported that vertical roots do not contribute significantly to slope stability, as they will cross the shear plane at an oblique angle, whereas roots that are perpendicular to the slip face provide a considerable contribution. However, tests conducted on fibre reinforced soil, indicated that the optimum angle for inclusions is 60°, while inclusions at 90° to the shear plane give similar improvement in strength to the randomly orientated fibres (Bailey 2000).

The mechanical effects of the roots of vegetation are to enhance the confining stress, resistance to sliding and increase the strength of the soil root mass through the binding action of roots in the fibre/soil composite; the soil friction angle is thought to remain unchanged (Coppin and Richards 1990). The increase in shear resistance of root permeated soil has been incorporated in the Mohr Coulomb model (Waldron 1977) equation 2.3.

$$S_r = c + \sigma \tan\phi + \Delta S \qquad \textbf{(2.3)}$$

Where:

S_r	=	Shear resistance of rooted soil
c	=	Cohesion intercept
ΔS	=	Contribution of roots to soil shear resistance
σ	=	Normal stress
ϕ	=	Angle of internal friction

The contribution of roots to soil shear resistance was defined by Operstein and Frydman (2000) by breaking it down into its component parts of the quantity and directional distribution of roots, the tensile strength of the roots, the Young's modulus of the roots and the soil root interface friction.

Gray and Ohashi (1983) and O'Loughlin and Ziemer (1982) found that fibres and roots did not affect the angle of internal friction within soils and the contribution of vegetation to root reinforcement is thought of as a supplemental 'cohesion' that is added to the soil shear strength in the Mohr-Coulomb equation. Therefore, the contribution of root reinforcement is often considered as an increase in the cohesion intercept (Figure 2.6). Barker (1986) suggests that 'a root content of 1-2 per cent can increase cohesion by two or three times'. However, the enhanced 'cohesion' observed in rooted soil is an increase of the cohesion intercept, rather than any increased attraction between particles. Enhanced cohesion is a function of root reinforcement, and does not necessarily alter the fundamental adhesion or cohesion properties of the soil matrix and is often referred to as apparent cohesion.

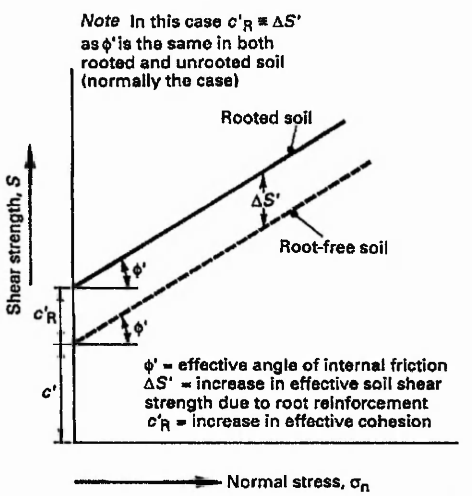


Figure 2.6 Effect of root reinforcement on the shear strength of soil (Coppin and Richards, 1990)

The models of Wu (1976) and Gray and Leiser (1982) are applicable to roots that span the potential slip plane at depth, however, the majority of roots are concentrated near the soil surface (Abe and Iwamoto 1986a; Leaf *et al.* 1971). Therefore, Krogstad (1995) proposed a root reinforcement model that considers the contribution of lateral roots and the interwoven network that occurs between trees. However, this model is also dependent on the roots crossing the slip plane, only at the surface where the slip plane daylights within the root zone.

Although there is an analogy between manufactured reinforcement and root reinforcement, it is limited, and the correlation is not exact. Some root reinforcement may be analogous to soil anchors or embedded geotextiles, but the variability in material properties and distribution of roots and root systems are not as well understood as fabricated reinforcement. However, the principles for assessing the mechanical contribution of vegetation to slope stability are similar to those for manufactured reinforcement. The root properties required for assessing root reinforcement include tensile strength, stiffness, distribution and morphology, location, orientation and spacing along with the soil root interaction or bond strength.

2.2.2 Anchorage, Buttressing and Arching

Taproots and sinker roots can extend deep enough to penetrate bedrock cracks or stable underlying strata, and therefore, can potentially anchor the soil to the slope (Gray and Megahan 1981). In general, root systems with strong deeply penetrating vertical or sinker roots that cross potential slip surfaces are more likely to increase stability against shallow sliding (Gray and Sotir 1995). A block of soil, which is held in place by basal or lateral roots, can act to buttress a less stable block upslope and prevent slope failure (Gray and Megahan 1981). The trunks and principal roots act in the same manner as a toe stabilising pile (Coppin and Richards 1990).

If the trees are closely spaced arching can occur further stabilising the slope. Arching refers to the occurrence of stress transfer through mobilisation of shear strength in soils, and if tree root systems are considered as buttresses it is possible to apply the soil arching restraint theory to determine critical spacing of trees, in order to obtain maximum stabilisation illustrated in Figure 2.7 (Gray and Leiser 1982; O'Loughlin and Ziemer 1982). The magnitude of the arching effect is influenced by:

- Spacing, diameter and embedment of trees;
- Thickness and inclination of the yielding stratum of slopes; and
- Shear strength properties of the soil.

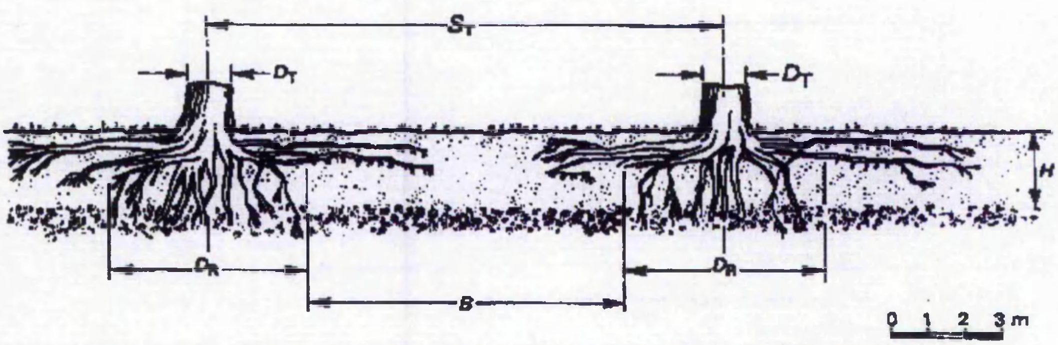


Figure 2.7 Critical spacing for arching, from tree root systems (Gray and Leiser, 1982)
B = Spacing between root cylinders, D_T = Diameter of trunk at breast height,
D_R = Diameter of vertical root cylinder and S_T = Centre to centre spacing between trees

2.2.3 Surcharge

Surcharge is only considered for trees or forested areas, due to the negligible weight of grasses and herbs. The surcharge imposed by trees may have beneficial or adverse affects on slope stability depending on their location on the slope. The surcharge of a single tree or stand can contribute to stability if they are located toward the base of the slope, however, this surcharge would be added to the disturbing forces should the vegetation be near the top of the slope. As an approximate guide, surcharge values of a mature forest stand range between 1 and 10 kN/m^2 (O'Loughlin 1974; Wu *et al.* 1979). Gray (1970) demonstrated that the initial effect of harvesting the trees was to reduce the number of slides occurring due to the reduction in weight applied to the slopes, however, after a number of years the roots decayed reducing the reinforcing effect and the number of slides increased.

2.2.4 Wind Loading

Wind loading is considered an adverse factor, however, this is usually only significant where prevailing winds are stronger than 11 m/s (Coppin and Richards 1990). Slope destabilisation may result from wind forces transferred through the vegetation to the earth. However, it is more likely that individual trees would be uprooted after which a reduction in slope stability would occur in localised areas (Greenway 1987). Whether a tree breaks or uproots is influenced by several factors including wood density, presence of compression wood, the nature of the root architecture, and a stem that is weaker than the root anchorage resistance will rupture before the tree overturns (Coutts 1983b). Prolonged dynamic sway in the tree stem results in tissue fatigue and often stem or root failure (Stokes *et al.* 1995). An analytical model of tree anchorage ForestGALES developed by the UK Forestry Commission (Gardiner and Quine 2000) has been employed to model the vulnerability of trees on sensitive slopes (Achim *et al.* 2005). This may also be used to assess whether prevailing winds provide a sufficient disturbing force to be included in the slope stability analysis.

2.3 HYDROLOGICAL EFFECTS OF VEGETATION

Vegetation modifies the soil water regime of a slope in two main ways, either directly depleting soil water through root uptake and subsequent transpiration, or indirectly by intercepting rainfall, thus reducing the net precipitation reaching the soil surface. Additionally, the root network permeating the soil can improve the infiltration capacity; this may prove beneficial or adverse depending on whether the water moves away from or into a sensitive area. The uptake of water through the root system and loss from the leaf surface results in lower pore water pressures within the slope (Hoogland *et al.* 1981; Lafolie *et al.* 1991), potentially leading to increased effective shear strengths and increased slope stability. The growth of trees can result in relatively deep drying or desiccation of the soil, which can extend to 5 m below the ground surface and extend horizontally up to 15 m away from the tree (Simons *et al.* 2002).

2.3.1 Root Water Uptake

MacNeil *et al.* (2001) comment that the ability of roots to take up water from the soil is influenced by the amount of water in the soil, the matric potential of the soil, the length, placement and specific activity of roots, and the density of the roots within a given volume of soil. Water is absorbed along roots differentially, at rates that depend on cell structure and development, and follow the water potential gradient (Tindall and Kunkel 1999), which is influenced by pressure, solutes and wettable surfaces. Water moves passively from areas of high water potential to areas of low water potential, and a water potential gradient in excess of 2 MPa is required to move water from the roots to the leaves of a giant redwood (Moore and Clarke 1995). Once water has entered the root system it is transferred into the root xylem where it responds to the water potential gradient, created by evapotranspiration on the leaf surface, and moves up the stems to the leaves (Tindall and Kunkel 1999).

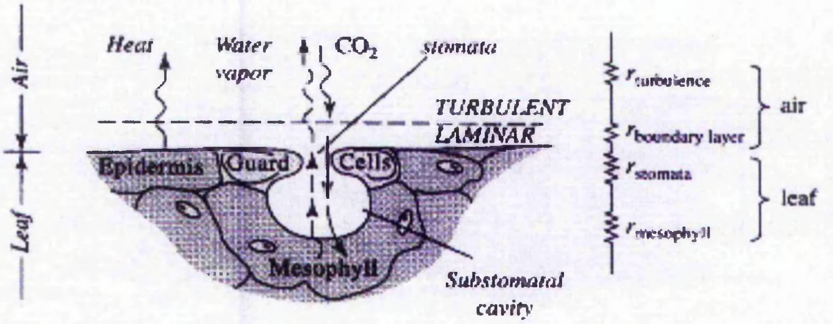


Figure 2.8 Cross section of leaf and related resistances to water flow (Kramer and Boyer 1995)

The term evapotranspiration refers to the two components by which water is lost to the atmosphere, transpiration and evaporation. Transpiration is the biological process by which the water taken from the soil is lost to the atmosphere through the stomata on the underside of leaves, as a by-product of photosynthesis (Figure 2.8). Evaporation is the loss of intercepted or exudated water from the foliage surface. Many plants exhibit a diurnal cycle, which effectively reduces transpiration to zero during night time due to lack of light and a marked decrease in net radiation inputs (Oke 1987).

A study by Watanabe *et al.* (2004) to examine seasonal changes on a sugarcane and maize crops in Thailand, showed evapotranspiration rates between 2 mm and 6 mm per day in the wet season and 1 mm a day in the dry season. The water loss from the top 0.5 m of soil was found to be much less than the evapotranspiration loss in the dry season, suggesting that capillary rise from deeper soil layers provides significant amounts of water to the upper soil layers. Lambs and Berhelot (2002) utilised oxygen isotopes to study water uptake in riparian woodland using their sap extractor system, water movement can be followed by either the ratio of $^{1}H/^{2}H$ (Hydrogen/ Deuterium), or $^{16}O/^{18}O$, as these isotopes remain stable until the water evaporates.

The determination of evapotranspiration rates are complex and rely on many variables including temperature, aerodynamic resistances, canopy resistance, stomatal resistance, Leaf Area Index (area of leaf surface over the projected ground surface of the canopy) and Vapour Pressure Deficit (VPD), which is the difference between saturated vapour pressure and the actual vapour pressure. An increase in VPD increases the vapour gradient, which drives evaporation, and in turn increases the canopy resistance (Wilkinson 2000). Several methods for calculating transpiration and evapotranspiration are available, the most commonly used were summarised by Wilkinson (2000) as:

- The Penman model, (Penman 1948) derived from energy balance and aerodynamic equations;
- The Priestely Taylor model, (Priestely and Taylor 1972) uses a very simple semi empirical formula which can not incorporate the necessary parameters for individual species (Wilkinson 2000); and
- Penman-Montieth model; Montieth (1965) first recognised that stomata pose the key resistance to water loss and expanded on the Penman model to improve simulation of vegetation feedbacks.

2.3.2 Soil Water

Water is contained within the soil structure in one of three ways; as gravitational, capillary or hygroscopic water. Both hygroscopic water and gravitational water are not available to plants (Moore and Clarke 1995). Gravitational water is excess water that drains away by gravity leaving the soil at field capacity. While at the other end of the spectrum hygroscopic water is always present in a soil but is bound to the soil particles. Capillary water is attracted to the hygroscopic water and forms a film around it, but has a lower cohesive bond strength so is freely available to plants. Wilting point refers to the boundary beyond which capillary water is not available to plants. The rate that water drains from the soil depends on the permeability and the water retention capacity, which in turn are dependent on the texture, structure and composition of the soil.

Once the gravitational water is lost from the system the water content will remain at field capacity unless water is removed through evaporation or root water uptake. Field capacity may approximate to unsaturated or saturated soil conditions depending on the soil type, as fine soils can remain saturated for several metres above the groundwater surface (Powrie 1997). Vegetation can influence the depth of saturation through root water uptake. Most plants are capable of applying between 1 and 2 MPa of tension to the pore water prior to reaching their wilting point (Taylor and Ashcroft 1972). However, if dry conditions persist wilting point will be exceeded for a prolonged period, and plants that are not adapted to drought conditions may die. Some vegetation compensates for dry spells by extending roots deeper, and some plants are able to redistribute deep soil water to a dry surface (Burgess *et al.* 1998). Burgess *et al.* (2000a) recommend that only methods capable of measuring slow and reverse rates of flow, which do not require assumptions of zero flow during the night, are applicable to studies with roots. Scholz *et al.* (2002) used a heat pulse system to measure bi-directional sap flow in eight dominant savannah trees and observed positive flow (soil to plant) during the day and negative flow at night.

The potential for water to be retained within the soil matrix is defined as the potential energy per unit volume for moving that mass from the reference state, which is typically free water (Tindall and Kunkel 1999). Total suction is a negative pressure that represents the amount of energy required to extract water from the soil, and may be expressed as atmosphere (atm), Pascal (Pa) or using the logarithmic Pf scale (Croney and Coleman 1961).

The two main components of total suction are matric potential and osmotic potential. Matric potential results primarily from adsorptive and capillary forces associated with the soil matrix. The capillary phenomenon arises from the surface tension of the water air interface (Figure 2.9), which is equal to the difference between pore water and pore air pressure (Powrie 1997).

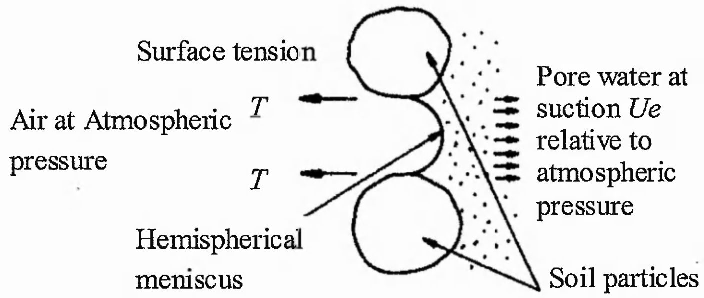


Figure 2.9 Surface tension for pore water at the air entry value (Powrie 1997)

Osmotic potential is the solute component of free energy and is related to the amount of salts dissolved in the pore water, and is derived from the measurement of the partial pressure of water vapour in equilibrium with the soil water, relative to the partial pressure of water vapour in equilibrium with free water (Fredlund and Rahardjo 1993).

Below the groundwater surface positive hydrostatic pressure is observed if there is no flow, while above the water table a variety of pore water pressure curves are possible depending on the soil type, climate and vegetation cover (Figure 2.10).

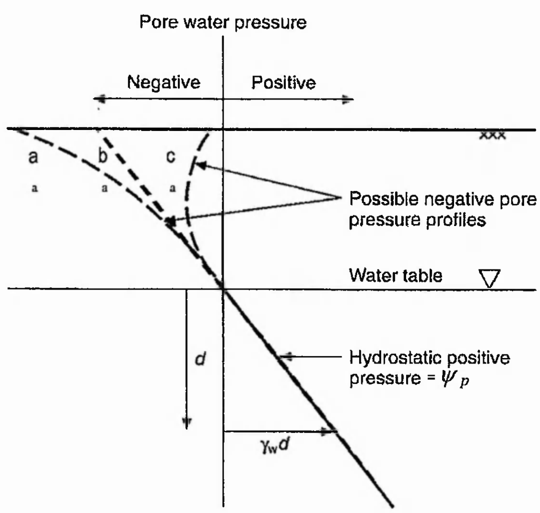


Figure 2.10 Distribution of pore water pressure with depth a Excessive evaporation, b Equilibrium with water table, c flooding of desiccated soil (Simons *et al.* 2002)

Vegetation cover dries the surface soil by applying tension to the pore water through evapotranspiration. The prolonged water extraction can lead to desiccation and the formation of surface cracks in certain susceptible soils, as the tension applied can readily exceed the lateral confining pressure in the soil (Fredlund and Rahardjo 1993). Anderson and Kneale (1984) observed the formation of shrinkage cracks on a clay embankment, and reported that although they closed up during the following wet season, the permeability had nevertheless been permanently increased by about two orders of magnitude. Desiccation cracks provide primary pathways for water to enter the soil system at depth, in some cases in close proximity to the shear surface (Greenway 1987). Therefore it is important to look out for the onset of desiccation. The influence of water demand and desiccation has been recognised in the construction industry, along with the converse effect (heave) resulting from tree removal (BRE 1999).

Numerous slope failures are caused by the changes in negative pore water pressures associated with heavy rainfall events (Fredlund and Rahardjo 1993). Therefore, the increase in total suction, induced by the removal of soil water through evapotranspiration must be carried through into the wet season to sufficiently contribute to slope stability.

2.3.3 Interception

Interception can have a significant effect on the sub-surface soil hydrology, reducing the amount of water entering the soil will in turn reduce the advance of any wetting front within the unsaturated zone and thereby reduce the pressure head, increasing slope stability. Rainfall is intercepted by foliage, and can either evaporate back into the atmosphere or reach the ground below the plant by one of three ways

- Direct through fall, where precipitation passes through gaps between plants and leaves;
- Stem flow water may flow down the stem or trunk; and
- Leaf drip this is an indirect form of through fall whereby the water has been stored temporarily on the foliage.

Interception losses are influenced by a number of factors, namely; rainfall intensity and duration, vegetation type and species, season and climate and the amount of vegetation cover. The interception process for trees is quite different to that observed in long grasses (Wilkinson 2000). Trees intercept a significant amount of rainfall under low intensities, but as rainfall intensity increases the storage capacity becomes saturated and interception rates decrease. While long grass allows a significant amount of through fall in low intensity storms intense rainfall flattens the grass forming a semi permeable barrier. This 'thatch effect' was observed on experimental plots in Hong Kong, where between half and three quarters of all rain formed runoff, without the infiltration capacity of the soil having been reached (Lamb and Premchitt 1990).

2.3.4 Hydraulic Conductivity

Increased capacities for infiltration have been experimentally observed on grassed slopes, Nassif and Wilson (1975) noted a four fold increase in infiltration rate on a gentle grassed slope, compared to a bare slope comprised the same clayey sand. Increased permeability and infiltration capacity of the surface soil layers of vegetated slopes may be attributed to the presence of roots, vacant root channels and increased macroscopic surface roughness (Greenway 1987). Roots exude as well as absorb water in response to gradients in water potential, and so act as conduits to deeper dry soil horizons (Burgess *et al.* 2000b).

An increase in permeability and infiltration capacity can result in a net increase in soil water hence higher pore water pressures, causing a decrease in the effective shear resistance of the soil. However, these effects are generally offset by increases in interception, transpiration and slope angle (Coppin and Richards 1990). If the hydrological discontinuity is marked enough, perched water tables may develop at the base of the root zone, causing the critical slip surface to change from deep and circular in nature to shallow and non circular (Wilkinson 2000).

2.4 CHEMICAL EFFECTS OF VEGETATION

Vegetation can also alter its local environment by adapting the soil chemistry, which is associated with the formation of topsoil. Topsoil is the product of a combination of soil forming factors including climate, flora, fauna, parent material and topography (Cruickshank 1972). The formation of topsoil results from the addition of living organisms (Biota), decayed organic matter (humus), water and air to the subsoil, which has formed through the weathering of the parent material (Waugh 1990). The decomposition and chemical and microbial transformation of organic matter is known as humification and gives rise to humus, which is an important component of topsoil. Humic and fulvic acids, although known to give specific characteristics to the soil are hard to identify and a satisfactory method has not been established (Tindall and Kunkel 1999).

A study conducted by Berger *et al.* (2004) compared an admixture of beech to spruce stands, each on a nutrient rich and an acidic soil, to establish how the species affect nutrient cycling and consequently soil chemistry. Soil analyses indicated more pronounced top soil acidification by spruce on the nutrient rich soil than on the acidic soil, while, the admixture of beech caused higher pH values in nutrient rich soil due to the observed accumulation of calcium (Ca) from deeper soil horizons (Berger *et al.* 2004). Brandtberg *et al.* (2000) also reported that concentrations of K, Ca and Mg were significantly higher in soil below mixed birch plots than in plots with pure spruce. Similarly, legumes are nitrogen fixators while heathers, rhododendrons and bracken can lower the pH of a soil to improve their surroundings. In addition, the ability of some species to partition certain heavy metals has been recognised and utilised for the phytoremediation of contaminated soil (Pilon-Smits 2005).

Liechty *et al.* (2005) studied the impact of two forest management systems on soil fertility, continual harvesting compared to a repeated harvesting and burning system thought to restore the site. The study revealed that mineralizable N, total N, C, Ca, and pH of the surface soil were higher in the restored stands than in the stands without restoration activities (Liechty *et al.* 2005). Alternatively, the potential for coarse woody debris to create a spatially discrete soil imprint through the release of carbon rich, acidic dissolved organic matter (DOM) was investigated by Spears and Lajtha (2004), because DOM has been implicated in many soil processes such as humus formation, nutrient immobilization, podzolisation, and the dissolution of soil minerals. However, Spears and Lajtha (2004), reported the effect of coarse woody debris on soil chemistry was small and limited to surface mineral soils.

Therefore, soil fertility is an important factor influencing plant growth, which in turn can be modified by the vegetation. The effect vegetation has on the soil chemistry may not directly have an impact on slope stability, especially if it is confined to the shallow surface horizons. However, soil fertility will have an indirect impact on the contribution of vegetation to slope stability, in that it will determine whether plants will populate the slope and potentially the depth of root penetration. Thomas (2000) concluded, from a study of root distribution and soil properties, that under the climatic conditions of Central Europe, the vertical root distribution of *Q. petraea* is more influenced by the availability of nutrients, especially that of nitrogen, than by the amounts of plant-available soil water.

When assessing the development of vegetation on roadside verges anthropogenic influences must also be considered. Colwill *et al.* (1982) conducted a survey to determine the sensitivity of shrubs to roadside conditions, for planting in central reservations. The research concluded that although there is a complex of traffic dependent factors from exhaust fumes, particulates and wind gusts, the main hazard to plants is salt from de-icing operations. However, Colwill *et al.* (1982) also stated that there is little salt hazard to deciduous trees and shrubs a distance of six metres from the highway, and salt tolerance can be increased by the use of lime and potassic fertilisers, where salinity is not an overriding factor (Colwill *et al.* 1982). Therefore, the application rates of salt for the region may need to be considered if the vegetation is planted close to the highway.

2.5 VEGETATION DEVELOPMENT

Vegetation has adapted and evolved to survive and exploit many environments, from tropical to tundra and from below sea level to high altitudes. The colonisation of a bare plot of soil with enough time and the absence of human intervention will exhibit natural stages of succession (Sere). A sere identifies the stage of development of the vegetation in an area and range from 'pioneer', where early colonisers such as herbs and grasses (weeds) are dominant, succession continues until the 'climatic' climax, is achieved. The vegetation that has reached equilibrium with the environment defines the climax vegetation. The climax vegetation for most of the UK is mixed oakwood across the lowlands or pine and birch further north (Pears 1985). In certain areas the climatic climax vegetation will not inhabit an area due to inappropriate soil properties in this instance the climax vegetation is referred to as an edaphic (rather than climatic) sere. Human influence, either management, farming or general disturbance of an area has resulted in climax vegetation becoming rare in many parts of the world (Pears 1985).

The long term stability of natural slopes may be influenced by sere succession or retrogressive succession, either of which, may be a response to climate change or management. Therefore, it is necessary to bear in mind when investigating a vegetated slope that the vegetation can change, and note that a site ought to be re-evaluated after a period of time. However, it is more likely that the timescale for a change in sere is less of a concern than the more immediate threat of drought, disease or forest fires.

2.5.1 Survival Strategies

Various plants have adapted different techniques to maximise and survive the cycle of the seasons. Annual plants complete their life cycle of; germination, growth, reproduction and death within one year while perennial plants grow for more than two years and generally have a dormant period to survive the winter. Raunkiaer (1934) reported several over wintering survival strategies of perennials, the evergreens such as conifers have waxy leaves to survive the cold and reduce transpiration, while deciduous plants may either shed their leaves or the plant may die back during the dormant period. Many fine roots are ephemeral and die back during a plants dormant period, as the roots shrink back or decay small conduits or open pore spaces are left increasing the hydraulic conductivity. The larger storage roots are perennial and act as a nutrient reserve, and support the plant, while the decaying organic matter is recycled into a nutrient source by soil micro-organisms.

The biomass is at a minimum during the dormant period, as both roots and shoots will die back reducing the reinforcing and buffering effects. In addition, the metabolic activity and transpiration are lower during the dormant period, which reduces the effects vegetation may have on the hydrogeology. Therefore, the ability of the plant to function as an engineering component throughout this period is an important consideration (Coppin and Richards 1990).

2.5.2 Root Development

Vegetation has been shown to contribute to slope stability through root reinforcement, anchorage and buttressing (Coppin and Richards 1990; Ekanayake and Phillips 2002; Wu *et al.* 1979). The effectiveness of any root reinforcement is dependent on the geometry and distribution of the roots, which are a function of the root development. Root development and growth are limited by a plant's genome, this genetic disposition (genotype) may initially affect the roots, but ultimately the development and structure is governed by environmental signals such as light, gravity and water and nutrient availability (Coutts 1982; 1983b; 1989; Coutts *et al.* 1999; Coutts and Nicoll 1991; Moore and Clarke 1995).

An awareness of the different functions of the various parts of the root is an important consideration when investigating the contribution of vegetation to the stability of a slope. The root hairs near the root tips are responsible for the majority of root water uptake, and the soil water content may be depleted where such roots are abundant. Whereas the mature roots do not absorb much water or nutrients but will contribute to soil reinforcement, however, cell differentiation within certain species can create weaknesses within the root structure, which in turn can influence the measurement of soil root interaction.

The growth and development of each individual root occurs at the root tip, which is divided into two key regions in front and behind the meristem (Figure 2.11). The meristem is a region of specialised tissue whose cells undergo cellular division, responsible for root growth. The meristem is protected by the root cap while the subapical region is located behind the meristem. The root cap not only provides protection against abrasive damage to the root tip, but also is involved in the simultaneous perception of a number of environmental signals (pressure, water and gravity, resulting in the related tropisms) that are of critical importance for the growth of the individual roots, and collectively for the shaping of the root system (Barlow 2002). Cell division within the root cap pushes the cells out to the periphery of the root cap where they differentiate into peripheral cells and are shed as the root grows (Moore and Clarke 1995).

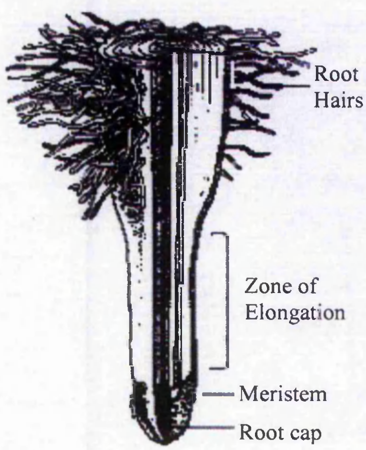


Figure 2.11 Section through root tip (Wray 1997)

The peripheral cells secrete mucigel, a hydrated polysaccharide containing sugars, organic acids, vitamins, enzymes and amino acids, which protect the tip from desiccation and lubricates the tip as it is forced through the soil (Moore and Clarke 1995). The first direct measurements of maximum root growth pressures, ranging from 0.7 to 2.5 MPa for different plant species, were recorded by Pfeffer in 1893 (Gill and Bolt 1955). Pfeffer concluded that for the root to elongate, the mechanical impedance of the soil matrix acting against the cross section of the root must be less than the pressure exerted by the root itself (Moore and Clarke 1995). More recent studies by Bengough and Mackenzie (1994), reported pressures of up to 0.1 MPa in seedling pea roots, and observed an increase in root diameter in response to mechanical impedance. A micro morphological analysis conducted by Hutchings *et al.* (2001) showed roots exploited weakness in the soil rather than actively penetrating it. However, the ability of some species to penetrate stronger soil layers may be due to wider roots being less likely to deflect or buckle when strong layers are encountered (Clark *et al.* 2003).

The subapical region is subdivided into zones of elongation and maturation. The zone of maturation is distinguished by the presence of root hairs, which are fragile extensions of epidermal cells that only live a few days and are constantly replaced by new ones closer to the root tip soil (Moore and Clarke 1995). Root hairs increase the absorptive surface area of the roots several thousand fold, and so enable the plant to extract water and dissolved minerals from soil, while microbes may modify or secrete compounds to be absorbed (Moore and Clarke 1995). Beyond the zone of maturation a few centimetres behind the root tip is the mature region. The outer cells become waterproofed with the waxy substance suberin (suberizered) and root hairs are no longer present, in some woody species there is secondary growth of protective bark, resulting in little absorption of water and nutrients in the mature region.

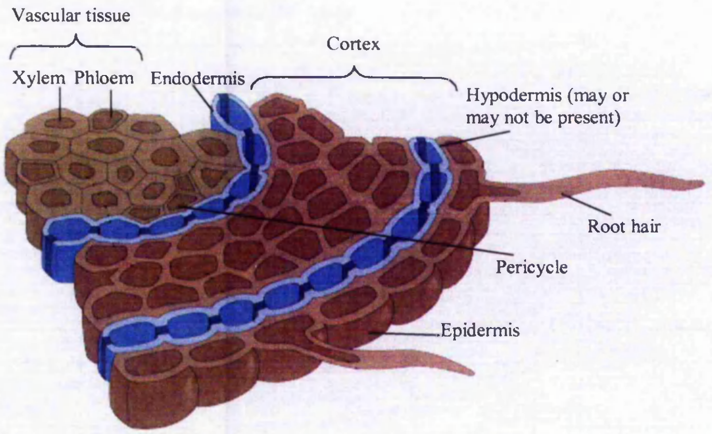


Figure 2.12 Key cell differentiation illustrated in root section soil (Moore and Clarke 1995)

The non-absorptive or mature region contains differentiated cells and a cross section of the root structure (Figure 2.12) exhibits concentric layers of the epidermis (protective outer layer), cortex (bulk of the root cross section), and the endodermis, which regulates the movement of nutrients into the vascular system, the collective term for the cortex and inner vascular tissue is the stele, while the epidermis is often referred to as bark. Some species exhibit a weakness between the bark and stele, evident when roots are pulled out of the ground. The pericycle is located between the central vascular tissue and pith, which is important as it produces the secondary or branch roots and also contributes to secondary growth in the roots of some plants soil (Moore and Clarke 1995). The pith or parenchyma tissue stores reserves for subsequent use and is not always present.

The mature region of the roots can produce second order roots that act as further anchorage for the plant, and lay down reaction wood in response to mechanical loading (Niklas 1992). Roots have been reported to respond to both wind loading and developing on sloping ground in a similar manner of growing tension or compression wood, forming asymmetrical roots (Chiatante *et al.* 2003; Di Iorio *et al.* 2005; Nicoll and Ray 1996; Stokes *et al.* 1998; Tamasi *et al.* 2005).

The mechanical input of root reinforcement is largely dependent on the mature region of the roots and the secondary growth that occurs in the structural roots of woody species. The strength of these roots is a function of their shape as well as composition. Gardiner and Quine, (2000) comment that the uneven shape found in structural roots, produces stiffer root systems and reduces the chance of the soil shearing and separating from the roots under self loading forces. Nicoll and Ray (1996) reported that much of the secondary growth occurs on the upper side of the root forming a T beam near the tree or an 'I' beam farther from the tree base (Figure 2.13). 'I' beams resist vertical flexing better than any other shape with the same cross sectional area, rectangular, elliptical or circular (Coutts *et al.* 1999). Watson *et al.* (1999) suggest that the response to overturning forces is based on the development of an asymmetrical root system to more efficiently distribute the tensile strength amongst the lateral roots.

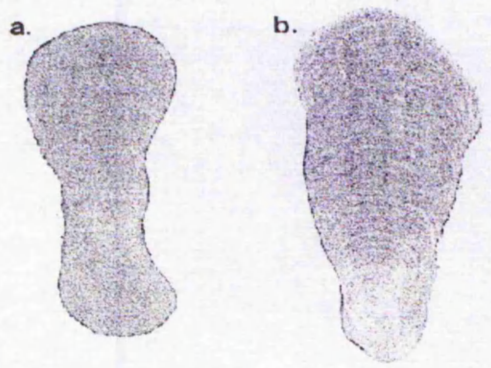


Figure 2.13 Cross sections of Sitka spruce structural roots a) I beam, b) T beam (Coutts *et al.* 1999)

2.5.3 Root Morphology

The magnitude by which vegetation can affect slope stability either mechanically or hydrologically depends on the depth, extent and density of the root system. Root system morphology is complex and exhibits much variation, depending on species, soil type and site conditions (Coutts 1983b). Root distribution is dominated by genotype along with the plant's response to environmental signals and a requirement for water, air, nutrients and stability, the permutations of which result in every root ball being unique. The plant's response to an environmental signal is known as a tropism, the most familiar are phototropism, gravitropism, hydrotropism and chemotropism. Thigmorphotropism is the response to movement evident in tree subjected to prevailing winds, which results in thickening of the root system.

Hydrotropism and gravitropism are two important controlling factors influencing root distribution as roots respond to environmental signals, such as water potential, and grow to exploit available water and nutrients within the soil (Coutts 1982; Coutts and Nicoll 1993; Tsutsumi *et al.* 2003). Coutts and Nicoll (1991) also demonstrated that some lateral roots are plagiogravitropic, they grow obliquely upwards, until they approach the soil surface and then respond to some environmental signal that causes downward deflection. The environmental signal was not determined but the downward deflection occurred in both samples that were and were not exposed to light (Coutts and Nicoll 1991).

Root development may also be influenced by edaphic conditions, Schtein, (1996) observed that root growth may be hindered by mechanical impedance, where obstacles such as gravel or a compacted soil layer may be encountered or the presence of a shallow water table (Coutts 1983a) or competition from other root systems (Dawson *et al.* 2001; Gray and Sotir 1995). When such obstacles are encountered by the root tip the genotype may be altered through adaptive growth and the phenotype is expressed.

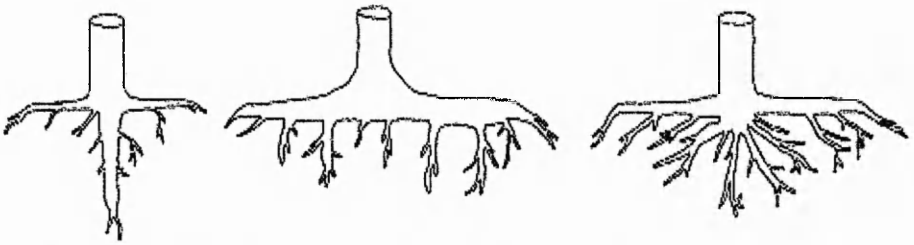


Figure 2.14 The three main idealised root system forms Tap, Plate and Heart (Stokes and Mattheck 1996)

However, root morphology for dicotyledons may be classified into one of three basic idealised root system forms proposed by Kostler *et al.* (1968) these are the taproot system, plate root system and the heart root system (Figure 2.14). Dicots have both tap and fibrous roots, while monocots, such as grasses, have fibrous roots only. More detailed root system classifications have been developed to incorporate secondary, adventitious and non-woody (fibrous) roots (Kolesnikov 2003).

A taproot system maximises support and storage and is found in self-supporting plants that require rigid elements in their anchorage systems to prevent them toppling. Small herbaceous dicotyledons tend to possess tap root systems, while larger herbaceous dicotyledons and trees possess the plate system (Ennos 2000) or a heart root system where lateral roots sink down at an angle some distance from the stump. The presence of excessive water in saturated or 'waterlogged' soils results in anaerobic conditions that can lead to the death of trees (Coutts 1983b) it can also result in a shallow plate like root system. Conversely, a well drained soil will encourage a deeper root system as the roots exploit the soil's reserves.

Procumbent and climbing plants, which must resist being uprooted vertically, are most efficiently anchored by a fibrous root system (Ennos 2000). A fibrous root system comprises a mass of similarly sized adventitious roots that maximise absorption. Adventitious roots develop from auxiliary buds or on an organ other than the primary root or out of its normal sequence (Moore and Clarke 1995). Fibrous roots tend to be concentrated near the soil surface due to the requirement for oxygen and nutrients, while taproots and sinker roots tend to penetrate deeper into the soil for anchorage and water. Sinker roots are secondary roots that grow vertically downward, excluding those vertical roots that have grown in sequence with the central root complex, such as the tap root (Sutton 1983).

Root morphology is also influenced by the response of the root system to tensile and compressive forces (Stokes *et al.* 1997), and a study by Schiechtl (1980) suggests roots growing up hill are stronger than their counterparts downhill due to the differences in tissue structure. Chiatante *et al.* (2003) found that plants on steep slopes develop asymmetrical root architecture while the same species on plane soil shows a normal symmetrical architecture. The lateral roots growing in the up and down slope directions present considerable anatomical modifications in shape and tissue organisation, which seems to increase the plant's stability by modifying the distribution of mechanical forces into the soil (Chiatante *et al.* 2003).

Mattheck (1997) reported that plants strive to enhance mechanical strength through adaptive growth in areas of highest strain. Similarly, adaptation of tree roots to wind loading occurs through the formation of reaction wood at those sites most affected by strain (Stokes 1999). Reaction wood may be formed in roots, shoots and stem of the plant, the vascular cambium produces secondary xylem (wood) that mechanically acts to correct the limb either by contraction or expansion, the wood that contracts is classed as tension wood and that which expands is compression wood (Niklas 1992). Therefore, predisposition of certain genotypes to exhibit particular root morphology depends on environmental triggers affecting the growth of each individual root.

2.5.4 Mycorrhizal Associations

The rhizosphere is the small area of soil around the root, which is affected by root respiration, exudation and mycorrhiza and the population density of microbes is 10 to 100 times that of the surrounding soil (Moore and Clarke 1995). The microbial activity, organic matter and nutrient cycling within the rhizosphere may not appear to directly contribute to slope stability. However, the distribution of root hairs, microbes and mycorrhizae can affect the efficiency with which a root can exploit the soil for water and nutrients and in turn affect the growth and distribution of roots. Mycorrhizae occur in more than 80% of all plants and are mutually beneficial associations between roots and fungi (Plate 2.1), which increase nutrient absorption as the fungal hyphae have a greater surface area and permeate a greater soil volume than roots (Moore and Clarke 1995).

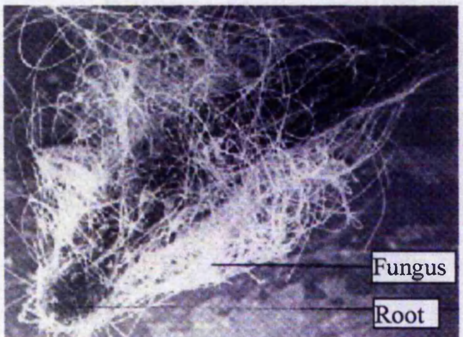


Plate 2.1 Scanning electron micrograph of a mycorrhiza (Moore and Clarke 1995)

The parts of the root system active in the uptake of water and nutrients are the short lived very fine roots, typically less than 0.5 mm diameter (BS 5837: 1991). Fine root production and turnover are important processes in the overall cycling of nutrients in a forest ecosystem (John *et al.* 2002), since the renewal and death of fine roots take place simultaneously, they continuously add nutrients to the soil system (Persson 1983). Kemp *et al.* (2003) estimated the proportion of the root system comprising hair roots and the mycorrhizal colonization in *Woollsia pungens* (Cav.) *F. Muell.* (*Epacridaceae*) and reported that hair roots persisted throughout the 12 month period comprising at least about 50% of the root system. The percentage of root length that was hair root varied with the season, being lowest in April/May (50%) and highest in October (70%).

A comparative study by Lee and Jose (2003) on cottonwood and loblolly pine showed that fertilization did not affect fine root production in either species, but microbial biomass was significantly reduced by nitrogen fertilization in both species. Lee and Jose, (2003) conducted multiple regression analysis which indicated that microbial biomass, soil organic matter, and soil pH were the major factors affecting soil respiration in cottonwood, while fine root production and soil organic matter were the major factors affecting soil respiration in loblolly pine.

2.6 SLOPE STABILITY

A slope is a dynamic open system that is affected by biotic, climatic, gravitational, hydrogeological and tectonic inputs, which vary in scale and time (Waugh 1990). Materials are governed by the laws of equilibrium and compatibility. Forces give rise to stresses, and if these are not in equilibrium the body may move. Displacements give rise to strains, which must be compatible so the material does not tear or overlap. The relationships between forces and displacements (stresses and strains) are governed by the material characteristics. To take account of approximations in the theories adopted for material behaviour, and uncertainties in the determination of strength and stiffness parameters, it is usual to apply a factor of safety in the design. These factors may be applied as partial factors to reflect various uncertainties or lumped together as a single value

The stability of a slope is dependent on the balance of disrupting and restoring forces, the ratio of which gives the Factor of Safety and is used to quantify the stability of a given slope. When these forces are equal the Factor of Safety is 1, and indicates the slope is on the point of failure, therefore, is unstable or marginal. Slope stability can be improved by ensuring the restoring forces are greater than the disrupting ones. This can be achieved in a number of ways including: loading of the toe, re-grading the slope angle or introducing appropriate drainage (Perry *et al.* 2003c).

2.6.1 Types of Failure

Mass movement refers to the downhill movement of any weathered material (rock or soil) in response to gravity, but excludes erosional processes due to ice, wind or water; however, water still plays a major role in slope stability. Bromhead (1992) uses three major classes of mass movement, based on their morphology: slides, falls and flows. A slide is characterised by the presence of a discrete boundary shear surface, the unstable material moves *en masse* and remains in contact with the underlying stable strata. In a fall the material becomes detached from the parent material and may encounter intermittent contact as it tumbles down a typically steep face. A flow suffers internal derangement and although can remain in contact with the ground it travels over, it is not always the case (Bromhead 1992).

There are many other classification schemes available for slope failure, based not only on the morphology but also the speed and the amount of water present, for example the scheme shown in Figure 2.15.

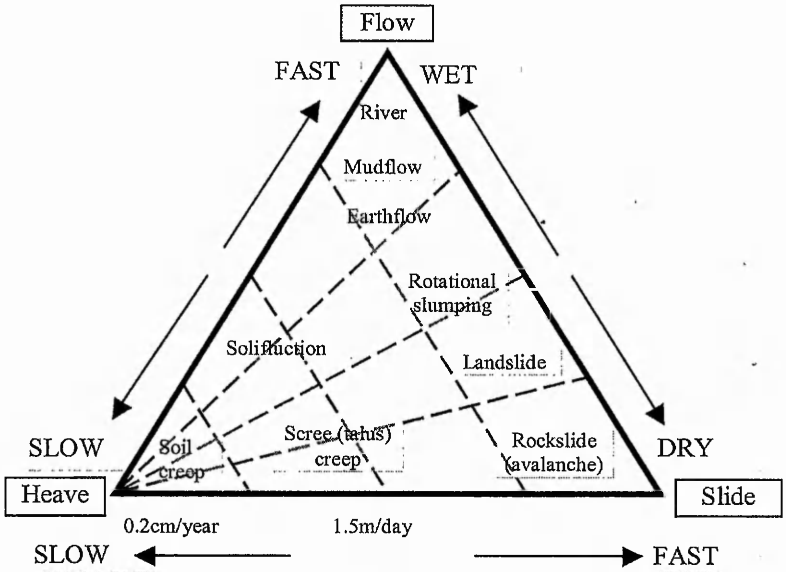


Figure 2.15 Mass movement processes classification (Waugh 1990)

Soil creep is often difficult to detect as it occurs at a rate of less than 1 cm per year, and is often identified by the distortion of walls, telegraph poles or trees. Therefore, trees are also commonly used as indicators of slope instability rather than considered for their bioengineering contribution. The movement of the surrounding soil may rotate saplings, but as the tree grows the root system becomes sufficient to stabilise the tree and the subsequent stem growth compensates to correct the trunk to near vertical. This adaptive growth results in a curvature near the base of the tree known as basal sweep (Moss

1971). Basal sweep can also occur in trees located on stable slopes. This happens when the roots do not provide sufficient anchorage resulting in lodging of the sapling, subsequent corrective growth occurs as the tree becomes established, however, the curvature at the base of the trunk will remain evident. Terracettes are another indicator of creep, which form where the covering vegetation is stretched and torn as the soil slowly moves, as a result of the continual expansion and contraction that occurs in shrinkable soils exposed to heavy rainfall and dry periods.

Landslides and rock falls on the other hand display a rapid movement when failure occurs. Landslides may be further subdivided by their morphology into translational and rotational slides. Translational slides can take the form of a slab sheet or block while rotational slides can be circular or non circular. Complex geology often results in the formation of compound slides, which is a combination of failures (Figure 2.16).

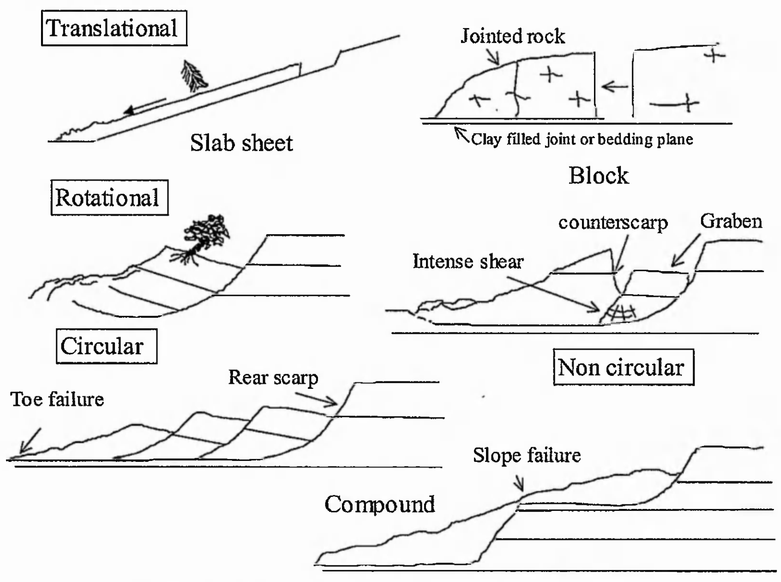


Figure 2.16 Types of slide (Bromhead 1992)

Unfortunately the depth of influence of the covering vegetation limits the beneficial contribution of vegetation to the surface soil horizons. However, the survey of embankment and cutting within the UK conducted by Perry (1989) revealed that the vertical depth of failure rarely exceeded 1.5 m with a minimum depth of 0.2 m and a maximum depth of 2.5 m, with 46% of the total slips between 1 and 1.5 m depth, which may fall within the zone of influence of many types of vegetation. In addition, reinforcement of the surface layers may reduce the occurrence of shallow landslips, creep and erosion, but will not necessarily effect falls, flows or deep seated landslides. Intermediate depth slip surfaces may be influenced by the root zone where the critical surface daylights. Alternatively, vegetation can improve the soil properties of the shallow horizons sufficiently to alter the morphology of the critical surface and by doing so can marginally increase the factor of safety of the slope. However, the focus of most bioengineering techniques has been to stabilise shallow instability and prevent erosion.

2.6.2 Bioengineering Techniques

Mitchell and Jardine (2002) suggest the use of trees and shrubs in combination with other techniques of slope reinforcement, such as gabion buttresses, geotextiles and crib walls. Although, Mitchell and Jardine (2002) do warn that vegetation takes a considerable time to become established and external factors may result in deterioration or destruction, and conclude that it would be wrong to rely on any contribution from vegetation to provide slope stability. However, Gray and Sotir (1996) outline several bioengineering techniques, such as live staking, fascines, brush layering and branch packing (Figure 2.17).

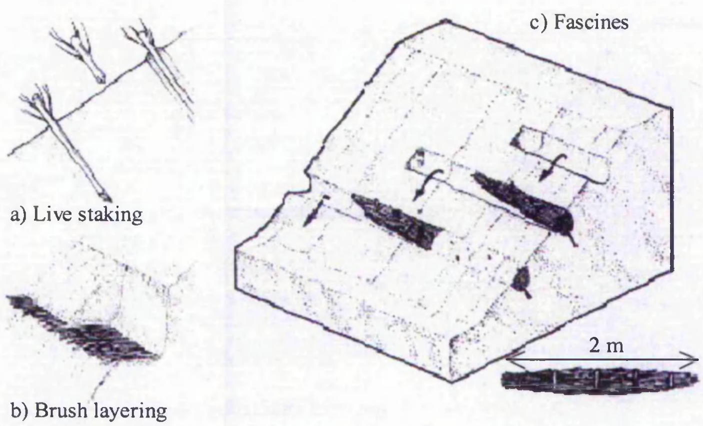


Figure 2.17 Bioengineering techniques, a) willow poles, b) brush layering and c) fascines (Coppin and Richards 1990)

Live staking involves the insertion of live, vegetative cuttings into the ground such as willow poles, which will take root; these may be inserted directly into soft ground or placed into predrilled holes with a backfill of suitable topsoil. Fascines are bundles of live rootable plant material such as stems and branches of willow, dogwood and alder; these may be anchored into shallow trenches with live stakes (Coppin and Richards 1990). Brush layering and branch packing utilise live cut branches interspersed between layers of soil, brush layering is considered more successful when conducted during construction while branch packing is a remedial technique used to repair holes and depressions in slopes (Gray and Sotir 1996).

2.6.3 Methods of Analysis

There is an iterative loop between investigation and analysis the input parameters may determine the testing conducted during the investigation, but at the same time the testing techniques will determine what parameters may be available to input into a model to analyse the stability of a slope. Quantitative methods of slope stability analysis have been developed over the last century; some changes have been the product of better investigation techniques while other developments have encouraged improvement in testing techniques. Therefore, even though stability analysis may be the final stage of a slope assessment, knowledge of the significant parameters will determine what investigation is conducted, while available testing techniques may limit the number or quality of the parameters obtained. Similarly, to investigate a slope to determine the contribution of vegetation to slope stability it is important to be aware of the available methods of analysis and the required input parameters, which have been developed from an understanding of the effects vegetation can have on the various soil properties, and also understand the limitations of the testing and sampling techniques available.

Crozier, (1986) outlines the most salient advancements from the development of the principle shear strength model (Coulomb 1776; Mohr 1914) through differentiation of 'total' stress and 'effective' stress and accommodation within Mohr-Coulomb law by Terzaghi (1936). Effective stress led to the necessity for a range of testing procedures and the determination of pore water pressure, and Bishop (1955) incorporated negative pore water pressures (or suctions) into the effective stress model. Further developments followed from the distinction between 'long term' and 'short term' failures (Skempton 1964) to the development of probabilistic approaches in slope stability analysis (Lumb 1974; Ward *et al.* 1981).

Other advancements include the 'Method of slices' developed by Fellenius (1927), the frictional circle method for rotational landslides in homogeneous soils (Taylor 1948), infinite slope analysis for shallow translational slides on planar surfaces (Henkel and Skempton 1954), a non circular routine developed by Janbu (1973), the inclusion of seepage forces within the infinite slope analysis (Hartsog and Martin 1974) and the modification of the general limit equilibrium method to analyse the influence of soil suction on slope stability (Fredlund *et al.* 1981). Similarly, Greenwood (1983) developed the simplified method of slope stability analysis.

Since then numerical models have been developed that combine both slope hydrology (incorporating both positive and negative pore water pressures) and slope stability (Anderson and Howes 1985; Anderson and Lloyd 1991). Both finite element and discrete element models are available for slope stability analysis allowing the engineer to model and analyse the likely failure mechanism, timescale and amount of movement. Constitutive models are now being utilised to predict the behaviour of soils and include factors such as anisotropy and over consolidation stress history, on the shear stress strain and volumetric behaviour of clays (Pestana *et al.* 2002).

While geotechnical models have been developing certain researchers have focussed on the development of models to include the contribution of vegetation to slope stability. Wu *et al.* (1979) incorporated the effects of vegetation in the form of increased cohesion (due to root reinforcement), surcharge and disturbing force (due to wind loading) into the infinite slope model, which formed the basis for a parametric study described by Bache and MacAskill (1984). Lee (1985) applied a modified form of the Janbu method to assess the Factor of Safety for a vegetated slope in Hong Kong. Along with the aforementioned vegetation parameters Lee (1985) also considered soil arching, hydrostatic pressure and expressed increased soil suction due to vegetation as an enhanced cohesion rather than a reduction in pore water pressure.

The Greenwood simple equation (1983) has been modified to account for the contribution of vegetation, detailed in Coppin and Richards (1990) which has subsequently been incorporated into the SLIP4EX model (Greenwood 2005). Vegetation has also been incorporated into the Combined Soil Hydrology – Slope Stability Model (CHASM), a finite element package (Wilkinson 2000). Meanwhile, Ekanayake and Phillips (2002) developed an energy approach model to analyse the contribution of vegetation to slope stability and more recently another finite element package FLAC, has been modified to include root reinforcement (van Beek *et al.* 2005).

The aforementioned models require geotechnical and vegetation parameters with additional hydrological parameters for the CHASM model. Some of the parameters may be assumed; however, to produce a useful output from the model, it will be necessary to determine most of the parameters directly from an effective investigation of a vegetated slope.

2.7 SUMMARY

The effects of vegetation on slope stability can be beneficial or adverse depending on the soil/rock type, slope morphology and type of vegetation cover. To ascertain the stability of a slope and to determine the influence of the vegetation present it is necessary to understand the effect vegetation has on its local environment. This chapter has highlighted the factors influencing root development and the effects vegetation can have on the slope, soil, water and chemistry, which are summarised below.

Vegetation is recognised as an organic weathering mechanism, disintegrating the rock and facilitating soil formation. Trees have often been considered detrimental to rock slopes, as roots can penetrate joints and bedding planes within the rock and steadily widen the cracks, eventually blocks may become separated from the parent material and become unstable. The decay of plant material, which is assisted by the action of bacteria and fungi forms vegetable humus, and eventually soil, however, the pH of humic acid promotes chemical weathering (Blyth and de Freitas 1984).

Vegetation cover provides a protective buffer zone between the atmosphere and the soil, which partially absorb the erosive energy of wind and water (Miura *et al.* 2003; Styczen and Morgan 1995). The contribution of vegetation has been observed through forest management practice (Dhakal and Sidle 2003; Ziemer and Swanston 1977) and successfully used for erosion control on stream banks and grassed waterways (Amarasinghe 1996; Hewlett *et al.* 1987; Hoitsma 1999). Mountain forests not only protect their immediate environment from soil erosion but may also protect people, buildings and infrastructure from the direct impact of natural hazards such as snow avalanches and rockfall (Brang 2001).

Roots have been shown to enhance soil shear resistance by binding or reinforcement (Abe and Iwamoto 1986b; Endo 1980; O'Loughlin 1974; Waldron 1977; Ziemer 1981b). However, reinforced soil relies upon deformation for its effectiveness, i.e. soil strain has to be transferred to the reinforcement for it to develop its tensile or bearing resistance. Researchers have also demonstrated that root strength deteriorates within a few years of felling (Burroughs and Thomas 1977; O'Loughlin and Watson 1981; O'Loughlin and Ziemer 1982; Watson *et al.* 1999; Ziemer and Swanston 1977) and the propensity for shallow landslides is increased after clear felling of forested slopes (Furbish and Rice

1983; Gray 1970; Gray and Megahan 1981; O'Loughlin 1974; Sidle 1992; Sidle and Wu 1999; Wu *et al.* 1979).

As roots decay small conduits are left within the soil increasing permeability and infiltration capacity (Archer *et al.* 2002). The increase in infiltration can be a beneficial factor allowing water to drain out of the system more readily, however, water will pond if it encounters a discontinuity in the hydrological profile, such as a less permeable layer below the root zone. Ponding can result in an increase in pore water pressure, which in turn can promote failure.

Wind loading may be a factor, where trees are present, as the forces induced in vegetation by wind can be sufficient to disturb upper soil layers, which can in turn initiate landslips (Coppin and Richards 1990). However, increase in wind loading is only considered relevant when new edges are created by harvesting or clearing for road construction (Gardiner and Quine 2000). Trees grown within a stand are protected from wind loading by the surrounding canopy, while those established near the edge of the stand will have adapted to the increased exposure while growing, and therefore, are at no greater risk than those within the forest stand (Morgan and Cannell 1994). Surcharge can act as a restoring or disturbing force depending whether it is placed toward the toe or crest of a slope, respectively. Surcharge from grasses and shrubs may be considered negligible, however, estimated values of a mature forest stand range between 1 and 10 kN/m^2 (O'Loughlin 1974; Wu *et al.* 1979).

The reduction of rainfall into the soil system and uptake of water from the system increases soil suction and soil strength. Marsland (1997) reported that a small relative increase in suction from 10 kPa to 15 kPa can prevent a slope from failing, but in shrinkable clay soils desiccation cracks form. Albrecht and Benson (2001) reported that hydraulic conductivity increased by as much as 500 times with the formation of desiccation cracks, facilitating the problematic flow of water down to the critical slip circle or ponding at a hydraulic discontinuity, and promoting failure.

Equipped with the understanding of how vegetation effects its environment it is then possible to ascertain the most pertinent parameters for characterising a vegetated slope, to ascertain the contribution of vegetation to slope stability. To facilitate the quantification of these parameters it is necessary to investigate which are the most suitable techniques available and then compile them to develop a framework for the geotechnical investigation of a vegetated slope. Therefore, the following chapters outline the techniques available for the determination of geotechnical, biomechanical and hydrogeological parameters necessary to characterise a vegetated slope and ascertain the contribution of vegetation to slope stability.

Geotechnical Investigation Techniques

3

Art is born of the observation and investigation of nature.
Cicero (106 BC - 43 BC)

Chapter 2 established the effect vegetation can have on slope stability either directly or indirectly, and the importance of selecting appropriate parameters and testing techniques to produce a meaningful slope stability analysis. Similarly, to develop a framework to investigate a vegetated slope an understanding of the available techniques and the actual parameters that may be obtained is required. Geotechnical and hydrogeological parameters are essential for slope stability analysis regardless of the potential contribution from vegetation. Therefore, geotechnical slope characterisation is an integral component of a vegetated slope investigation, and as such it is important to ascertain which techniques are most suitable for investigating a vegetated slope; either because the technique will have minimal impact on the vegetation or because the sample quality is not influenced by the presence of vegetation.

Methods for ground investigation include excavation of exploratory holes to facilitate *in situ* testing and sampling, subsequent laboratory testing and the installation of monitoring instrumentation, and in certain circumstances geophysical techniques may be employed. A selection of the available methods is required to assess the ground conditions and ascertain the key parameters for slope stability analysis. This chapter outlines the parameters employed for a geotechnical slope stability analysis and the established ground investigation techniques available to obtain this information. Although vegetation has been demonstrated to increase shear resistance and exert suctions that can improve slope stability it is still important to assess the soil parameters despite the vegetation, but without destroying it, because the vegetation present may prove to be beneficial to the slope.

The inclusion and evaluation of soil sampling and testing techniques in this chapter is primarily concerned with the impact on the vegetation or the susceptibility of sample quality to the presence of vegetation. However, the acquisition of geotechnical data is of such importance that some soil sampling and testing will have to be conducted regardless of the impact on the existing vegetation.

Although hydrogeological parameters are usually ascertained in a geotechnical investigation and could be included in this chapter, the techniques employed to determine the hydrogeological parameters and the effect of vegetation on soil water conditions are discussed together in Chapter 5. Techniques for evaluating the vegetation cover and assessing the mechanical contribution of vegetation will be discussed in Chapter 4.

3.1 SOIL PROFILE

Before discussing geotechnical investigation techniques it is necessary to clarify what part of the soil profile is of interest to geotechnical engineers; which is soil that can be used as an engineering material. Powrie (1997) comments that geotechnical engineers are not interested in the top metre of soil as it is too variable, too near the surface, too loose and compressible, has too high an organic content and is too susceptible to the effects of plants, animals and seasonal changes in the groundwater level. Therefore, topsoil and subsoil are often given cursory evaluation or overlooked when conducting a geotechnical investigation. Hence, the British Standard for topsoil (BS 3882: 1994) specifies requirements for topsoil as a material and establishes three grades (Premium, General purpose and Economy). However, these grades are not appropriate for the grading, classification or standardization of *in situ* topsoil or subsoil.

The Highways Agency (HA 44/91 1991) illustrates the distinction between agricultural and engineering soil (Figure 3.1), however, this is a simplistic model, and the entire soil profile is considered by a number of disciplines, but to varying degrees of detail depending on their bias. The study and classification of soil by pedologists is quite different to the engineering soil descriptions employed by geotechnical engineers (BS 5930: 1999). Pedology studies the morphology, genesis and distribution of soils in the places where they have formed, while agricultural scientists are more concerned with classifying the soil as a resource, which is essential for the successful growing of crops. Although, agricultural scientists may focus on the soil fertility and its properties as a substrate, the pedological classification of the soil profile provides a fundamental framework.

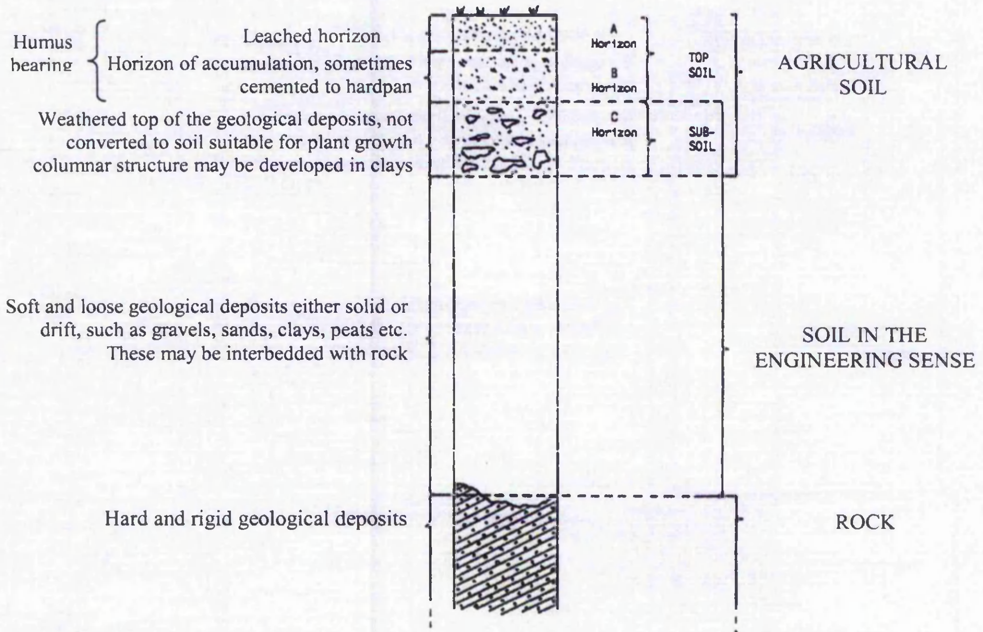


Figure 3.1 Relationship between agricultural and engineering soil (HA 44/91 1991)

Dokuchaev proposed an elementary classification, the A, B, C sequence of horizons, of natural soils in the 1880s (Cruickshank 1972). Attempts have been made to establish new nomenclature, following new understanding of soil genesis, however, the A, B, C system has prevailed as it can be subdivided to provide a complete scheme of soil horizon possibilities. Guidelines for the description of soil have been published by the Food and Agriculture Organisation of the United Nations (F.A.O. 1990).

3.2 SITE INVESTIGATION PROCEDURE

Site investigation is the process by which geological, geotechnical and other relevant information, which might affect the construction or performance of a civil engineering or building project is acquired (Clayton *et al.* 1995); whereas, ground investigation is the process, involving the acquisition of information on the ground conditions, in and around a site (Simons *et al.* 2002). However, the two terms are often used interchangeably. Site characterisation is a term coined in the geo-environmental discipline, the purpose of which is to determine the biological, chemical and physical properties at a site that directly affect the movement of contaminants (Tindall and Kunkel 1999). This term may be considered more applicable to the investigation of vegetated slopes, as other disciplines are employed alongside geotechnical.

Best practice for a geotechnical site investigation comprises three phases, namely the initial, main and review stage. The initial stage includes a desk study to facilitate the acquisition of any available data, a site visit for the visual assessment and concludes with a preliminary report and fieldwork plan. Slope parameters such as the overall height and angle of slope may be obtained in the initial phase, either from sufficiently detailed maps or a topographic survey conducted during the visual assessment. The main stage includes the ground investigation which comprises; *in situ* testing and sampling and laboratory testing to obtain the soil parameters, all of which is summarised in a final report. The review stage includes monitoring during excavation and construction and feedback reports. Site investigation is an iterative process and information obtained during the main or review stages may lead to supplementary investigation.

Various standards are currently available worldwide, however, the most pertinent to the UK are the British Standard (BS 5930: 1999). Other key documents available to facilitate effective site investigation include the Association of Geotechnical and Geo-environmental Specialists (AGS) 'Code of conduct for site investigation' (AGS 2004) and the Thomas Telford series 'Site investigation in construction' (Site Investigation Steering Group 1993). CIRIA have also published guidelines for the appraisal of infrastructure cuttings and embankments, C591 and C592, respectively (Perry *et al.* 2003a; 2003b).

3.3 SOIL PARAMETERS

In order to evaluate the techniques available to characterise a vegetated slope it is necessary to assess what parameters can be ascertained from the available investigation techniques. Slope stability analysis may be conducted using one or more of; limit equilibrium; bound methods; and finite / discrete element modelling. All the methods involve certain approximations and simplifications and as a result may over estimate or underestimate the factor of safety of the slope. To minimise errors in modelling it is important to input good quality data obtained from the ground investigation, or at least have an understanding of the limitations of the test and the reliability of that data.

The input parameters for most slope stability analyses include height and angle of slope, depth of strata and soil strength parameters, along with pore water pressure, groundwater and seepage data, obtained from the ground investigation. Soil is stress history and path dependent, its behaviour is governed by the recent stress and strain history and current stress and strain changes (Atkinson *et al.* 1986) therefore, strength tests ought to be conducted *in situ* or on intact samples with the *in situ* stresses are replicated.

Finite element analysis utilises internal friction angle and shear strength parameters, but to determine displacements at relatively low stress levels, parameters gained from advanced field and laboratory testing such as the coefficient of earth pressure at rest (K_o), shear modulus (G_{max}), Poisson's ratio (v), and Young's modulus (E) are also required. So far the contribution of vegetation to slope stability has only been reported in terms of relative increase in shear strength of mass via reinforcement rather than shear modulus, because it is treated as two elements in terms of stiffness.

The choice of failure or strength states will affect the overall slope stability analysis and different factors of safety will be obtained from using peak or residual parameters. The pore water pressure and water content also influence the strength of a soil. Therefore, the distinction between drained or undrained tests is also important as the data from such tests are used for either effective or total stress analysis. Simons *et al.* (2002) state that for effective stress analysis the relevant parameters are not the peak or the residual parameters but approximate to the critical state values or 'fully softened' strength. Should a pre-existing failure surface be present in a slope, the relevant parameters for design or analysis are the residual values.

3.3.1 Strength States

The strength of a soil is the maximum stress the soil can sustain as it suffers large shear strains. A stress is the intensity of loading given by a force acting on a unit area while a strain is the intensity of deformation given by a displacement over a unit gauge length. The unit area or gauge length must be, large enough to include a representative number of soil grains, and because uncemented soils cannot sustain tensile stresses compressive stresses are taken as positive (Atkinson 1993).

The soil may exhibit either ductile or brittle failure when subjected to the maximum stress it can sustain (Figure 3.2), and the failure state of the soil is affected by the stress history and water content. Heavily over consolidated clays or dense sands (on the dry side of critical) will dilate on shearing and will reach a peak shear stress before failure, while loose sands and normally consolidated clays (on the wet side of critical) reach an ultimate state where the shear stress is constant and there are no more volumetric strains (Atkinson 1993).

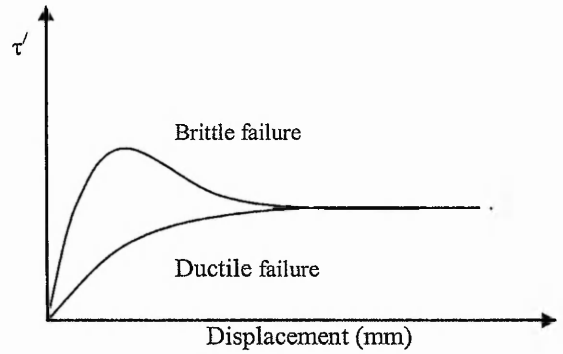


Figure 3.2 Ductile and brittle failure

Peak state will normally be reached at strains of 1% while the ultimate states will be reached after strains greater than 10% and in some soils 50% (Atkinson 1993). A residual state occurs in fine soils over large displacements and is associated with laminar flow, (Figure 3.3) where the flat clay particles have become orientated parallel to the rupture zone. Residual strength parameters are usually employed for back analysis of old landslides where the residual strength has been mobilised, parameters from the failed portion of a slope are employed in the analysis by assuming factor of safety equal to unity. Residual parameters may give over conservative values, if used for determining the factor of safety of slopes that do not exhibit any fissures or slip surfaces, while peak strength parameters may overestimate the factor of safety for some slopes.

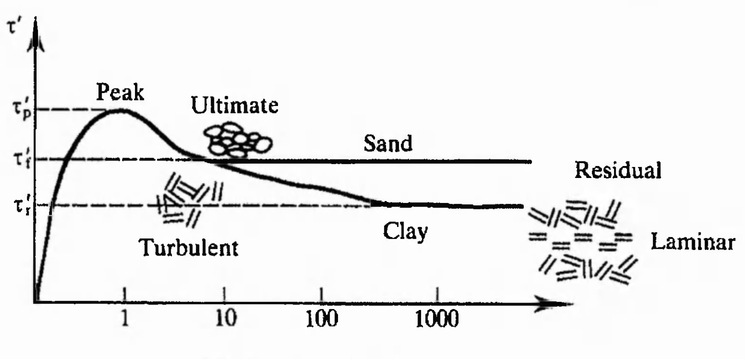


Figure 3.3 Failure states for sand and clay (Atkinson 1993)

Geotechnical engineers work with ultimate states to demonstrate that the soil will not fail and working states to show movements are acceptable (Atkinson 1993). Critical state parameters can be used to model elastoplastic behaviour, enabling soil displacements up to failure to be determined (Craig 2004). The ultimate or critical state is associated with turbulent flow and represents the unique relationship between the shear stress, normal stress and the voids ratio, and is attained regardless of initial state (Atkinson 1993). Turbulent flow is encountered in soils with dominant rotund grains where laminar flow is not possible or during the transitional phase for soils with dominantly flat/platy particles. However, the determination of critical state parameters for root reinforced soil has not been investigated.

The stability of slopes can be determined by either total or effective stress parameters depending on whether temporary or long term stability is at issue. Temporary cut slopes and trenches in fine grained soils with low permeability may be calculated using total stress parameters, as equilibration of pore water pressures may not occur within the design life of the temporary structure; therefore, undrained strength is adequate. However, this analysis is only valid for undrained (constant volume) conditions, as pore water pressure equilibration with time refers to the appropriate increase or decrease in pore pressure. The equilibration of pore water pressure after cutting construction results in soil softening and stability deterioration.

Natural and constructed permanent slopes require effective stress parameters, as the critical conditions are at the end of swelling when pore water pressures have reached equilibrium with steady state seepage or with hydrostatic conditions (Atkinson 1993). Many slopes constructed in over consolidated clays have suffered shallow failures due to softening, as the pore water pressures return to equilibrium (HA 44/91 1991). Therefore, drained shear strength or undrained shear strength with pore water pressure measurements are required to determine the long term stability of the slope.

When evaluating vegetated slopes effective strength parameters would be considered the most appropriate as long term stability corresponds to the critical condition. However, some of the *in situ* techniques conducted to assess the contribution of vegetation are restricted to undrained conditions and cannot include pore pressure measurements, due to the nature of the test and the inclusion of roots within the soil matrix.

3.3.2 Total Stress

Total stress analysis utilises undrained shear strength data, as it is based on the assumption that no drainage occurs during the construction of a slope or immediately afterwards, for the term of its temporary design life. The undrained shear strength of fine grained soil is commonly measured in the field or laboratory using a field or hand vane, or in the laboratory by the unconsolidated undrained triaxial test or direct shear box, if the specimen is of low permeability and the rate of test is rapid enough for the test to be considered undrained (BS 1377-7: 1990), it is also derived from standard penetration test data by various material specific empirical correlations (Stroud 1989). Measurements of undrained strength are often considered unrepresentative because of problems of rates of testing, confinement conditions and discontinuities in the soil and are likely to depend on the test method (HA 44/91 1991).

The undrained strength parameters are shear strength (S_u) and the internal angle of friction (ϕ_u) in a frictional material. The undrained shear strength does not change so long as the voids ratio does not change and is independent of normal stress (Atkinson 1993), as demonstrated by the Tresca failure criterion (Figure 3.4).

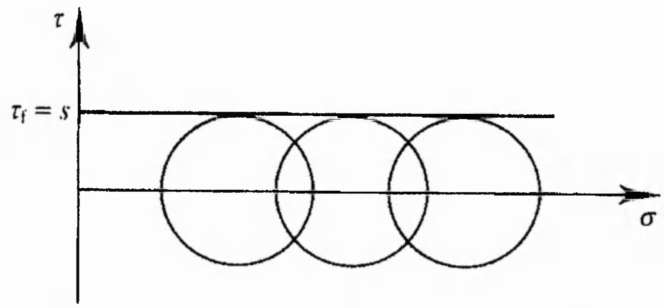


Figure 3.4 Tresca Failure criterion (Atkinson 1993)

It is well recognised that S_u does not have a single value when determined experimentally for two reasons; the strength is affected by the condition and size of the sample tested, and the strength depends on the method by which it is determined (Wroth 1987). Many of the derived soil properties are often dependent on empirical correlation ideally based on some theoretical framework, the valuation is complicated by the fact that S_u is not a unique parameter and depends on type of test, rate of strain, orientation of failure planes and water content; among other parameters (Wroth 1984).

3.3.3 Effective Stress

Terzaghi (1936) discovered the relationship between total stress, effective stress and pore water pressure. Effective stress is the stress transmitted through the soil skeleton only (σ'), while the total stress (σ) is the sum of pore water pressure (u) and effective stress. Thus:

$$\sigma' = \sigma - u \qquad \textbf{(3.1)}$$

Effective stress parameters c' and ϕ' (Figure 3.5) may be obtained using laboratory shear strength tests including the direct shear box, consolidated undrained triaxials with pore water pressure measurements or drained triaxial tests (BS 1377-6: ; BS 1377-7: ; BS 1377-8: 1990).

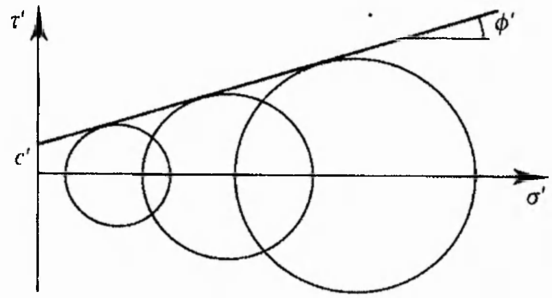


Figure 3.5 Mohr-Coulomb failure criterion (Atkinson 1993)

The effective shear strength of a soil is given by the Mohr-Coulomb criterion, equation (3.2).

$$S = c' + \sigma' \tan \phi' \tag{3.2}$$

Where

S	=	The shear strength at zero effective pore pressure
c'	=	Cohesion intercept or apparent cohesion
σ'	=	Effective normal stress
ϕ'	=	Angle of shearing resistance

Although the principle of effective stress has been confirmed to a high degree of accuracy for engineering purposes, appreciable errors occur for partially saturated soils and therefore, will only apply to fully saturated soils (Skempton and Henkel 1961). Partially saturated soils contain an amount of air that can exist in one of three states (Tindall and Kunkel 1999):

- Closed state, in vacuoles between particles, enveloped with film of bonded water
- Free state, gases can communicate with atmosphere, do not participate in distribution of pressures between soil particles.
- Dissolved state, dissolved within the soil water

When the Terzaghi expression for effective stress is used for unsaturated soils inaccuracies occur therefore, Bishop (1955), put forward a more general expression for effective stress, which differentiates pore air and water.

$$\sigma' = \sigma - [u_a - \chi(u_a - u_w)] \tag{3.3}$$

Where:

u_a	=	pore air pressure
u_w	=	pore water pressure
χ	=	parameter related to the degree of saturation (fully saturated soil equals unity)

A similar revised effective stress equation was proposed by Jennings (1961), for the free state, where pore air is continuous and in contact with the atmosphere the pressure in the water and water films will almost always be negative, while the gas pressures in the continuous voids would be atmospheric, equation 3.4. In this expression a positive term is used to represent suction although it is a negative pressure ($-u_w$).

$$\sigma' = \sigma + \beta p'' \tag{3.4}$$

Where:

β	=	A statistical factor incorporating the contact area across the plane
p''	=	Soil water suction ($-u_w$)

Fredlund and Morgenstern (1977) proposed a two stress state variable constitutive model to analyse partially saturated soil. Rather than consider the soil as a three phase system (soil, water and air). Fredlund and Morgenstern, (1977) recognised that four phases need to be considered, due to the air water influence or contractile skin and included effective stress state variables ($\sigma'/-u_a$) and suction (u_a-u_w).

Weather induced pore pressure cycles have been experimentally observed using centrifuge studies (Take 2004). Take and Bolton (2004) remark that following the observation of Skempton (1964) that the shallow depth of influence of seasonal variations were possibly of great significance to geomorphological processes but unlikely to prove important to deeper long term stability of clay slopes, has led to a design philosophy for slopes in which the highest possible pore pressures are to be estimated, allowing for long term elimination of transient negative pore pressures, whether caused at construction by cutting or compaction, or subsequently by erosion.

3.4 GEOPHYSICAL INVESTIGATION TECHNIQUES

There are many geophysical techniques such as ground probing radar, seismic reflection or refraction, electrical resistivity, electromagnetic conductivity, and gravity, in use to determine underlying strata without disturbing the site. Initially geophysical investigation was not greeted with much enthusiasm by civil engineers (McCann and Green 1996) as it was considered to represent black box technology and a specialist must interpret the data retrieved. The geophysical survey is often used to pin point anomalies and is becoming more common as part of the preliminary investigation as it can aid in the design of the intrusive phase field investigation. However, in many cases the geophysical data still requires confirmation through comparison with soil samples retrieved from exploratory holes, but it is being employed more frequently to 'fill in' stratigraphic data between conventional boreholes. Therefore, geophysical techniques may form an important part of the investigation of a vegetated slope, not to investigate the vegetation *per se* but to minimise disturbance to the vegetation by reducing the number of exploratory holes required to determine the subsurface stratigraphy.

Different soils and rock types have different electrical characteristics, the presence of groundwater and pollutants also alter electrical resistivities. A current is directly injected into the ground and the resulting voltage is measured either by steel electrodes pushed into the ground or by an array which is pulled over the surface (McDowell *et al.* 2002). Interpretation of results is aided by the use of microprocessors, which allow automatic data processing and recorded resistivity curve fitting in the field (McCann and Green 1996). Self-potential, resistivity, and temperature anomalies are associated with sites of increased landslide activity, hence measurement of these properties have been analyzed for characterization of the seepage flow through a landslide body Bogoslovsky and Ogilvy (1977).

The electromagnetic conductivity is measured by inducing a low frequency electromagnetic signal into the ground and measuring the resulting signals with a coil. The depth penetration generally equates to not more than half the spacing between the coils, therefore, can be increased by the size and spacing of the coils (Hack 2000). Low frequency EM surveys are simple and quick to execute but can not determine boundaries with sufficient accuracy, unless the target is a thick horizon or there is a strong contrast between the materials (Hack 2000). Similarly, gravity methods are being increasingly used for the detection of cavities, mines and tunnels. A gravity survey measures the naturally occurring variations in the density of soil and rocks, which affect the underlying gravitation field. A contour map across the anomaly is produced from detailed data processing and interpretation. The application of this technique is more suited to large scale anomalies and therefore, may not be the most appropriate method for determining subsurface horizons on a vegetated slope. The two most commonly employed geophysical techniques are Ground Penetrating Radar (GPR) and seismic methods.

3.4.1 Ground Penetrating Radar

Ground penetrating radar is an increasingly popular technique and has benefited greatly from modern low cost portable computers both at the data acquisition stage and in data processing, interpretation and display. A radar antenna transmits short electromagnetic pulses, at frequencies between 25 MHz and 1 GHz, into the ground; the pulse energy is partially reflected back by subsurface geology and structures and is detected by a receiving antenna (McDowell *et al.* 2002). Soils and rocks exhibit different dielectric properties, and where there is change from one dielectric to another a reflection horizon is produced, allowing the device to detect different horizons or buried objects.

Depth of penetration is a function of both frequency of the pulse and the electrical conductivity of the ground (McDowell *et al.* 2002). A low frequency 50 MHz antenna will give a better depth penetration but the signal is prone to attenuation especially in high conductivity (clay rich) soils. High antenna frequencies can be used to achieve greater resolution but there is a trade off with penetration (Hruska *et al.* 1999). Grandjean *et al.* (2000) studied three GPR techniques for locating sub-surface structures, and concluded that the performance of each technique is mainly conditioned by the material properties and the source frequency used. Resolution and attenuation varied from a few centimetres to 0.25 m and 2.5 to 45 dB/m, respectively and penetration varied from 1 to 5 m (Grandjean *et al.* 2000).

Ground Penetrating Radar has been used experimentally by Charlton (2001) to determine soil water content and demonstrated that an effective and reliable estimate of volumetric water content was derived using the mean instantaneous amplitude. Ground Penetrating Radar has also been used to determine root distribution to varying degrees of success due to the trade off between penetration and resolution, which is discussed further in Section 4.4.

3.4.2 Seismic

Seismic methods are based on the principle that velocity of propagation of a wave or impulse in an elastic body is a function of Young's modulus, Poisson's ratio and the density of the material (Hvorslev 1949). The propagation of seismic waves are initiated by the transfer of seismic energy into the ground, single impulses are produced by a falling weight, hammer blow or an explosive charge, while continuous impulses are provided by a vibrator fixed to the ground (Gordon *et al.* 1996). There are two groups of seismic wave, body and surface. P (compression or primary) and S (shear or secondary) waves are body waves and Rayleigh and Love waves are surface waves. The seismic energy transmitted through the ground is detected by geophones positioned on the surface or down boreholes.

Seismic refraction relies on the first arrival of a wave front and is the simplest data to acquire and process. Traditionally geophysicists used P wave surveys to provide deep geological sections, however, S wave surveys provide data at shallow depth and enable the calculation of shear moduli.

Seismic reflection has been a standard technique in the petroleum industry for the last 70 years, and relies on measuring the travel times of P waves reflected back to the surface from the different geological strata. The advent of high-resolution seismographs and increasingly powerful computers has resulted in the use of this technique on some land based site investigations.

3.5 INTRUSIVE INVESTIGATION TECHNIQUES

In order to determine the parameters necessary for slope stability analysis *in situ* tests are conducted or soil samples are taken either from excavations or boreholes for laboratory analysis. There are several intrusive techniques available to investigate ground conditions, from manual auguring and digging through to cable percussion and rotary drilling. Some of this plant is prohibitively large, for the scale of slopes typically investigated in the UK, and would require vegetation clearance, negating their suitability for investigating vegetated slopes. In addition, many sites have restricted access, are over steep or are confined to a small area such as highway and railway cuttings and embankments. Therefore, only the medium and lightweight plant, which are considered the most appropriate for the geotechnical investigation of a vegetated slope, are summarised in Table 3.1.

In some instances on railway embankments it is possible to attach heavier plant such as rotary equipment to a 'road railer' and work from track level, however, this method has a limited reach and drill depth. Alternatively it is necessary to erect a scaffold platform or excavate a berm to utilise a large rotary rig or a cable percussion rig, which again will require a degree of vegetation clearance. Therefore, this heavier plant was omitted from the summary table of most appropriate plant, however, such plant is readily available should the investigation require deeper exploratory holes.

Table 3.1 Summary of suitable plant for ground investigation on a slope (compiled from BS 5930: 1999; Clark 2000; Clayton *et al.* 1995; Eccles and Redford 1999; Weltman and Head 1983)

Investigation Technique	Specific Plant	Advantage	Disadvantage
Hand held plant			
Hand pitting	Spade, shovel, graft	Work on slope without platform if Health and Safety permits, hand held equipment, Can obtain undisturbed block samples Allows detailed visual assessment of stratification, discontinuities and pre-existing shear surfaces	Achievable depth limited to 1.2m with out shoring Unsuitable for inclinometer installation.
Hand auguring	Iwan head or corkscrew augur, T bar	Work on slope without platform if Health and Safety permits, hand held equipment, Auger diameters from 20mm to 200mm available	Limited achievable depth 5-6m. Disturbed sampling only. Unsuitable for inclinometer installation.
Window/ windowless sampling	Jack hammer and Window Sample attachments	Work on slope without platform if Health and Safety permits. Can use hand held equipment for drive in slip indicators and piezometers etc. Sample tubes 38-80mm outside diameter (Eccles and Redford 1999)	Limited achievable depth 8-10m (Clark 2000) Sampling only. Small diameter up to 66mm internal diameter Unsuitable for inclinometer installation.
'Light weight' Ground Investigation plant			
Dynamic Cone penetration	Super heavy 63.5 kg hammer or heavy 50 kg Dynamic probe	Small platform design required. Possible to bench suitable work area. Window sampling attachments may be used to collect samples. Blow counts can be related to Standard Penetration Test	Blow count data only when probing, produces no samples for correlation Limited depth of casing when window sampling Limited achievable depth 7-15m depending on soil type (Eccles and Redford 1999)
Solid auger	Minute man rig	Small platform design required/possible bench suitable work area. Can achieve 9m depth with 76.2mm auger (Clark 2000)	Disturbed samples collected Undisturbed samples possible from augers with 140-150mm internal diameter but larger rig required (Clayton *et al.* 1995)
'Medium' sized Ground Investigation plant			
Mini excavator	Tracked rig	Small tracked excavator can access most sites to mechanically dig trial pits. Can obtain undisturbed samples from pit.	Achievable depth limited to 2.5m. Can disrupt vegetation cover
De-mountable cable percussion rig	~0.5 or 1.0 tonne modular rig	Less onerous platform design required than for standard cable percussion rig. Undisturbed samples may be collected Standard Penetration Tests (SPT) possible	Hole depth limited by depth of casing. Set up may take time
Percussive rig	Competitor rig	Small platform design Undisturbed sample retrieved in liner Dynamic probing possible	Hole diameter (restricting inclinometer installation depth), limited depth of casing and inability to chisel.
Air line rig	Drifter rig	Power supply remote from drill rig reducing amount of plant on slope	Hole depth limited by depth of casing. Set up may take time
Hollow stem auger	Various	Small platform design required Does not require casing.	Typically uncased Disturbed samples only
Modular rotary rig	Various	Small platform design required	Sample integrity only applicable to rock
Static Cone Penetrometer	Various	Range from track mounted mini rigs to truck mounted. Continuous testing, cone resistance indicates physical and mechanical soil properties and groundwater	Small rigs have limited reaction force therefore limited depth achievable. Large rigs difficult to position on some slopes No soil samples retrieved, use in conjunction with sampling techniques to verify strata.

The intrusive phase of the site investigation is designed following the preliminary desk study, health and safety implications have to be considered and a designer's risk assessment is drafted following the Construction Design Management regulations (HSE 2002). At this point it is necessary to decide what information is required and the best site investigation techniques to be utilised to retrieve the data given the limitations/restrictions associated with the site, health and safety regulations and the budget allowed.

Current practise requires a degree of site clearance to facilitate the ground investigation and visual assessment. Small shrubs and undergrowth are cleared and large trees cut back to allow excavation plant into position. Although, vegetation has been shown to improve shear resistance and increase the factor of safety of a slope, it is becoming apparent that the site investigation ought to be mindful of the vegetation present, and include assessment and testing of the vegetation. However, the acquisition of geotechnical data is imperative and vegetation clearance may still be inevitable, regardless of its potential contribution. The requirement for large rotary drill rigs or continuous flight augers to obtain data from deeper rock or soil strata may necessitate a large excavation to bench out and provide a safe working platform or the erection of a scaffold platform. These factors will have to be considered on a site by site basis to achieve a balance between the geotechnical investigation and the characterisation of the vegetated slope to produce a coherent investigation of a vegetated slope.

Slope failures normally start with minor movements along the failure surface(s), which may not show at the surface initially or be hidden by extensive vegetation cover (Clark 2000) for this reason characterising a vegetated slope can prove problematic as it may be necessary to remove vegetation to assess the slope but at the same time it is important to leave as much vegetation intact if it can prove beneficial to the slope.

3.5.1 Manual Excavation

The hand auger is light portable and economic, it is suitable for shallow investigations, although depths of 5-6 m may be reached in fine soils above the water table, gravel, groundwater and unstable strata can prove problematic for this excavation method, limiting the maximum attainable depth. Sampling is restricted to disturbed materials and so this method is most frequently used for preliminary investigations (Weltman and Head 1983). The hand auger can also be used to conduct *in situ* permeability tests and estimate depths to the various soil horizons, although it is not possible to determine the nature of horizon boundaries or any soil structure from the disturbed samples. Therefore, trial pits are excavated by hand to examine the soil profile and retrieve undisturbed samples from shallow depths, as any excavation greater than 1.2 m must be shored. Hand excavated trial pits are a pre requisite for other intrusive investigation techniques to check for services (Clark 2000), this provides an ideal opportunity to assess some of the vegetation parameters prior to the progression of the exploratory hole, as the majority of roots are concentrated in this area, 90% of the roots are in the upper 0.6 m of soil (Dobson and Moffat 1995).

3.5.2 Lightweight Equipment

The dynamic probe and window sampling rigs available have proved to be invaluable to the investigation of slopes, they are frequently used on road and rail infrastructure projects, where access is limited and soil sampling and penetration data are required (Clark 2000). A variety of wheeled or tracked rigs are available, which drive either dynamic probe rods or hardened steel window or windowless sample tubes into the ground, manual or hydraulic jacks are then used to extract the rods or sample tubes.

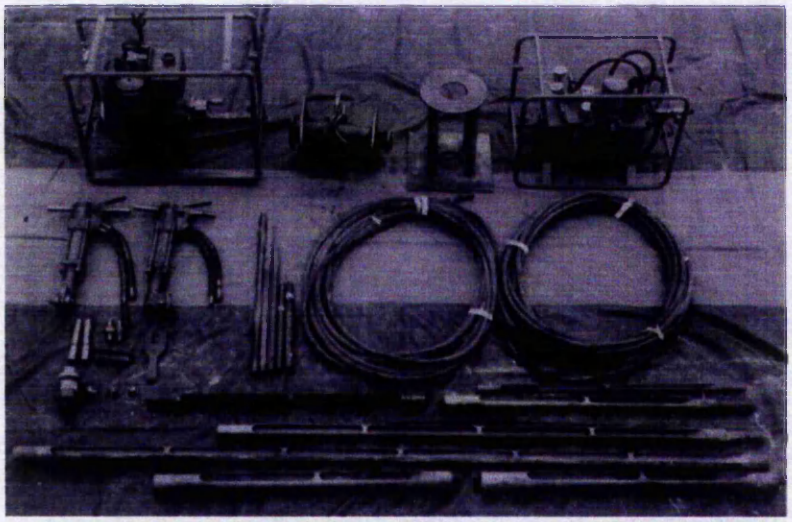


Plate 3.1 Hydraulically powered dynamic sampling equipment (Eccles and Redford 1999)

These rigs may be manoeuvred into most locations being around 2.5 m tall and 1.5 m wide; however, where access is problematic the sampling tubes may be driven into the ground using a hand held percussion hammer (Plate 3.1). A specification for dynamic sampling is not included in the British Standard (BS 5930: 1999) or the Specification for Ground Investigation (Site Investigation Steering Group 1993) possibly due to it being a relatively new technique at that time. However, the procedure for dynamic probing is included in BS 1377-9 (1990) (see section 3.7).

The sample tubes range in diameter from 80 mm down to 38 mm to enable deeper penetration through stepped excavation and depths of between 7 m and 15 m may be achieved (Eccles and Redford 1999). Unfortunately the limited sample diameter negates the qualification of undisturbed, but intact samples are retrieved, to enable some classification testing and soil description, and possible quantification of root biomass. The solid stem auger or 'minuteman' rig is comparable in size to the dynamic probing rig; unfortunately it is not possible to obtain continuous intact samples as with window sampling. The small diameter hole also limits the potential instrumentation that may be installed, and inclinometers that require an annulus around the tube will not fit, but a range of slip indicators, pneumatic and standpipe piezometers have been successfully installed.

3.5.3 Drilling Equipment

The cable percussion drilling rig is a mainstay of geotechnical ground investigation in the UK, the smaller cut down rig is often used on slope investigations and where limited headroom is an issue. The resulting borehole is of a sufficient diameter (typically with a minimum internal diameter of 150 mm) to facilitate *in situ* tests and allow subsequent installation of inclinometers or other similar instrumentation. The key restriction to the use of the cable percussion rig or its cut down counterpart on vegetated slopes is the site access and disruption, if safe working practice permits the drilling to commence on such a slope.

Continuous flight augering typically uses augers with hollow stems, with internal diameters of approximately 75 mm and 125 mm and produce boreholes of about 150 mm and 250 mm diameter boreholes, respectively. The continuous flight auger requires considerable mechanical power and weight so the machine is therefore mounted on a heavy vehicle (BS 5930: 1999). Site access and the requirement for minimal site disturbance make this technique unsuitable for investigating vegetated slopes. Rotary drill rigs are usually truck mounted as they too require the kentiledge, however, as they are used to progress boreholes through rock, beyond the influence of the most persistent vegetation the balance between vegetation characterisation and geotechnical investigation may not be as problematic where a rotary drill rig is required. Figure 3.6 illustrates the relative size of truck mounted and 'A' frame drilling equipment.

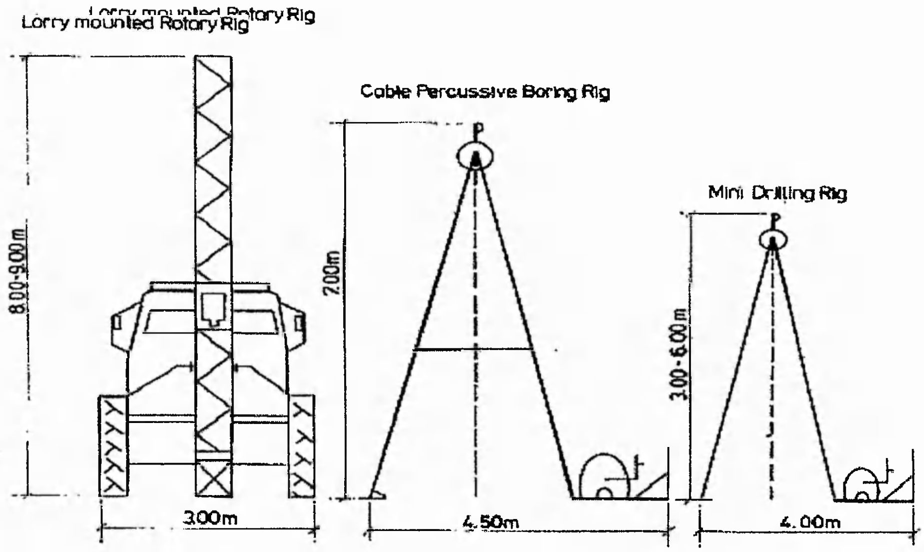


Figure 3.6 Relative size of rotary, Cable Percussive and Mini Drilling Rigs (Clark 2000)

Although a phased approach may be adopted to facilitate vegetation characterisation prior to the geotechnical investigation it is not the most practical solution. An evaluation of the existing vegetation and its contribution to slope stability, prior to vegetation clearance to facilitate the geotechnical phase may be considered a waste of resources if the vegetation is irretrievably damaged. Similarly, an assessment of the vegetation remaining following the geotechnical investigation phase will depend on whether there is sufficient vegetation remaining to facilitate a characterisation of the vegetation. Therefore, consideration of the vegetation is required when planning the geotechnical investigation phase, to minimise the potential damage by reducing the use of heavy plant. If the geotechnical investigation requires such heavy plant it may be prudent to designate areas for destructive sampling and vegetation characterisation and extrapolate the data for the two areas.

3.6 *IN SITU* TESTING TECHNIQUES

Field tests are preferable when laboratory tests are unable to mimic the site conditions and therefore are considered to not represent the mass properties of the soil, or where sample disturbance is an issue. Field tests are particularly suited to coarse grained soils, as it is difficult to obtain samples of sufficient quality without having altered the mechanical properties of the soil. The most common field tests conducted on slope investigations are given in Table 3.2.

Table 3.2 *In situ* tests (Compiled from BS 1377-9: 1990; BS 5930: 1999; Clark 2000; Clayton *et al.* 1995)

Test	Method	Advantage	Disadvantage
Surface tests			
Hand vane	Four bladed (cruciform) vane manually pushed into soil and slowly rotated (BS 1377: 1990)	Small portable device Gives indication of undrained peak and residual shear strength	Test not suitable for fibrous peat, sands or gravels or in clays containing laminations of sand or silt, or stones
Hand/pocket penetrometer	Rod pushed into soil to a given depth. Penetration resistance measured with calibrated reaction spring in body of penetrometer	Small portable device Gives indication of peak undrained shear strength	Scale on spring 0 to 4.5 or 5 units must be converted to kPa for particular soil type Used to aid description only
Direct shear test	*In situ* direct shear test (BS 5930: 1999)	Test carried out in undisturbed sample prepared *in situ*	Depth of the test is restricted to the size and depth of the excavation
CNS Farnell Dynamic cone penetrometer	8kg free fall hammer is manually lifted and dropped; small diameter rods and cone tip are driven into the ground. Number of blows per 10cm increment counted	Small portable equipment Blow counts can be related to California bearing ratio	Penetration limited in very dense or granular materials with large particles Maximum depth 850mm
Borehole tests			
Dynamic probing	The blow count gives an indication of the density of the soil (BS 1377-9: 1990)	The rig is small and lightweight	Maximum depth can be limited in certain soils
Standard Penetration Test (SPT)	A drop hammer of standard weight is used to drive a rod into the ground, the blow count gives and indication of the density of the ground (BS 1377-9:1990)	The test is empirical and much published work links the results with other soil parameters	Test is carried out using cable percussion rig Energy loss through rods needs to be corrected for
Vane test	A cruciform vane is forced into the soil at the base of a borehole and is rotated; the torque is then related to the shear strength of the soil (BS 1377-9:1990).	Test carried out in undisturbed sample at base of borehole	Test is carried out using cable percussion rig
Pressuremeter	Probe lowered down borehole Uniform pressure applied to the ground via a flexible membrane Measuring unit at surface records applied radial pressure and resulting deformation	Simple and robust Can be used in soils and rocks to give stiffness or strength data	Self boring pressuremeters cannot penetrate very hard, cemented or stony soils (Clayton *et al.* 1995)
Cross hole seismic	Source and receiver arrays are lowered down adjacent boreholes 5-7m apart different sondes used for different parameters (BS 5930: 1999)	Can calculate shear modulus G if soil density is known	Susceptible to oversimplified interpretation Poor signal to noise ratio when small energy sources used, poor data quality
Down hole seismic	Detector located down single borehole source activated at one or more source points on surface different sondes used for different parameters (BS 5930: 1999)	Fewer boreholes needed Small strain dynamic shear modulus can be estimated to within 30% (Ricketts *et al.* 1995)	Susceptible to oversimplified interpretation Poor signal to noise ratio when small energy sources therefore, poor data quality

3.6.1 Dynamic Penetration Testing

The standard penetration test (SPT) has been a popular test since its inception in 1927 in the USA (Weltman and Head 1983). The test can be carried out with cable percussion or rotary drill rigs and uses a free falling standard mass of 63.5 kg (Weltman and Head 1983) or 65 kg (BS 1377) dropped a standard fall height of 760 mm. The test section is divided into six 75 mm increments and the number of blows required to progress each 75 mm increment are counted. The blow counts for the first two increments are classed as seating blows and the results for the final four increments (300 mm) are added to obtain the SPT N value. Various charts have been published which are used to correct the SPT N values to allow for the effects of overburden pressure (Peck *et al.* 1974; Thorburn 1963) and energy loss through the rods, if tests are carried out at great depths. The SPT N value has been correlated to relative density amongst other relationships of coarse grained soils (Nixon, 1982 and (Weltman and Head 1983) and the undrained shear strength of fine grained soils through empirical correlations (Eddleston 1991; Stroud 1989)

Dynamic penetration testing is well established as a prospecting tool in many countries throughout the world; although its use as a site investigation tool is limited to a few countries in Europe as the rest of the world have followed the USA with the use of the SPT (Butcher and McElmeel 1996). Dynamic penetration testing uses a drop weight of fixed mass and travel to drive a metal tip into the ground, the number of blows required to drive the rod a fixed distance is then record. There are a variety of recommended test procedures for the light (DPL), medium (DPM), heavy (DPH) and super heavy (DPSH) test specifications (Eitner and Stölben 2004). The British Standard (BS 1377-9: 1990) outlines the equipment and procedure for the heavy and super heavy tests while the German standards (DIN 4094 1980) cover the range of test specifications. The super heavy dynamic probe has a drop weight of 63.5 kg and is designed to closely resemble the standard penetration test; however, a relationship has been established between the DPH N10 and the SPT N value (Butcher and McElmeel 1996).

The CNS Farnell probe is a lightweight hand held dynamic cone penetrometer developed in conjunction with the Transport Research Laboratory (TRL) to assess pavement layers. The 8 kg free fall hammer is manually lifted and dropped and this distance of penetration per blow recorded, continuous measurements can be made to a maximum recommended depth of 2 m. This test is lightweight and portable and useful for profiling the shallow strata. Although the progress of the cone may be obstructed by sizeable roots, the penetration tests have not been used to assess the contribution of vegetation as they are generally considered of an inappropriate size to record any root influence, or the mass properties of root reinforced soil. However, they are suitable to assess the geotechnical properties of a vegetated slope rather than any contribution from the vegetation.

3.6.2 Static Cone Penetration Testing

Static cone penetration or cone penetration testing (CPT) was developed in 1934 in Holland and has been used since to investigate the properties of soil *in situ* (Clayton *et al.* 1995), The CPT is a recognised standardised test and is included in the current standard (BS 1377: 1990). The cone is hydraulically pushed into the ground at a constant speed (2 ± 0.5cm/s) and the force is recorded. Originally the CPT only measured tip resistance, sensors and a piezocone tip have been added over the years and now CPT instruments can measure friction along the sleeve, arrival of seismic shear wave and pore water pressure (Abdrabbo and El Hansy 1998).

The seismic cone penetration test (SCPT) has one or two three-component geophone array (Clayton *et al.* 1995). The single element cone works well provided there is an excellent trigger and source in uniform ground conditions (Robertson *et al.* 1996). The dual array reduces operator influence and avoids errors due to depth measurement and has proved a valuable tool for determining the benchmark value of very small strain stiffness (Butcher and Powell 1996). The geophones are set a fixed distance of 1.0 m or 0.5 m where more detailed information is required (Jacobs and Butcher 1996) and can be used for cross hole or the more economical down hole testing.

Significantly high pore water pressures are developed in cohesive, low permeability materials, due to consolidation around the cone. Consolidation and dilation can occur in higher permeability soils giving a lower reading than the equilibrium pore water pressure. This may be overcome as pore water pressure can equilibrate if penetration of cone is arrested, the time taken for dissipation depends on hydrological and mechanical properties (permeability, compaction, strength etc) of the soil, and the ability to map the water table or potentiometric surface using equilibrium pore pressure depends on site specific conditions (Aggarwal 1998).

The CPT or SCPT are potentially useful investigation techniques for characterising a vegetated slope, given the effect vegetation can have on the pore water pressure. Unfortunately, the use of the CPT or SCPT rig to this application is limited due to the size of the apparatus defined by the mass of kentiledge required (typically the size of a large truck), which may not be able to access certain vegetated slopes, or sample locations within densely vegetated areas without clearing the site first.

3.6.3 Strength Testing

The undrained shear strength may be determined using the field or hand vane or the *in situ* direct shear box, if conducted at a suitably rapid rate of strain to be considered undrained (BS 5930: 1999). The field vane is conducted at ground level or in the base of the borehole and like the hand vane is unlikely to give a representative determination of shear strength in a root reinforced soil, as the test is not suitable for peats, sands or gravels, or clays containing laminations of silt sand or stones (Clayton *et al.* 1995), anisotropy effects can give rise to values unrepresentative of the engineering problems being studied (Weltman and Head 1983). The measured failure surface occurs around the periphery of the vane, and roots may cause obstructions to the turning blades in a similar way to gravel, rather than giving an indication of the mass properties of the soil erroneous results may be recorded as the obstruction affects the torque resistance measured.

The *in situ* direct shear box is normally designed to measure the peak shear strength although it is possible to measure residual strength if the test has sufficient travel. The maximum sample size is often limited by practical considerations of loading and accessibility, rock and soil samples between 600 mm and 1500 mm square have been tested (BS 5930: 1999). The *in situ* shear box has been developed to quantify the contribution of roots to shear resistance and is discussed in Section 4.5.

The *in situ* stress, stiffness or strength of weaker materials can be ascertained with a borehole or self-boring pressuremeter (Clayton *et al.* 1995). The pressuremeter is usually used to obtain stiffness and earth pressure data for tunnel and retaining wall design but the undrained shear strength can be derived from the pressuremeter test. The values obtained are a function of the type of pressuremeter (and hence installation technique), the quality of the test procedure and the model chosen to interpret the data (Clarke and Sadeeq 1996). The pressuremeter is a very good test for obtaining high quality data; however, the sampler has to be in intimate contact with the soil, which is not feasible in a root permeated sample. Therefore, the potential for errors negates the suitability of the test.

3.6.4 Sampling Disturbance

The quality of test results depends ultimately on the quality of the sample tested. Sample disturbance is an important consideration for geotechnical samples and can occur during drilling, sampling and after sampling. During sampling the area ratio and cutting edge taper are the most important causes of disturbance (Clayton 1986). Sensitive soils may be sampled using a thin walled or piston sampler, to minimise sample disturbance, however, care still has to be taken during transportation, storage and test preparation of the sample. The main components of sample disturbance are mechanical disturbance causing a breakdown in structure, and partial loss of suction set up by the stress relief upon sampling, and also water content change as a result of swelling while drilling or sampling or redistribution between laminations within the sample (Coatsworth 1986), the soil water content can also change during storage. The principle causes of soil disturbance are listed in Table 3.3 (Clayton *et al.* 1995).

Table 3.3 Principle causes of soil disturbance (Clayton *et al.* 1995)

Before sampling	During sampling	After sampling
Stress relief	Stress relief	Stress relief
Swelling	Remoulding	Migration of water within sample
Compaction	Displacement	Loss of water
Displacement	Shattering	Freezing / Overheating
Base heave	Stones at the cutting shoe	Vibration
Piping	Mixing or segregation	Chemical changes
Caving	Failure to recover	Disturbance during extrusion

The presence of roots within the soil matrix may also augment some of these factors. Roots traversing the soil horizon may be of sufficient stiffness to dissipate the stresses imposed during sampling creating a greater mechanical disturbance. Similarly, roots within a sample can provide preferential flow paths, which can facilitate a change in water content during storage or accelerate the dissipation of pore water pressures.

3.7 LABORATORY TESTING

Laboratory tests are used to classify a soil and identify certain parameters suitable for slope stability analysis, which may be derived from correlation with the index properties (Wroth and Wood 1978). Classification tests include natural water content, particle size distribution, Atterberg limits, shrinkage and swelling, particle density and soil suction. Identification tests include: strength testing such as the triaxial, direct shear box and ring shear, soil deformation testing permeability and suction tests (Table 3.4). Although, Abe and Iwamoto (1986b) have dismissed triaxial testing as insufficient to suitably test root permeated soil due to the sample size, it is still an integral test for the acquisition of geotechnical parameters. However, so as far as vegetated soil is concerned *in situ* tests are considered more appropriate.

Table 3.4 Standard laboratory classification, identification and strength tests (after BS 5930: 1999)

Laboratory Test	Method	Soil type	Parameter
Water content	BS 1377-2	Fine to coarse	Gravimetric water content
Soil Suction	(Chandler *et al.* 1992)	Fine soils	Negative pore water pressure
Atterberg limits	BS 1377-2	Fine soils	Liquid and plastic limits
Volumetric shrinkage limit	BS 1377-2	Fine soils	Water content below which soil does not shrink
Linear shrinkage	BS 1377	Fine soils	Magnitude of shrinkage on desiccation
Particle density	BS 1377-2	Fine to coarse	Specific gravity (Gs)
Mass density	BS 1377-2	Fine to coarse	Unit weight (γ)
Sedimentation	BS 1377-2	Fine soils	Particle size distribution
Sieve analysis	BS 1377-2	Fine to coarse	Particle size distribution
Unconsolidated undrained triaxial	BS 1377-7	Fine to coarse	Peak undrained shear strength S_u
Undrained with pore pressure measurement	BS 1377-8	Fine to coarse	Mohr coulomb c' and ϕ'
Drained with volume change measurements	BS 1377-8	Fine to coarse	Mohr coulomb c' and ϕ'
Direct shear box	BS 1377-7	Fine to coarse	Undrained Mohr coulomb c and ϕ or residual
Ring shear	BS 1377-7	Fine soils	Residual strength

Small strain behaviour (E′) data, to derive stiffness, can be obtained from consolidated triaxial testing on undisturbed samples (usually block samples) taken in the mid and lower slope to ascertain the detailed deformation characteristics. This is particularly important for shrink and swell, finite element and finite difference modelling where one of the input parameters is stiffness (Perry *et al.* 2003a).

3.8 INSTRUMENTATION

Instrumentation for slope stability analysis is commonly used to investigate failures to aid the design of remedial works, or to monitor the performance during and after cutting or embankment construction. The primary requirement of any instrumentation is that it is capable of measuring the required parameter, without changing it (Clayton *et al.* 1995). The main parameters that may require measurement are ground movements, groundwater level, pore water pressure and rainfall. Permeability and water retention are fundamental properties in slope stability analysis as antecedent rainfall can lead to a maximum reaction of a slope in terms of pore water pressure development (Alonso *et al.* 2003) this is discussed further in Chapter 5.

3.8.1 Ground Movements

Ground movements are normally measured in terms of the displacement points which can be positioned on the surface of the ground or within the ground mass. Absolute displacement is measured relative to a stable datum over a period of time, and sufficient measurements are required to define the movement in three directions (BS 5930: 1999). Surface movement may be measured (referenced to a remote datum) using conventional surveying, Electronic Distance Measurement (EDM), photogrammetric methods or global positioning systems (GPS).

Internal movements or displacements may be measured by the installation of slip indicators or inclinometers for lateral movements, or extensometers and settlement gauges can be used for vertical displacements. Cooper *et al.* (1998) reported on the inclinometers installed for the Selbourne cutting stability experiment and commented that the torpedo and access tube system passed an angular distortion of 35°, but did so at great risk to the instrument. While the inclinometer strings remained fully functional with angular distortions of up to 42° between successive 1 m gauge lengths, thus provided continuous movement monitoring, but at reduced precision.

Unfortunately the magnitude of pre-failure deformations, which are of interest are often in the same order of magnitude as the accuracies of inclinometers and surface surveys, therefore, in a large number of cases, measurements are taken over a period of time to obtain trends, thus enabling the certainty of ground movement to be established (Dixon *et al.* 1996). A number of researchers have been assessing acoustic emission techniques to determine shear deformation of soils (Dixon *et al.* 2003; 1979; Koerner *et al.* 1978; Kousteni 2002). Field trials indicate that acoustic emission monitoring may be used as a compliment to existing deformation monitoring methods and has a particular application as an early warning system (Dixon *et al.* 2003).

Time Domain Reflectometry has been applied to detect and locate earth and rock movement since the 1970s (Anderson and Welch 2000). The coaxial cable is grouted into a borehole or trench vertically or horizontally using a compliant grout (Dowding and O'Connor 2000). Movement along a single 2 mm thin shear band can be detected or multiple shear bands as close as 6 mm resolved, whereas the inclinometer can only distinguish shear events separated by at least 60 cm (Dowding and Pierce 2000). However, this is dependent on the cable grout composite system, as both are required to deform as the soil shears, so adequate installation design is essential. Grout strength should be low enough to fail before bearing capacity of the surrounding soil is reached but high enough to deform the cable it encapsulates (Dowding and O'Connor 2000).

3.9 SUMMARY

Geotechnical and slope parameters are essential for the assessment of slope stability, whether the slope is vegetated or not. The key slope parameters are the height and angle of slope, which may be obtained from a topographic survey conducted during the visual assessment of the slope or following the ground investigation to take in the exploratory hole locations. The fundamental geotechnical parameters required for a slope stability analysis include the depth of the soil horizons and the groundwater surface, along with the soil parameters for each soil horizon. Soil testing, either laboratory or *in situ*, is required to obtain parameters such as natural water content, unit weight and shear strength of the soil.

The shear strength of a soil is dependent on the water content and stress history of a soil, a dense, over consolidated or dry soil will exhibit brittle failure, where the maximum shear stress sustained produces a peak followed by a residual phase, whereas, loose or moist soil does not display a peak due to the ductile failure mechanism. The use of peak strength values may overestimate the factor of safety of a slope while residual values will underestimate the stability, however, residual values are most appropriate for back analysis of a failed slope. The ultimate or critical state lies between the peak and residual states and is thought to best represent the fully softened condition.

The strength parameters may be determined under drained or undrained conditions to provide effective or total stress parameters, respectively. Total stress parameters (S_u and ϕ_u) are suitable for the evaluation of short term stability, while effective stress parameters (c' and ϕ') are preferred for long term stability analysis. Finite element modelling for slope stability analysis also requires parameters gained from advanced field and laboratory testing to determine displacements at relatively low stress levels.

Geotechnical investigation is an integral part of the investigation of a vegetated slope. However, current practise requires a degree of site clearance to facilitate the visual assessment and ground investigation. Small shrubs and undergrowth are cleared and large trees felled to allow excavation plant into position, while grass is trampled underfoot. Although it is preferable to minimise damage and disruption, to conserve a potentially beneficial component of a vegetated slope, site clearance and loss of vegetation is inevitable in order to carry out a thorough ground investigation for slope stability analysis. However, to incorporate the characterisation of vegetation into a geotechnical investigation and assess the contribution of vegetation to slope stability it is necessary to be sympathetic to the vegetation cover and keep the clearance to a minimum, which may be achieved by selecting lightweight and medium size plant in preference to large truck mounted rigs. The employment of geophysical investigation techniques to 'fill in' stratigraphic data and consequently reduce the number of exploratory hole across the site, is one way to minimise damage, however, its success will depend on the appropriateness of the technique selected for the site conditions.

The most suitable geotechnical ground investigation techniques for investigating a vegetated slope have been outlined. Exploratory holes may be progressed manually, or by mechanical apparatus of increasing size, depending on the depth of hole required. The selection of one or a number the techniques discussed in this chapter will depend on the individual slope, the ecological sensitivity of the site and the pertinent data required to conduct slope stability analysis. Although the geotechnical site investigation is an integral part of an investigation to characterise a vegetated slope it is not appropriate as the sole procedure to assess the contribution of vegetation to slope stability. However, the phased approach of a geotechnical site investigation does provide a robust structure that can adopt techniques from other disciplines, and may form the foundation for the development of a framework for the investigation of vegetated slopes and assessment of the effect of vegetation on slope stability. The following chapter outlines techniques available for appraising a vegetated slope and quantifying the mechanical contribution of vegetation to slope stability.

Vegetation Investigation Techniques

4

The more precisely the position is determined, the less precisely the momentum is known in this instant, and vice versa.
Werner Heisenberg (1901-1976). Uncertainty Principle

Chapter 2 outlined the effects vegetation can have on the soil and subsequent slope stability, and established the vegetation parameters required to ascertain the contribution of vegetation to slope stability. A framework for the investigation of vegetated slopes to assess the contribution of vegetation to slope stability will include procedures from a standard geotechnical site investigation discussed in Chapter 3, along with ecological survey procedures, and biomechanical testing techniques discussed in this chapter along with procedures to characterise the hydrogeological aspects, which are discussed in Chapter 5.

Although destructive testing is necessary to determine the geotechnical parameters for slope stability analysis, it is also important to ascertain the interaction between the vegetation, soil, groundwater, climate and faunal factors. Such parameters may be determined from an ecological survey. Therefore, it is proposed that ecological data collection is conducted prior to the conventional ground investigation phase or areas are selected for destructive and non destructive testing to take place concurrently. This chapter outlines the parameters and elements of a vegetation survey required for their determination. Suitable biomechanical testing techniques utilised to characterise the mechanical contribution of vegetation to slope stability are also reviewed. Although still in its infancy biomechanical testing yields significant data, which are essential to quantify the contribution of vegetation to slope stability. The three main *in situ* biomechanical tests available are the shear box, root pull out and static load tests, which can be augmented with laboratory testing of the root properties. The selection of the appropriate method for the biomechanical characterisation of vegetation depends on the size of the subject plant.

4.1 VEGETATION PARAMETERS

In order to characterise the vegetation on a slope it is important to identify the vegetation present and quantify the amount of vegetation and its location on the site. A comprehensive guide for assessing natural forests and artificial plantations (Adlard 1990) outlines the procedures required to develop an inventory of the vegetation and site appraisal, which may be used to monitor tree growth and site change. The manual was developed to facilitate the scientific management of forests and plantations by documenting procedures for the selection and setting up of sample plots, their constant measurement and re measurement and the preliminary stages of data processing (Adlard 1990). Therefore, it outlines procedures relevant for characterising a slope vegetated by trees along with procedures pertinent to foresters and plantation managers.

The vegetation may be classified by its species or a number of species can be grouped according to their functional type. The amount of each species or functional type can then be assessed by its distribution across the site. As well as knowing how much vegetation covers the slope it is also important to know the location of the vegetation, whether trees occur as discrete elements or cover the slope the spacing between the trees can give an indication of potential interaction between the trees and any subsequent contribution to slope stability. Similarly, any wind loading or surcharge factors may be included in the slope stability analysis if the location of a stand of trees is identified.

It is important to assess the current condition of the vegetation, such as vitality, age and defects or disease as the vegetation can be detrimental or beneficial to the slope. However, it is also necessary to take a long term view when assessing the vegetation, because anthropogenic or environmental factors can cause deterioration of the existing vegetation or the contribution to slope stability can increase with the development of the vegetation. A dense stand of mature trees toward the toe of a slope may act as a restoring force by surcharge alone or contribute by anchorage and buttressing, while a stand of saplings will need time to develop, however, the mature stand may be approaching the end of its lifespan (natural or silvicultural) and may not aid stability in the future.

However, to characterise a vegetated slope with regard to determining the contribution of vegetation to slope stability, vegetation has to be considered as an engineering material. This can only be achieved by simplifying the variables associated with vegetation to quantifiable parameters such as type, amount and location. Root reinforcement is a function of density (volume of root material per unit volume of soil), tensile strength, tensile modulus, length to diameter ratio, surface roughness and the alignment and orientation of roots with respect to the failure plane (Hiller and MacNeil 2001). Material parameters such as tensile strength and stiffness of the roots can be determined and used in reinforcement models, or the contribution to shear resistance may be measured directly through direct shear box tests of root reinforced soil. Similarly, the root soil interface friction may be determined through root pull out testing and the resistance of a tree to uprooting through wind loading may be ascertained from static load tests. Therefore, characterisation of vegetation requires quantitative data to ascertain the contribution to slope stability and qualitative data to augment the conceptual model.

4.1.1 Identification and Classification

Vegetation is identified and classified into the various taxa using the hierarchical classification system of taxonomy, which forms a framework for understanding the significance of biological diversity (Ingrouille 1995). The work of Linnaeus in the eighteenth century is taken as the start of modern plant taxonomy. The highest taxonomic rank is Kingdom yet the most important taxonomic name is the species name. The convention for the generic and species names are Latinised and written in italics or underlined. Although it is important to identify what vegetation is on the slope it may not be necessary to identify each individual species, which may require the skills of a botanist or ecologist, but rather group the species according to their morphology or regeneration characteristics.

Plant functional types are non-phylogenetic groupings of species that show close similarities in their response to environmental and biotic controls (Duckworth *et al.* 2000). Although functional types were originally formulated in the last century, there has been an increased interest in the concept over the last decade (Duckworth *et al.* 2000), and biogeographers and functional ecologists employ functional grouping to understand and predict the various responses of plant communities to disturbances, either natural or anthropogenic, and improve management strategies (Gondard *et al.* 2003).

Smith *et al.* (1997) defined functional types of vegetation as biotic components in a plant community that present the same function or group of functions. Functional classifications often cut across taxonomic classifications and may be more appropriate for the geotechnical characterisation of a vegetated slope. However, in order to distinguish units to group several species under a common expression it is necessary to have a comprehension of the taxonomy. Therefore, the plant functional type approach is probably best viewed as a complementary approach to description using traditional taxonomy (Duckworth *et al.* 2000).

For the purpose of a geotechnical characterisation of a vegetated slope, the vegetation may be grouped into functional types according to the potential contribution to slope stability that it may provide. Ziemer (1981a) estimated that tree roots were between one and a half and three times stronger than grassy roots of a similar diameter. Coppin and Richards (1990) state that trees are generally more effective than grasses in terms of reinforcement due to higher root densities, tensile strengths, and being both laterally and vertically more extensive. This distinction may be further subdivided for deciduous or coniferous plants or classified by the anticipated root morphology to distinguish deep and shallow rooted species. The distinction of functional types may be arbitrary depending on the site and the complexity of the ecology, to provide a valuable method to aid the evaluation of the overall effect of vegetation on the stability of the slope and any potential for seasonal change.

4.1.2 Distribution

The amount of vegetation per unit area for a site may be quantified in one of four ways cover, frequency, density and biomass. Cover is the percent of ground covered by a species within a quadrat/survey area and can exceed 100% in a multi strata system. Cover classes like the Braun-Blanquet, Domin-Krajina or Daubenmire are used to simplify the estimation of percentage cover, as it can be difficult to estimate the cover of plants to the nearest percent. Fixed quadrats may be surveyed throughout the year to assess the seasonal variation of ground cover. The Jaccard Index (Equation 4.1) can be applied to compare similarities between species present on different areas or compare a fixed quadrat at different times of year, similarities are indicated when J is equal to or near 1.

$$J = c/a + b - c \tag{4.1}$$

Where:

a = The number of species in a
b = The number of species in b
c = The number of species common to a and b

Frequency is predominantly used for population studies, and is defined as the percentage of total samples in an area that contain at least one individual of the species in question. The presence or absence of each species is recorded in each sample area (quadrat or transect section) and the sample areas where the species are present is given as a percentage of the total number of areas sampled. While relative frequency is the frequency of one species as a percent of the total plant frequency. Frequency provides a measure of the distribution and abundance of a species but is dependent on the size of the quadrat and plant.

Density is the number of individuals per unit area, and is used to indicate how densely populated an area is by a particular species. This method does not give an indication of how much ground is covered by a species as individuals can vary in size. Relative density is the density of one species as a percent of the total plant density. A comparative study conducted by Lyon (1965) set out to compare the accuracy and precision of several of the more common density sampling techniques, and concluded that none of the methods were particularly desirable as all required an unreasonably large sample area to attain an acceptable degree of precision. In addition, Lyon (1965) commented that large samples did not guarantee accuracy because some sampling techniques will not produce the correct result with any sample size.

Biomass is all matter living or not, organised in a permanent manner as a constituent of a living organism (Adlard 1990). For the purpose of a vegetation survey biomass is the mass of a plant species per unit area and may by subdivided into root biomass and extant (stem and leaf) biomass. To quantify biomass destructive sampling is required, extant biomass is measured by harvesting, clipping at ground level, the vegetation in a sample area and measuring the dry weight. While, root biomass can be determined from soil cores or from the biomechanical test samples as long as the volume of soil from which the roots are extracted is known. Biomass is a quantitative method, and therefore, is the most effective way to determine plant production, but may not be sustainable if the subject area is destroyed for sampling. Biomass is an important parameter for tree covered slopes as it can be used to determine the surcharge. However, tree biomass may be extrapolated from the measurement of sub samples from each part of the tree and an estimate of the tree dimension. Therefore, the surcharge may be extrapolated from the biomass and population density.

In addition, to an estimation of the amount of vegetation covering a slope it is also important to determine the location of the vegetation. For example, a stand of trees located at the top or base of a slope can contribute to a localised surcharge or be subject to wind loading. Similarly, the spacing of trees ought to be recorded, to determine the potential for the interweaving of lateral roots or arching between buttressed pillars of soil formed by the deep rooting of some trees.

4.1.3 Root Distribution

When assessing any reinforcement material it is necessary to know the form, extent, orientation, spacing, dimensions and location of the reinforcement. When analysing the stability of a slope the reinforcement potential of the vegetation may be modelled in one of two ways, either as a veneer or disperse elements. Therefore, it is important to determine the vertical and lateral extent of the roots. Although the orientation of reinforcement regarding the slip plane is an important parameter for manufactured reinforcement, it is not practicable to model the individual roots crossing a shear plane, because unlike manufactured reinforcement vegetation occurs relatively randomly, even though the growth and development of root systems is not altogether random (Section 2.5). Therefore, it may be more appropriate to assume a random orientation when modelling roots crossing the potential slip plane. However, the orientation of the main roots is a useful parameter, as it can facilitate extrapolation to determine the location of the root system out from a tree trunk.

Different sized roots serve different purposes for the plant; fine roots provide water and nutrients to the plant while large structural roots provide anchorage. Studies of the size and frequency of dead tree roots in soils cleared of their forest cover (Burroughs and Thomas 1977; O'Loughlin and Watson 1981; O'Loughlin and Ziemer 1982; Stokes and Mattheck 1996; Watson *et al.* 1999; Ziemer and Swanston 1977) and of dead roots exposed on landslide scars (Abe and Iwamoto 1986a; Gray and Megahan 1981) indicate that roots under 20 mm diameter are most important to slope stability. Tests carried out by Abe and Iwamoto (1986a) on Japanese Cedar (*Cryptomeria japonica*) confirmed that when a tensile force is applied to a root greater than 10 mm diameter, the root is broken at a finer point and pulled out of the soil. Therefore, it is also important to identify the size class when quantifying the root distribution. Nieuwenhuis and Wills (2002) studied the root architecture of young Sitka spruce (*Picea sitchensis*) and reported that very little of the root cross sectional area was found beyond 60 cm from the root stock in either the vertical or the horizontal directions, even after seven growing seasons. Therefore, the root systems may be considered as discrete elements dispersed across the slope, if the trees are spaced widely apart, unless the lateral extent of the root systems are sufficient to interact with the roots of adjacent trees, whereby the root permeated horizon may be considered as a reinforced veneer.

4.1.4 Root Strength and Stiffness

Roots exhibit a tensile strength, which may be mobilised if a stress is imparted on a root system (Abe and Ziemer 1991b). Roots generally tend to break in tension rather than shear during slope failure, and the tensile strength of roots has been incorporated into root reinforcement models. Therefore, it is necessary to measure the tensile strength of representative sample roots. However, root tensile strength and morphology do not depend solely on the species; root tensile strength can vary markedly between species and within species (Ziemer 1981b).

The inter and intra species variation can be due to climate, season and local site characteristics such as nutrient and water availability. However, some of the variability may be accounted for by the quality or location of root diameter measurement. Tensile strength is a function of the inverse square of the radius; therefore, a small decrease in root diameter can give an appreciable increase in the calculated root tensile strength (Watson *et al.* 1999). Burroughs and Thomas (1977) found that root systems of the same species take on different shapes and strengths, according to the slope angle, soil type and groundwater, for example the roots of the coastal Oregon Douglas Fir were found to be twice as strong as the central Idaho Douglas Fir. Burroughs and Thomas (1977) also demonstrated that the tensile strength of Douglas fir roots declined rapidly after tree felling. Therefore, tensile strength data are regarded as specific to species and site (Schiechtl 1980).

The reinforcement model proposed by Wu (1976) includes Young's modulus of the root as a variable, because deformation and stiffness of the root inclusion are significant factors that provide reinforcement to the soil shear strength. Young's modulus may be determined from the linear part of a stress strain plot of either a direct tensile or bending stress test. However, it is imperative that the root is straight and securely clamped, because the root straightening or slipping from the clamp will yield erroneous results.

4.1.5 Root Soil Interaction

The contribution of vegetation to slope stability is most readily associated with the enhancement of shear resistance through root reinforcement. Root reinforcement is a function of the root tensile strength, stiffness and embedment length combined with the soil properties and the interface friction between the two materials (Section 2.2). The increase in shear resistance can be determined by comparative analysis of shear test results of a root permeated and a fallow soil. Shear box tests of root reinforced soil have been conducted in the laboratory and *in situ*.

The contribution of roots to the stability of soil slopes can also be regarded as a function of their tensile strength and ability to resist pull-out over the embedded length (Abe and Ziemer 1991a). The pull out resistance of individual roots or entire plants may be determined from *in situ* pull out tests, analogous to tests conducted on tension anchors. However, pull out tests on manufactured reinforcement are much simpler to analyse because the element has known dimensions of a standard shape, whereas root morphology is typically heterogeneous and the root dimensions are not easily obtained as a portion of the root may remain in the soil.

4.2 DISTRIBUTION INVESTIGATION TECHNIQUES

To characterise the vegetation on a slope it is necessary to identify the vegetation present and classify it according to species or functional type. It is then possible to conduct a vegetation survey to quantify the amount, distribution and location. The maturity and vitality of the vegetation are important factors when assessing the vegetation, as growth and decay cycles will impact on the overall slope stability. The amount of vegetation present can be quantified as cover, frequency, density or biomass. This may be done using survey techniques such as quadrats, or transect lines to estimate low lying vegetation. Whereas, trees and shrubs may be measured and located as discrete elements or the edge of a stand may be surveyed and the spacing between trees within the stand recorded. The cover of a canopy can be derived from the leaf area index determined from below the canopy. Alternatively, remote sensing techniques can be employed to estimate the vegetation cover of remote or inaccessible slopes.

4.2.1 Survey Methods

A simple and effective way of estimating vegetation cover requires the use of a quadrat to demarcate the unit area over which the vegetation is estimated. The dimensions of the quadrat depend on the size of the site and the target species. For areas covered by trees rather than low lying vegetation a fixed plot may be marked out, again the size of the plot will depend on the site and target species. Adlard (1990) recommends that circular plots should be used in plantations with regularly spaced trees and square plots used for natural stands and open, irregularly stocked plantations.

Fixed quadrats can be surveyed seasonally to assess the ground cover to determine the seasonal variation. If destructive sampling is required to quantify the biomass, a survey plot may be subdivided to minimise disrupting the vegetation, so that seasonal measurement of biomass will not influence the assessment of vegetation cover. However, if the subdivision of plots is not an option destructive testing should be conducted toward the end of the survey.

Canopy cover of trees is difficult to visually estimate from below due to the lack of reference points. The leaf area index (LAI) is the ratio of total leaf surface to total ground surface and can be determined by foliage collection, whereby the number of leaves on a branch are determined for ten branches of a sample tree and scaled up for the size of the crown. However, because the leaf area index changes throughout the year frequent determinations will be required. Therefore, a rapid estimation of the LAI from direct measurement of the light interception using equipment such as the LI-COR LAI 2000 device may be preferable. The device comprises a wide angle fish eye lens to measure the distribution of light and shade giving a ratio of sky to leaves present, (Lopez-Serrano *et al.* 2000). When held below a canopy or individual tree the contrast in light and shade is recorded giving the LAI. As the leaf area index varies seasonally it should be monitored continually throughout the year.

4.2.2 Remote Sensing Methods

Remote sensing techniques such as LIDAR, (LIght Detection And Ranging), have been used to study vegetation cover and determine canopy density (Harding *et al.* 2001; Kotchenova *et al.* 2004; Lefsky *et al.* 1999a; Riano *et al.* 2004b). LIDAR uses the same principle as RADAR (RAdio Detection And Ranging) systems but utilises electromagnetic radiation at optical frequencies (Kavaya 1994). The LIDAR transmits light which interacts with and is changed by the target, the reflected light is analysed by the instrument and some properties of the target may be ascertained, such as crown bulk density, while the travel time can be used to determine the distance to the target (Riano *et al.* 2004a).

A study of various remote sensing data sources conducted by Hyyppa *et al.* (2000) concluded that LIDAR produces better results than aerial photography, airborne hyperspectral radar or airborne profiling radar. LIDAR studies do not predict foliage biomass directly but give a total aboveground biomass estimate (Lefsky *et al.* 1999b) which has correlated well with forestry inventory estimates for western Oregon (Lefsky *et al.* 2005). A validation study at plot and tree level conducted by Riano *et al.* (2004a) found that tree height and crown base height correlated well with the field measurements, and provided accurate crown bulk density estimates at plot level, but was problematic at tree level.

4.3 ROOT DISTRIBUTION INVESTIGATION TECHNIQUES

It is important to ascertain the lateral and vertical distribution of the roots to differentiate the limits of the vegetation's zone of influence, from which it may be possible to determine the effect of vegetation on the hydrogeological parameters and quantify any potential root reinforcement. There are various techniques available to ascertain the distribution of a root system, which may be grouped into invasive and non invasive methods. The invasive methods require the excavation of a portion of or the entire root system, which can then be digitized or mapped, consequently either the root system or the soil root bond is disturbed. Alternative non invasive methods such as ground penetrating radar or differential electric conductance techniques do not damage the roots but forfeits the quality and accuracy of root system data that may be achieved by exhumation.

4.3.1 Invasive Methods

The importance of root system architecture for the stability of trees has received considerable attention (Coutts 1983b; Nicoll and Ray 1996; Schiechtl and Stern 1996; Stokes *et al.* 1997; 1998; Tsukamoto 1987). Root systems may be exhumed intact using trowels and spades, or the soil may be sluiced away with a jet of high pressure water or compressed air, using an instrument such as the air spade (Plate 4.1). The supersonic jet of air moves the soil causing minimal disturbance to the root system, even fine roots are left intact. However, the spoil is scattered and backfilling the hole can be problematic. Similarly, the use of water flushes away the soil creating a mess on site and altering the soil properties negating the use of any *in situ* tests in close proximity to the excavation. The use of a trowel can damage the fine roots when scraping away the soil, therefore, the selection of excavation technique depends on the reason for excavating.

Plate 4.1 Excavation of tree root system using air spade (Nadezhdina and Cermák 2003)

The root morphology has an important influence on the contribution of roots to the shear strength of the soil root composite. Wu *et al.* (1999) reported that a taproot system is more likely to mobilise the full tensile strength of the tap root, while plate and heart root systems will have many roots that do not fail in tension at shear displacements up to 400 mm. Studies of structural root morphology have successfully employed the Polhemus fast track digitiser to map root systems (Chiatante *et al.* 2003; Danjon *et al.* 1999).

Figure 4.1 Digitised root system of a 25-year-old ash (Drexhage 2002)

The digitiser utilises a low frequency electromagnetic field to map significant points on the root system, such as branch points, change in direction or nodes, in the x, y and z planes. The maximum and minimum diameter of the root is measured at each point and a precise and complete numerical 3-D representation of a structural root system is produced using AMAPmod software (Danjon *et al.* 1999) (Figure 4.1).

Small root systems may be analysed digitally using commercially available software packages such as winRHIZO and Delta T Scan (Bouma *et al.* 2000), whereby the root system is placed on a scanner and the image is scanned into the computer. This does not give the level of quality obtained from the digitization of a root system because of the overlap and cross over of roots intrinsic to 2D scanning rather than the 3D mapping, however, comparison of computerised analyses with microscopic measurements showed good total root length and diameter distribution agreement (Bouma *et al.* 2000). Therefore, scanning roots is an effective method for the rapid collection and assessment of data, providing the relevant procedure for preparation and scanning are employed.

A manual method for recording the root morphology outlined by Nicoll *et al.* (1995) records the azimuth and orientation of individual roots manually using a compass clinometer and the vertical and horizontal diameter measured with callipers. Nicoll and Ray (1996) adapted the method with the introduction of a frame and plumb bob to record depths and spacing from the tree, while Mickovski and Ennos (2002) employed a similar method to that used by Riestenberg (1994) of recording the azimuth and diameter 0.2 or 0.3 m from the stump. Mickovski and Ennos (2002) used a polar plot to chart the mean cross sectional area and R value, whereas Riestenberg (1994) plotted the data for each tree on both a rose diagram and a stereographic projection to illustrate different aspects of the root morphology.

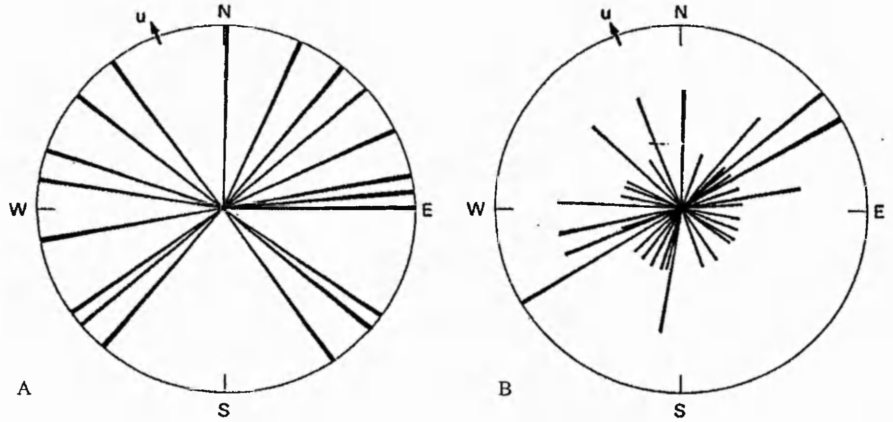


Figure 4.2 Rose diagrams to illustrate the azimuths of A) white ash and B) sugar maple root systems. U marks the upslope direction (Riestenberg 1994)

Figure 4.2 illustrates the directional trend of lateral roots with relation to the slope as plotted on a rose diagram. Figure 4.3 shows the root distribution, using the cross sectional area of roots, plotted on a stereographic projection. A concentration of roots near the centre of the plot indicates near vertical roots and low angle roots plot near the circumference.

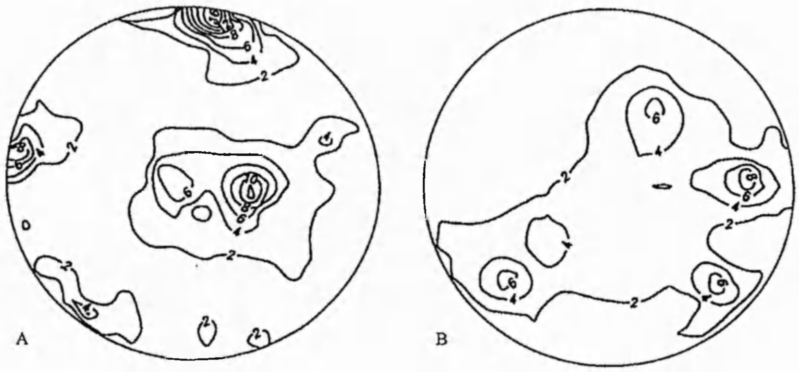


Figure 4.3 Stereonets of cross sectional area of roots cutting the lower hemisphere (Riestenberg 1994). Plot A) shows a white ash taproot and lateral roots, while the sugar maple plot B) is shallowly rooted

Wu *et al.* (1999) analysed the data of Riestenberg (1994) and reported that the ultimate load was reached at 100 mm displacement for sugar maple, while the white ash root system, primarily taproot, failed abruptly at 30 mm, and so concluded that tensile failure depends on root morphology (Wu *et al.* 1999).

There are two different types of stereographic projection, the equal area and the equal angle nets. The equal area projection net is distorted to facilitate contouring of the data points and subsequent statistical evaluation of the angular relationships (Figure 4.3). While the equal angle net is geometrically correct and used by geologists to visually solve angular relationships. Both the rose diagram and stereographic projection are crude representations compared to the digitised image produced by the polhemus digitizer, as they only represent a snapshot of the roots at a particular depth and distance from the tree. However, less data is required to produce the rose diagram and stereographic projection plots compared to the digitized image and so more root systems may be quantified in this way, making this a more appropriate way to illustrate a trend in root growth on the site. Therefore, rose diagrams and stereographic projection plots are a simple and effective way to demonstrate any anisotropic growth anticipated on a slope.

The vertical distribution of roots may be determined by excavating a pit or trench 'the trench/profile wall method' (Böhm 1979) or from splitting undisturbed samples retrieved from augering 'soil core break/auger method' (Böhm 1979; Escamilla *et al.* 1991). In the trench method root density is determined by counting the number of roots of a certain size class exiting the face of a trial pit /trench using a quadrat. The results may be expressed as number of roots per square centimetre of soil (N), or given a term of abundance such as the system adopted by the British Columbia Ministry of Forestry (Table 4.1).

Table 4.1 Root size class and abundance (Meidinger 1998)

Size Class	**Very fine**	**Fine**	**Medium**	**Coarse**	**Very coarse**
Size (mm)	<1	1-2	3-5	6-15	>15
Reference area	25 cm^2			100cm^2	
Abundance	Very fine	Fine	Medium	Coarse	Very coarse
None	0	0	0	0	0
Few	<10	<10	1	1	1
Plentiful	10-50	10-50	2-10	2-5	2-5
Abundant	>50	>50	>10	>5	>5

Bengough *et al.* (1992) modelled root growth in three dimensions and estimated that 70-80% of fine roots could be missed by visual inspection. However, the precision of fine root estimation is not a consideration for slope stability analysis, for although the fine roots can contribute to shear resistance, and bind soil particles, many fine roots are ephemeral and their abundance may vary seasonally. Alternatively the sum of the root cross sectional area per unit area may be reported. Operstein and Frydman (1990) represented the relationship thus:

$$A_r = F_r / F = \sum f_i * n_i / F \quad (4.2)$$

Where:

A_r = Root area ratio
F_r = Total root cross sectional area
F = Total cross sectional area of soil
f_i = Cross sectional area of roots of size class i
n_i = Number of roots of size class i

The size class boundaries are arbitrary and may be selected to suit the soil / root profile, for example the size class system of Böhm (1979) ranges from very fine (<0.5 mm) to very large (>20 mm), which is different to that illustrated in Table 4.1.

The core break/auger method involves extracting a soil core of known volume and washing the roots from the sample to measure root biomass or length to give length per unit volume of soil (L_v). Root biomass estimates from cores can be highly variable where root distribution is uneven and the quality of these estimates depends on matching sample size with the coefficient of variation (Butnor *et al.* 2003). Vogt and Persson (1991) reported that soil cores were useful to study fine roots, but were not suitable for coarse root (>2 mm) analysis due to the unequal distribution and decreasing density with increasing distance from the stump.

Pierret *et al.* (1999) proposed analysing soil cores with X-ray Computed Tomography (CT) to determine the amount of fine roots within the core. The method consists of sampling from various positions around the base of trees by impregnating the soil with epoxy resin, to stabilize the sample, the extracted cores are then scanned with a medical X-ray CT device (Pierret *et al.* 1999). Heeraman *et al.* (1997) compared L_v from destructive testing with CT measured L_v and reported results between 44 and 60 cm/cm^3 and 76 cm/cm^3, respectively. The under estimation of root length from the destructive method may be a function of root loss during washing, alternatively, there may be an overestimation from the CT method, as the 3D image is generated by connecting points on the 2D slices, and points assumed to be roots are connected (Pierret *et al.* 1999).

Various methods to measure soil microbial biomass are available, including quantifying the amount of biomass phosphorous (Brookes *et al.* 1982), biomass nitrogen (Brookes *et al.* 1985) and a parallel method for biomass carbon (Vance *et al.* 1987), in which the soil is fumigated with chloroform, incubated and then the quantities of carbon or nitrogen released measured. Alternatively, the changes in organic carbon may be determined by considering dehydrogenase and the activity of three enzymes involved in phosphate, sulphur and carbon cycles (de la Paz Jimenez *et al.* 2002) or measurement of adenosine triphosphate (ATP) as a surrogate for microbial biomass carbon (Castellazzi *et al.* 2004). More commonly the microbial biomass is measured as a whole from their production / respiration.

Such a detailed study of microbial biomass may not prove necessary for a ground investigation of vegetated slopes, however, it is important to appreciate that microscale distribution; microbial activity, mycorrhizal associations and fine root dynamics significantly affect plant performance through soil resource capture and carbon and nitrogen cycling (West *et al.* 2004).

Another method for determining root distribution with minimum disturbance to the site was proposed by Čermák and Kucera, (1990), whereby soil water content is measured using installed monitoring equipment, and the effective root area is calculated by equation 4.3.

$$A_{rt}^{ef} = Q_{wt} / \Delta M_{ws(i)} \tag{4.3}$$

Where:

A_{rt}^{ef} = Effective root area ground plan m^2

Q_{wt} = Transpiration of tree canopy

$\Delta M_{ws(i)}$ = Daily measured soil water decrease below $1 m^2$ of stand area in kg m-2 day-1.

This method is influenced by the placement of the moisture probes and it is necessary to have an idea where the roots responsible for water uptake are located with regard to the tree. A general rule of thumb is that the roots of young trees (up to four years old) do not extend far beyond the drip line of the canopy; however, as the tree grows the roots exploit the soil for water and nutrients and may extend two to four times the diameter of the tree canopy (Sillick and Jacobi 2004). A study by Sternberg *et al.* (2005) used a pulse chase technique to determine depth and breadth of water uptake using a deuterium pulse and deuterated water. They concluded that the rooting structure was characterized by a dense cluster of short roots associated with the main trunk and a few meandering long range lateral roots.

Rhizotrons (glass walkways) or minirhizotrons (glass tubes) can be installed to monitor root growth. Since data obtained from minirhizotrons are limited to the length and diameter of fine roots observed on minirhizotron tubes, data conversion is necessary to determine the fine root biomass per unit soil volume or unit stand area (Noguchi *et al.* 2004). Bernier and Robitaille (2004) reported problems in transforming images of roots captured along a two-dimensional plane into estimates of root volume or mass within a soil volume. Similarly, Davis *et al.* (2004) used rhizotrons and reported that the best estimates for the appearance and disappearance of fine roots were generated by harvesting roots rather than photographing them.

Unfortunately rhizotrons are expensive to construct and there are problems when using natural soil as the profile is disturbed during construction (Taylor *et al.* 1990). Minirhizotrons have also proved problematic as their installation provides preferential pathways for root growth, and tracking of the root down the side of the glass tube has been noted (Hiller and MacNeil 2001). The in growth core method has also been developed to ascertain root development, and may be used in conjunction with undisturbed samples to determine the total fine root biomass (Bauhus and Messier 1999). However, these methods are more appropriate for monitoring the development of roots rather than the determination of root location and density. Therefore, they are not considered to be an effective technique for the geotechnical characterisation of a vegetated slope, but are more appropriate as research techniques, which are necessary to increase the understanding of root development and morphology.

A review of direct and indirect methods for root biomass determination (Vogt *et al.* 1998) discusses and compares the results of the most commonly used techniques including: sequential root coring, ingrowth cores, minirhizotrons, carbon fluxes approach, nitrogen budget approach and correlations with abiotic resources. Vogt *et al.* (1998) reported no consistent relationships were apparent between the indirect and direct methods when used on the same site and concluded that until the different root methods can be compared to some independently derived root biomass value obtained from total carbon budgets for systems, one root method cannot be stated to be the best. Therefore, the method of choice will be determined from researcher's personal preference, experiences, equipment, and/or finances (Vogt *et al.* 1998).

4.3.2 Non Invasive Methods

Ground penetrating radar (GPR) has become a familiar part of geotechnical site (Section 3.4) and has also been used as a method to determine tree root distribution without disturbing the root system (2003; Butnor *et al.* 2001; Hruska *et al.* 1999; Stokes *et al.* 2002), as roots with a higher water content than the soil matrix provide the necessary contrast to be detected by the GPR (Wielopolski *et al.* 2000). Cermák *et al.* (2000) recorded the maximum rooting for two mature field maple trees (*Acer campestre*) at depths of 1.4 m and 1.7 m on a clay soil in an urban environment. The trade off between resolution and penetration affects the success of this method, as a high resolution is required to detect roots limiting the penetrable depth of the signal. This depends to a large extent on the soil type, as attenuation of the signal is affected by high conductivity soils.

Hruska *et al.* (1999) reported that it is possible to cover a 6 m area in 6 hours using a 0.25 m grid at 0.05 m intervals to acquire the raw data, which takes another 30 hours to evaluate, however, this time will be reduced as processing power increases. The raw data is manipulated using standard geophysical processing software, anomalies are then interpreted to produce a plan view of the root system, a 3D image may be created by applying depth correlations.

However, GPR can pick up high contrast areas such as stones or voids and these anomalies may be interpreted as roots resulting in erroneous data. Stokes *et al.* (2002) found errors where roots branched or crossed over and roots were interpreted from artefacts of the echogram, and concluded it was not possible to obtain the true root system architecture using this method. Such errors may be minimised with the development of specialised filters that would discriminate clutter and other artefacts typical to GPR (Wielopolski *et al.* 2000).

Hruska *et al.* (1999) reported it was not possible to detect roots less than 10mm diameter, while Stokes *et al.* (2002) reported they could not detect roots less than 20mm diameter, however, Cox *et al.* (2005) successfully employed GPR to detect root fragments 2.5 to 8.2 cm in diameter and buried at depths of 11 to 114 cm, and Butnor *et al.* (2001) reported that roots as small as 5 mm are directly detectable with GPR. Although they were unable to separate root size classes due to orientation of roots, geometry of root reflective surface and proximity of other adjacent roots, or even depth classes of root biomass in shallow profiles (Butnor *et al.* 2001).

Butnor *et al.* (2003) used a 1.5 GHz antenna on a loblolly pine stand, and achieved a maximum penetration depth of 0.7 m. The GPR results were correlated with soil cores and Butnor *et al.* (2003) reported that correlations exceeded 85% and also observed that fertilizer application had significant effects on signal attenuation. Butnor *et al.* (2003) concluded that the estimation of root biomass with GPR was improved with the aid of advanced signal processing techniques, horizontal distance normalisation and background removal techniques are necessary to standardise datasets, while Kirchoff curve fitting and the Hilbert transformation improved the correlation between actual and estimated root biomass.

Wielopolski *et al.* (2000) suggest using a multi frequency antenna may be required to cover a range of depths and resolution capabilities to overcome the compromise between improved resolution and reduced penetration with the high frequency antenna and vice versa for the low frequency, and concluded that with current technical capabilities and future developments, to image roots 2 to 3 mm diameter is a realistic goal. Barton and Montagu (2004) compared three different antennas (500, 800 MHz and 1GHz) on samples of damp sand containing roots of diameters from 10 to 100 mm buried at a single depth of 500 mm, and also varied the depth of burial 150 to 1550 mm of a similar diameter roots (50 mm). This resulted in a significant gain in clarity with roots appearing as discrete shapes, thereby reducing confusion due to overlapping of hyperbolas when many roots are detected (Barton and Montagu 2004). Barton and Montagu (2004) report that the waveform parameters represent a major advance in the processing of GPR profiles for estimating root diameters, which were predicted with a root mean squared error of 6 mm. Enhanced data analysis routines combined with improvements in GPR hardware design could make GPR a valuable tool for studying tree root systems (Barton and Montagu 2004). However, the success of GPR to detect tree roots is site specific as GPR is limited by the electromagnetic properties of the soil being surveyed (Doolittle *et al.* 2002), therefore, careful consideration to the soil suitability and other site factors that can limit the resolution required to detect tree roots is necessary (Butnor *et al.* 2003).

Alternative non invasive techniques to determine the distribution of roots include radioisotope, soil injection and differential electric conductance. Radioisotope aided methods may be broadly grouped into three, namely neutron moderation, plant injection and soil injection (Wahid 2001). The neutron moderation method takes advantage of the knowledge that roots deplete the soil water, especially near the feeder roots; therefore, root density is estimated indirectly by measurement of the soil water depletion rates, using a neutron moisture probe. The plant injection method introduced by Racz *et al.* (1964), uses a phosphate isotope (^{32}P) injected into the plant, the radionuclide is allowed to translocate, samples of the root core are then taken from different lateral distances and depths around the tree, and the root densities are calculated from the amount of radioactivity measured. Stabler & Rediske (1958) injected a rubidium isotope (^{86}Rb) and mapped the root system of a Douglas fir with a scintillation detector. Although plant injection has proved successful in some species it should be used with caution as the quantity of radioactivity necessary for a large tree is considerable and certain species may translocate the radionuclide to the leaves rather than the root system.

The soil injection method was developed in 1963 by Hall *et al.* and has been widely used since (Wahid 2001). A choice of radioisotopes may be used including phosphate (^{32}P), nitrogen (^{15}N) and rubidium (^{86}Rb) depending on plant type and length of experiment. The isotope is introduced to the soil and radioisotope analysis is conducted by radio assay, the root activity is evaluated by comparing the radioactivity in the roots to that in the soil. Again the use of radioisotopes has its own environmental implications and the dose varies on the species, plant size, soil type and seasonal activity.

Differential electric conductance has recently been employed to estimate the area of conducting root surface and given as m^2 per tree (Nadezhdina and Cermák 2003). This method is based on the differences in the conductivity of materials, and the fact that the zones in which roots absorb soil water are practically identical to the zones through which the electric current passes when the tree becomes part of the electric circuit, supplied from an external voltage source (Nadezhdina and Cermák 2003). Although the first results obtained from differential electric conductance for a range of seedlings and trees are promising more experience is needed before recommending this method for general use (Nadezhdina and Cermák 2003).

4.4 ROOT PULL OUT TESTING

The mechanical properties of a reinforced soil mass are improved by the reinforcement placed parallel to the principle strain direction, which compensates for the lack of tensile resistance in the soil. The stresses are transferred between the soil and reinforcement by friction and passive resistance, which depend on the soil properties and normal effective stress along with the dimensions and spacing, surface roughness and elongation characteristics of the reinforcement. The soil reinforcement interaction can be evaluated by the pull out performance of the reinforcement with respect to the pullout resistance and the displacement. To evaluate the reinforcement interaction the displacement required to mobilise the tensile force should be lower than the allowable displacement and the pull out load should be smaller than the critical creep load (Elias *et al.* 2001) .

The uprooting resistance of small shrubs and trees can be measured either by uprooting the entire specimen or by pulling individual roots. Pull out testing may be conducted manually using a clamp and spring balance/load cell or mechanically using a small frame or larger apparatus depending on the size of specimen. Different methodologies have derived from various research groups. Crop scientist have studied the uprooting resistance of rice and wheat plants (Bailey *et al.* 2002; Ennos 1991; Ennos *et al.* 1993; Goodman *et al.* 2001; Landi *et al.* 2001) while foresters and engineers have applied themselves to the uprooting resistance of trees either for tree and stump stability (Crook and Ennos 1996; Cucchi *et al.* 2004; Mickovski and Ennos 2002; Ruel *et al.* 2000) or slope and bank stability problems, (Karrenberg *et al.* 2003; Kitamura and Namba 1981; Nilaweera and Nutalaya 1999; Tsukamoto 1987; van Beek *et al.* 2005). Pull out resistance includes tensile strength at break, plus tangential friction between soil and root and the mechanical strength caused by pulling bent parts of the root through the soil, therefore, it is not appropriate to use only the maximum tensile strength to represent root reinforcing strength (Abe and Ziemer 1991b).

4.4.1 Root Pull Out Apparatus

The root pull out test has been conducted in one of two ways; the root is either pulled through the soil, perpendicular to the root direction of growth to measure the shear resistance, or is pulled out of the soil in line with the root direction to record the pull out force. The apparatus developed to conduct the root pull out test varies with each research project. Various clamps and winches have been incorporated into frames from which reaction could be mobilised, or adjacent trees have been employed to provide anchorage.

Wu *et al.* (1988) conducted root pull out tests by pulling the root through the soil horizontally, perpendicular to the root direction (Figure 4.4). However, this yield displacement is a different measurement to the displacement recorded if the root is pulled directly outward, parallel to the direction of growth. The set up also requires that the root is sufficiently embedded in the soil at both sides of the pit to maintain a symmetrical load distribution and facilitate consistent displacement recording. Therefore, the majority of other researchers have pulled roots or entire specimens out from the soil parallel to the direction of growth.

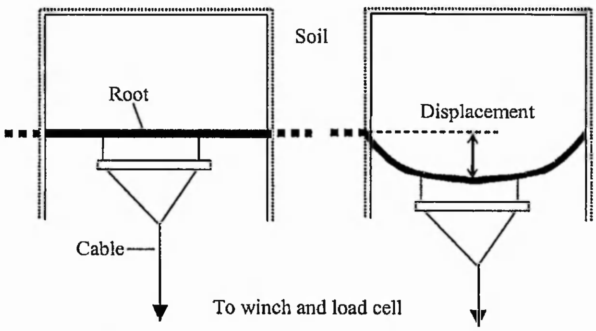


Figure 4.4 Plan view *in situ* pull out test apparatus and displacement measurement (after Wu *et al.* 1988)

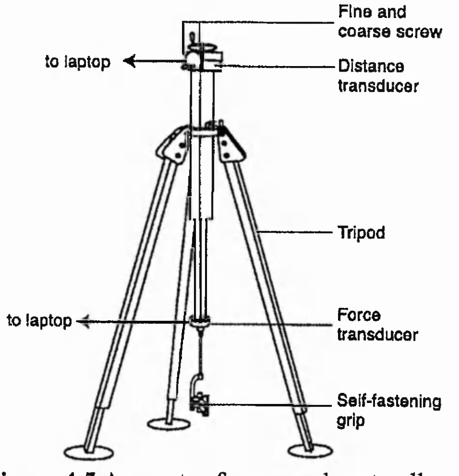


Figure 4.5 Apparatus for upward root pull out tests (Karrenberg *et al.* 2003)

Karrenberg *et al.* (2003) developed a tripod with a crank and gearing system to pull saplings vertically upwards (Figure 4.5), while Tsukamoto and Kusakabe (1984), Anderson *et al.* (1989a) and Riestenberg (1994) employed adjacent trees as anchorage for their pulley systems to pull lateral roots outward from the soil (Figure 4.6).

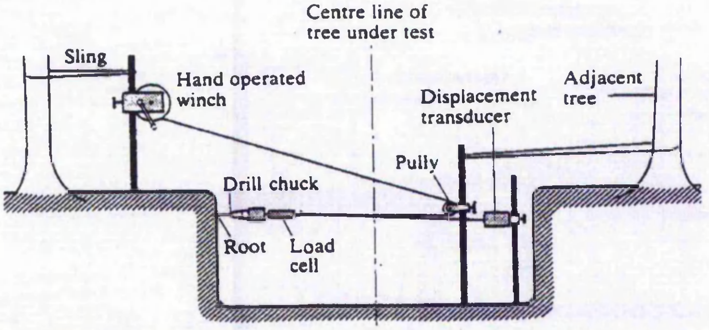


Figure 4.6 Apparatus for root pull out testing of lateral roots employed by Anderson *et al* (1989a)

The mechanical root pull out apparatus of Norris and Greenwood (2003) and similar lightweight frames (discussed in Chapters 6 and 7) have the versatility to pull roots out in any direction.

4.4.2 Failure Mechanisms

When roots that are embedded in the soil are pulled they will resist the pulling force, the resistance comprises the soil root bond, tensile strength of the root and shear strength of the soil. Therefore, there are three key failure mechanisms related to root pull out testing; the root may fail in tension (where the root snaps) the soil root bond may fail (where the entire root is steadily pulled out) or the soil may fail (where the root and its offshoots are pulled intact from the ground surrounded in soil).

Coutts (1983b) considered a simple theoretical model of root soil resistance, incorporating root tensile strength and soil shear strength to deduce the positions of failure for the root or soil or root / soil interface. Coutts noted that:

- A straight root of uniform diameter pulled at one end will snap where there is no soil root bond to reinforce the root.
- With a tapered root the distribution of strain is governed by the cross sectional area as well as the root soil bond. Strain increases as root diameter decreases but strain also decreases as the root soil bond increases, there will be a point of maximum strain along the root where it will break.
- Many branches cause root soil to act as a unit, the amount of root material in soil required to increase the root soil bond to equal the soil strength is termed Critical Root Density (CRD).
- Where root material diminishes so that root soil bond is less than the soil strength, strain will cause the soil to fracture first, because of its low elasticity, the force will then act on the roots causing them to fail beyond the soil fracture.

- An increase in root thickness or decrease in root soil bond will move root breakage away from the tree, while an increased root soil bond (from higher soil shear strength, dry soil) will cause roots to break nearer the base of the tree.

Nilaweera (1999) performed pull out tests on several species whose root system consisted of a large taproot, most failures were by tensile failure of the taproot at some point below the loaded end, in a few tests failure occurred in the soil and the entire root system was pulled out, none of the systems failed by interface shear. However, comparison of model and experimental data by Waldron and Dakessian (1981) showed that the strength of the soil root bond is the most important unmeasured parameter; and this value rather than root strength limited the root reinforcement in a saturated clay loam. Wu *et al.* (1999) reported on various root pull out studies, the sugar maple root system, with extensive branching failed by successive tensile failure of smaller branch roots.

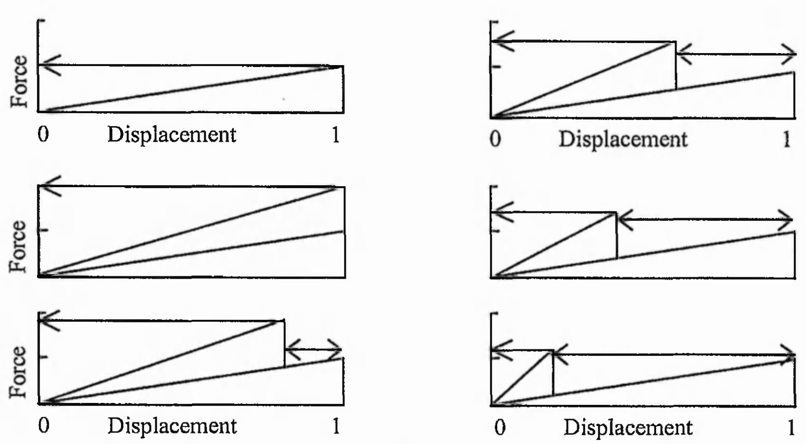


Figure 4.7 Diagrammatic explanation for peak pulling resistance force drops (Blackwell *et al.* 1990).

Bailey *et al.* (2002) tested uprooting force of onion and two mutants of onion, one without root hairs and one with reduced lateral branching observed a co operation between roots, where distance between drops in pull out force of separate roots can add to peak resistance based on spring like root model of Blackwell *et al.* (1990) (Figure 4.7). Blackwell *et al.* (1990) considered the root as an ideal spring which fails at a load of one unit, a second identical spring will result in the peak force being doubled, but if the second root fails before the first at a load of one unit the peak is still reduced. Assuming unit individual pulling force, the peak pulling force decreases as the distance between the failures of the two roots increases (Blackwell *et al.* 1990).

Stokes *et al.* (1996) conducted laboratory testing using copper coated steel wire embedded in 'wet' sand. Various branching morphologies were studied to identify whether changes in branching can affect the pull out resistance. Stokes *et al.* (1996) reported that an increase in root surface area influences uprooting resistance although if there are too many roots in a small space, the soil surrounding the roots may fail and the roots will come up surrounded by a block of soil. Stokes *et al.* (1996) also reported that of the branching angles experimentally tested, pull-out resistance was enhanced at an angle less than 90° and daughter roots with branching angles greater than 45° would be placed in torsion, and therefore, offer less resistance to uprooting. Stokes *et al.* (1996) concluded the depth of the root system is more important in determining its anchorage, as this is a result of shear strength increasing with overburden and increase in passive resistance.

Finite element modelling of root morphology was conducted by Dupuy *et al.* (2005) to identify factors affecting anchorage. Three simple morphologies were modelled, sinuous (simple zig zag), straight with herringbone branching and dichotomous branching (Dupuy *et al.* 2005). The finite element models showed that the branching angle was found to have a negative effect on the uprooting resistance and root failure in tension depended on the root strength, soil plastic properties and resistance of the soil root interface, similarly, different failure mechanisms were observed depending on the root geometry (Dupuy *et al.* 2005). Dupuy *et al.* (2005) concluded that the number of roots and the diameter of roots were major components affecting the resistance to uprooting.

Root pull out testing is theoretically the most direct way to measure the root soil bond strength, but it is not straightforward. The root morphology, root tensile strength, soil shear strength and water content may all affect the results, as will the rate of test and direction in which the root is pulled, and for tortuous roots there is not a direct solution. Anderson *et al.* (1989b) conclude from their study that the difference in stability on two different soil types cannot be explained in terms of force required to extract individual roots.

4.5 TREE WINCHING

Tree winching is a methodology used to assess tree stability under wind loading or tree stability on slopes (Crook and Ennos 1996; Mickovski and Ennos 2003; Papesch *et al.* 1997; Stokes 1999) rather than slope stability. However, several stability models incorporating vegetation have included uprooting resistance as a parameter. The tree winching methodology has been modified to quantify the uprooting resistance of an entire tree with regard to slope stability. Tree winching is usually conducted as a static load test because a prevalent wind direction is regarded as a static rather than a dynamic load. A subject tree is felled to a safe height of between 1.2 and 1.3 m; while nearby trees that may affect the winching results may be cut back or felled completely. A sling is attached to the remaining stem to facilitate winching (Figure 4.8) and the tree is winched in three directions upslope, down slope and cross slope rather than the windward or leeward direction, (as used in the original methodology) and the final loading tests the tree to failure.

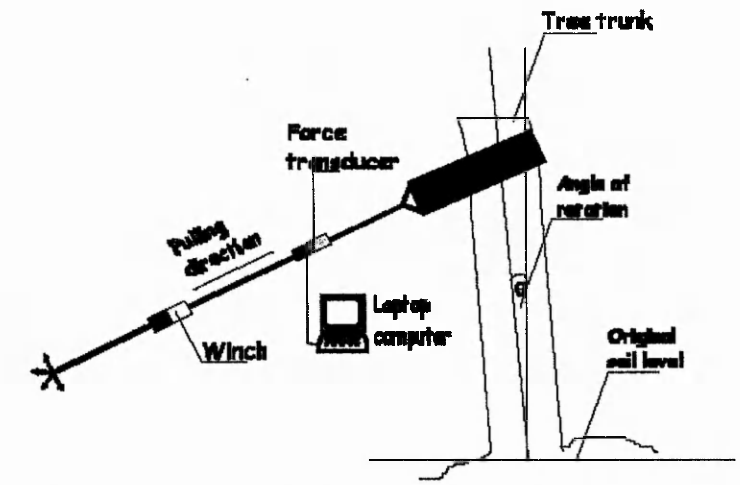


Figure 4.8 Schematic section of the tree winching test (Mickovski and Ennos 2002)

The force applied is measured with a load cell while strain gauges are attached to the tree base, stem and roots. Two inclinometers are also attached to the tree trunk to record stem deflection. The longitudinal strain, stem stiffness and Young's modulus are determined with the incremental loading and aid the quantification of the dissipation of wind forces from the stem into the soil (Stokes 1999). The final overturning stage gives an indication of the uprooting resistance and allows further study of the root architecture and biomass. However, because the tree has been felled to 1.3 m height the component of the overturning force due to the weight of the removed stem and crown has to be added to determine the maximum resistive bending moment (Papesch *et al.* 1997).

Two types of mechanical tree failure may occur during static load tests, either uprooting failure where the entire root plate is displaced and the tree trunk is overturned or stem failure which is characterised by breaks and fissures in the trunk, which propagate upwards from the base (Mickovski and Ennos 2002). The two failure mechanisms are not mutually exclusive and a tree may fail due to a combination of root and stem failure. In addition, to root or stem failure the soil can fail around the root plate, therefore, the tree stability is dependent on root morphology, soil properties and the extant geometry of the tree which is subject to wind loading.

The centre of movement about which the tree rotates during failure is affected by the root morphology and soil characteristics. Soil surrounding the root resists root pivoting by applying lateral forces against root with increasing intensities away from pivot point (Figure 4.9). Niklas *et al.* (2002) reported that wind-induced bending force F causes stem flexure and bayonet like root pivoting at L/2 in the absence of lateral root restraint (Figure 4.9a) or at L if lateral roots act as tensile guy-wire like mechanical elements (Figure 4.9b), therefore, the roots provide a counter-resisting moment M_R to stem flexure (Niklas *et al.* 2002). For a plate root system M_R is displaced from the stem axis, creating a hinge about which the tree rotates during failure (Figure 4.10). The hinge location depends on the size, location and amount of roots and their resistance to bending, and is also influenced by the soil properties. In addition, the location of the hinge may change during failure if the roots resisting bending fail, reducing the resistance available in front of the tree, which alters the geometry of system.

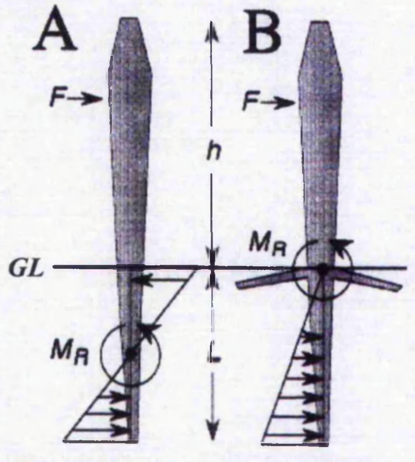


Figure 4.9 Mechanics governing root anchorage for A) taproot and B) taproot with laterals (Niklas *et al.* 2002).

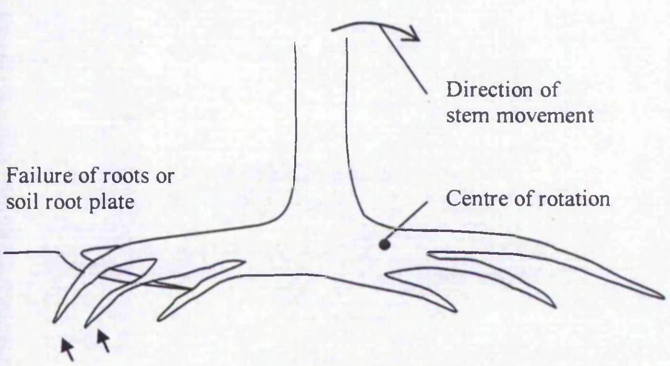


Figure 4.10 Centre of rotation for plate root system with sinker roots (compiled from Crook and Ennos 1996; Ennos 2000). Centre of rotation may move toward the stem if the lateral roots in front of the tree break during failure.

4.6 *IN SITU* SHEAR TESTING

One of the main effects of vegetation on slope stability is the contribution to shear resistance. Therefore, it is important to measure the shear strength of root permeated soil. It is difficult to measure and evaluate the effect of large roots using the ordinary types of shear apparatus, for example, the triaxial compression test, the small direct shear test and the vane shear test, because the scale of these tests are too small to shear soil with tree roots (Abe and Iwamoto 1986b). The British Standard (BS 1377-7: 1990) for laboratory shear box testing states, 'the size of the largest particle shall not exceed one tenth of the height of the specimen.' However, this does not account for elongated inclusions that span the height of the sample. If the one tenth of the sample height is interpreted as the diameter equivalent, the standard laboratory sample (approximately 20 mm high) is limited to inclusions of fine roots up to 2 mm diameter.

Therefore, various techniques have been developed to determine the *in situ* shear strength of root permeated soil, as *in situ* testing is considered necessary to minimise sample disturbance and produce representative results that may be used to quantitatively evaluate the effect of the vegetation on slope stability. Abe and Iwamoto (1986b) categorised the *in situ* shear box test with regard to other available tests (Figure 4.11).

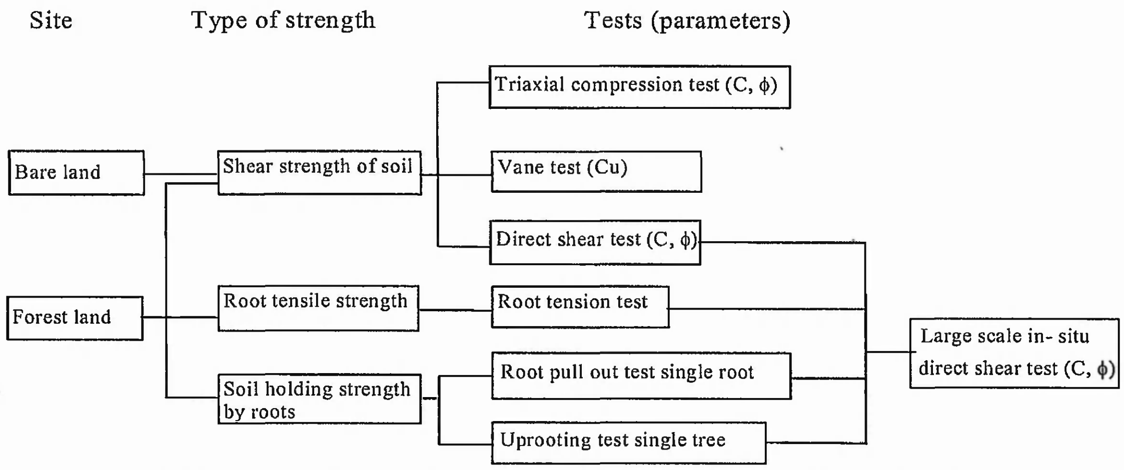


Figure 4.11 Position of large scale direct shear test (Abe and Iwamoto 1986b)

In situ shear box testing for non rooted soils and rocks is covered in the British Standard (BS 5930: 1999), however, *in situ* testing of rooted soil has only been applied as a research technique, and therefore, a different methodology and size of testing apparatus appears with each research group. There are two main types of *in situ* shear box; based on whether the box has four sides or open sides the different strategies for *in situ* shear box testing are summarised in Table 4.2.

Many researchers conducting *in situ* shear box texts have attempted to apply a normal load by adding weights to the sample surface. Abe and Iwamoto (1986b) used a normal load to replicate a 'reasonable' overburden pressure. A range of normal loads have been applied to the samples to produce a dataset from which the cohesion intercept may be determined. From comparative analysis of fallow and root permeated datasets the 'enhanced cohesion' through root reinforcement may be derived. The normal load has been achieved through the application of lead or iron bars or concrete blocks to the sample surface, this is more straightforward for grassed samples, which are relatively level. However, the presence of a tree stump is problematic as the load may be transferred through the root system rather than carried by the soil root composite. To ensure the even loading of the sample, the tree stump is cut flush with the ground surface, and a cover plate to place the weights on is used to achieve an evenly distributed normal load (Abe and Iwamoto 1986b; Endo 1980).

Table 4.2 Different approaches to four sided and open sided *in situ* shear box testing on vegetated soil

Author	Length x Width x Height (mm)	Displacement Force	Vegetation	Normal load (kg)
Four sided in situ shear box				
Abe and Iwamoto, 1986b	1000 x 1000 x 500	Jack	*C. japonica*	0, 50 and 100
Endo and Tsuruta 1969 Endo 1980	500 x 500x 300	Cable and Winch	Various trees	155 - 407
Barker 1986	610 x 300 x 175	Cable and hydraulic ram	Grasses	~100
Tobias 1994	500 x 500 x 150	Pull jack and chains	Herbaceous vegetation	Max 150
Yatabe et al. 1996	300 x 300 x 120	Hydraulic jack	Various trees and grasses	Variable
Norris and Greenwood 2003	135 x 135 x 100	Cable and hydraulic ram	Various young trees	None
Van Beek et al. 2005	600 x 600 x 400	Either cable and winch or bottle jack	*Pinus halepensis*	0 to 300
Open sided in situ shear box				
Ziemer 1981a	300 x 600 x 300	Jack	*Pinus contorta*	Not specified
O'Loughlin 1981 O'Loughlin *et al.* 1982	300 x 300 x 150	Jack	*Nothofagus fusca* and *N. truncata*	Not specified
Wu *et al.* 1988 (Apparatus of Ziemer 1981a)	300 x 600 x 300	Jack	Various trees	None
Ekanayake *et al.* 1997 (Apparatus of O'Loughlin 1981)	300 x 300 x 150	Jack	*Pinus radiata* and Kanuka	148
Van Beek *et al.* 2005	600 x 600 x 400	Jack	*Pinus halepensis*	0 to 300

Other researchers have omitted the normal load and concentrated on measuring any turning moment occurring during the test (Wu and Watson 1998). In addition to the shear box tests the torque method has been developed by the Scottish Centre of Agriculture Engineering, which has been utilised by some foresters (Smith 1986), for tree root systems that are too large for an *in situ* shear box.

4.6.1 Four Side *In situ* Shear Box

The four side shear box is similar to the laboratory shear box in that the sample is confined on four sides and a single shear plane forms along the base of the sample. The dimensions of the shear box vary from 135 mm (Norris and Greenwood 2003) to 1 m (Abe and Iwamoto 1986b). The other key difference between the types of apparatus is the application of force; the sample block may be either pushed with a jack (Figure 4.12) or pulled using a winch (Figure 4.13).

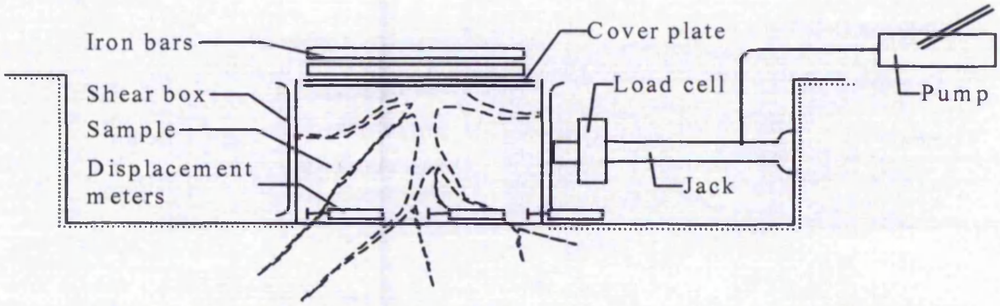


Figure 4.12 Four-sided shear box and jack set up (Abe and Iwamoto 1986b)

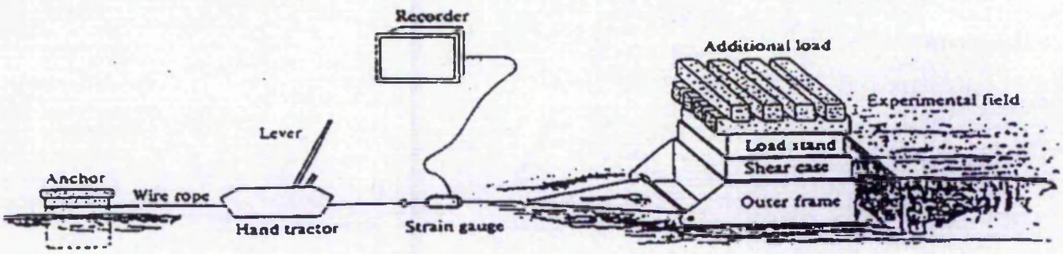


Figure 4.13 Four-sided shear box and winch set up (Endo 1980)

4.6.2 Open Side *In situ* Shear Box

The open sided shear box is designed so that the sample shears along two parallel vertical planes as well as along the base. Reinforcement due to the anchorage of lateral roots may be measured along with any taproot reinforcement present. This design is preferable for species with a plate like root system where a taproot is under developed or not present and lateral root reinforcement is prevalent (Figure 4.14).

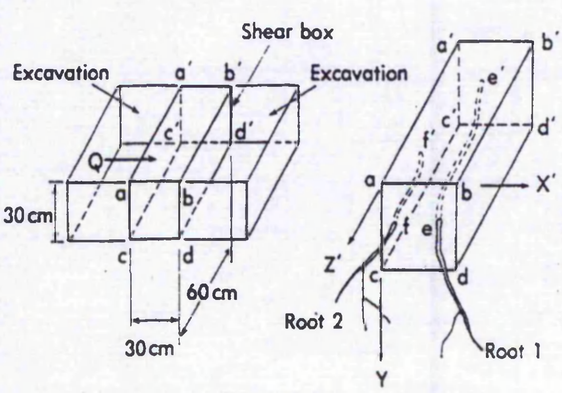


Figure 4.14 Open sided shear box and lateral roots, Q is direction of applied force (Wu *et al.* 1988)

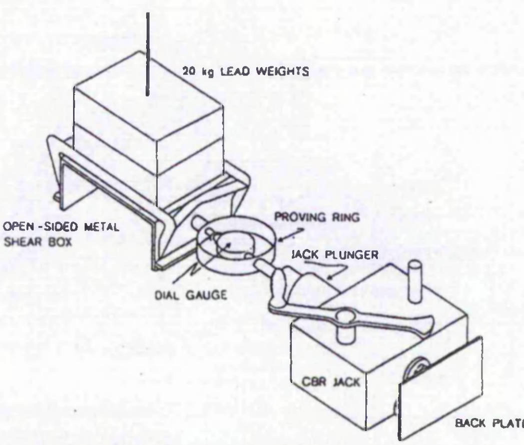


Figure 4.15 Open sided shear box set up of O'Loughlin (1981)

The open sided shear box is pushed, as the frame is generally not stiff enough to be pulled (Figure 4.15). There is less variability in the designs of the open sided box and the dimensions range from 300 mm (O'Loughlin 1981) to 600 mm (van Beek *et al.* 2005).

4.6.3 Torque Method

The torque method measures the *in situ* shear resistance of a root system by twisting the root plate relative to the underlying soil. For this method a tree is felled to 1m height and a trench 0.4 m wide is excavated around the tree at radius of between 0.3 and 0.8 m from stump to depth just beyond the maximum rooting depth the trunk is then rotated and the torque recorded (Figure 4.16). The torque and radius of the failure plane are then used to calculate the shear strength and the normal stress is the sum of the weight of the root plate and stump and the torque bar divided by the area of the shear plane.

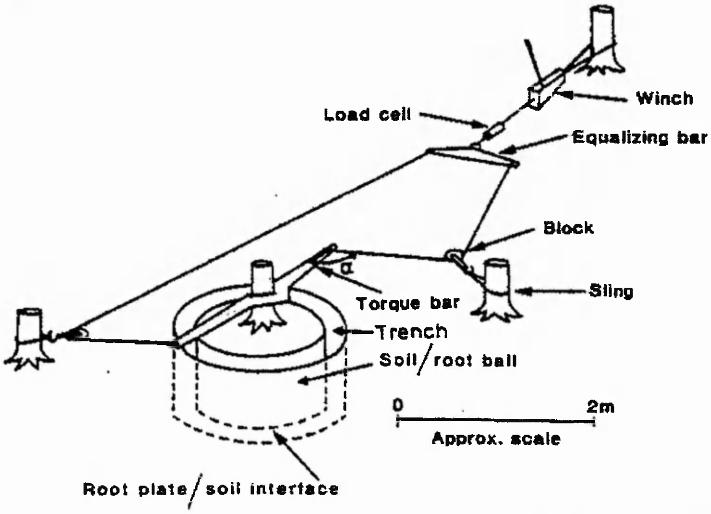


Figure 4.16 Torque method employed by Smith (1986) and Anderson *et al.* (Anderson *et al.* 1989a)

4.6.4 Evaluation of the *In situ* Shear Tests

The majority of *in situ* shear box tests conducted by researchers have been conducted to demonstrate the increase in shear resistance of a rooted soil compared to a non rooted soil. Abe and Iwamoto (1986b) reported the shearing strength values on the planted plot were 11-34% larger than those on the bare plot, and both the number of roots and the distribution influences the shear strength. Similarly Endo and Tsuruta, (1969) reported root content ranged from 4 to 12 kg of fresh roots per cubic metre of soil which raised shear strength between 5 and 10 kPa, and concluded the increase in shear resistance is proportional to fresh weight in roots per m^3 soil. However, the increase in shear resistance recorded can be a function of the dimensions of the sample and inclusions therein.

The *in situ* shear box configurations employed by previous researchers only use a top box confining a pedestal of soil while the surrounding soil confines the underlying part of the sample, for this situation there is no absolute sample height unless it is possible to determine to what depth the soil is influenced by the shear test. Therefore, without the sample height it is difficult to delimit a maximum inclusion size, according to the British Standard (BS 1377-7: 1990). Abe and Iwamoto (1986b) developed large *in situ* shear box (1000 x 1000 x 500mm) to overcome many of the influences of the boundary conditions for their research, while work conducted by Springman *et al.* (2003) observed, samples in the 250 x 250mm *in situ* shear box had gravel up to 100 mm on occasions giving a higher shear resistance than would be mobilized in the field.

The small direct shear box seems markedly influenced by boundary conditions, resulting interface friction angles exceed those that would develop along an unrestricted interface of soil and solid surface Paikowsky *et al.* (1995). A laboratory study conducted by Terwilliger and Waldron (1990) reported that shear strength values were an order of magnitude greater than the corresponding strengths of the large samples, and the inclusion of stones or roots appeared to increase soil strength far more in the small cores than the large diameter samples. Palmeira (1987) reported that direct shear tests on unreinforced sand samples showed that soil strength parameters were not affected by the test scale. Similarly, Dijkstra (2000) conducted *in situ* tests on loess using three different size *in situ* shear boxes (0.1, 0.2 and 0.3 m^2) and concluded that when the sample conditions are very similar the shear box size does not significantly affect the mobilisation and magnitude of shear strength. However, Jewell and Wroth (1987) reported that the scale of the direct shear has an influence on the boundary conditions and recommend a ratio of shear box length to average particle size in the range of 50-300.

Matsouka *et al.* (2001) developed a large *in situ* shear box to test coarse grained soils with a maximum grain size of 300 mm. The apparatus comprises a shearing lattice embedded in the ground, a normal load is applied, and the sample is pulled with a chain or rope. Matsouka *et al.* (2001) recommend a shearing frame at least four times the maximum grain size is required, and that the shearing frame and lattice dimensions are varied for different soil types.

The laboratory shear box does not have the facility to record pore water pressure, therefore, the test is considered drained without pore water pressure measurements, the same is true of the *in situ* test. However, if the specimen is of low permeability and the strain rate is sufficiently rapid the test may be considered undrained (BS 1377-9: 1990).

The rate of strain can induce pore water pressures if the material is of sufficiently low permeability to inhibit the dissipation of pore water during the test, conversely if permeability of the soil is high enough to facilitate the dissipation of pore water, no build up of pore water pressure occurs, resulting in a drained test. Therefore, the parameters obtained and the quality of the results are strain rate dependent. Furthermore, the presence of roots within a sample can influence the permeability of the soil, and ought to be taken into consideration when selecting the strain rate.

Chandler and Hamilton, (1999) conducted unconsolidated undrained shear box tests on sheared London Clay and commented that rigid boundary devices can be expected to overestimate the unconsolidated undrained shear strength of discontinuities in any clay. If the sample were intact the undrained strength would reflect the initial mean effective stress *in situ*, as a consequence the S_u measured in the shear box is likely to be much higher than that operating along horizontal planar discontinuities *in situ*. The measured strength thus appears to relate to the mean effective stress (or a slightly higher value), not to the *in situ* vertical effective stress, which is a consequence of stress relief during sampling that cannot be reversed in the shear box (Chandler and Hamilton 1999).

Research conducted by Jewell (1989) on sand demonstrated a need for symmetry within the direct shear test. This is achieved by applying the vertical load through a rigid top platen placed on the levelled upper surface of the prepared soil sample. Once the sample is prepared the spacers and connectors are removed and the soil supports the applied vertical load and weight of the top platen and top of the apparatus. This now mirrors the lower half of the sample thus providing symmetry. Any tendency for tipping during the test indicates symmetry is not being achieved. The sample must still be allowed to displace vertically during the test without resistance, while no additional unknown vertical forces should be introduced into the test. However, the introduction of reinforcement in a direct shear test introduces non uniformity into the sample and direct internal measurements are recommended (Jewell and Wroth 1987). Unfortunately, accurate measurement of vertical displacement is problematic when using the *in situ* apparatus and the measurement of internal strains is not practicable.

In addition, the *in situ* apparatus may have multiple badly defined shear directions (Hight 1986), as the sample will tend to travel along a path of least resistance, and this phenomenon may be accentuated in a root permeated soil. Similarly, a shear zone of undetermined thickness to form rather than a shear plane, observed in the laboratory tests. Shewbridge and Sitar (1989) showed root resistance and associated increase in strength are affected by the thickness of a shear zone, which in turn is a function of the stiffness of the reinforcing element. The effect of shear zone thickness on the difference in soil shearing resistance was investigated by Waldron and Dakessian (1981) using pine roots up to 6mm diameter. They found that when the shear zone was varied between 2 and 20 mm with other parameters held constant, the most significant effect on the change in shear strength was at displacements between 2 and 20 mm. In addition, Palmeira (1987) reported that shear band thickness at the centre of the sample was significantly affected by the scale of the test. Therefore, the size of shear apparatus and initial shear zone height are variables that must be acknowledged when conducting a comparative analysis.

Work conducted by Wu *et al.* (1979) performed *in situ* shear box tests (30.5 m^2) and laboratory shear box tests for comparative analysis, however, because of the large scatter in the data, no conclusions are drawn with regard to the differences. Although the *in situ* apparatus is based on a similar principle to the laboratory shear box, it is not as refined, and less is known about the stresses and strains occurring within the sample during the test. All the designs use a frame to confine the top of the sample and move it in relation to the ground below, therefore the sample is only partly confined in a rigid container. Dijkstra (2000) modelled the principle stresses and strains of a partly confined *in situ* shear box for loess, and reported one major curvilinear failure surface and a series of secondary failure planes, which occur predominantly along the base of the shear box within the same area as that enclosed by the shear box. However, an enclosed root system may significantly alter this failure mechanism, especially if rotation of the roots occurs during the test, eliminating the symmetry required in the laboratory test.

In summary, problems associated with the direct shear test especially the *in situ* shear apparatus of whatever design are exacerbated with the inclusion of roots. These problems include: potential rotation of the sample resulting in a loss of symmetry, lack of control over; drainage, height of shear zone and direction of shear, along with the uncertainty over the acceptable scale of test required to accommodate the dimensions of elongated inclusions, without being adversely affected by the boundary conditions. However, despite the drawbacks, the *in situ* shear box test is a useful tool for the comparative analysis of root reinforced and fallow soil, and may be used to evaluate the contribution of vegetation to slope stability, although the results should be treated in context.

4.7 LABORATORY TESTING FOR VEGETATION PARAMETERS

Frydman and Operstein (2001) conducted a numerical simulation of large direct shear tests performed on soil samples reinforced with roots, using soil parameters obtained from triaxial tests, and root properties from tension and pull-out tests. They reported that a good agreement was obtained between the analyses and the results of the laboratory tests. The root reinforcement model developed by Wu (1976) incorporates the root tensile strength, and further work by Waldron and Dakessian (1981) related root tensile strength to shear zone width and Young's modulus to tangential friction. Therefore, the tensile strength and stiffness of the root are important parameters, which can be ascertained from laboratory tests. The root properties are influenced by the water content, which should also be determined in the laboratory. It has also been demonstrated that laboratory shear box tests on root-permeated soils can give useful results, and although many researchers justify using *in situ* shear box techniques the laboratory test is not redundant with regard to root permeated soil.

4.7.1 Root Strength and Stiffness Determination

Direct tension laboratory apparatus, such as the Instron or Tensometer 20, are available to measure the tensile strength of roots, but many have a limited clamp diameter and usually accept roots up to 15 mm diameter. This may be considered a problem; however, as tensile strength measurements reflect the weakest point in the root segment, it is arguably representative to test the smaller diameter roots, which are more likely to fail in tension during slope failure, rather than the larger roots that tend to pull out intact. Abe and Ziemer (1991b) reported that most roots in the potential shear zone are less than 10 mm, and concluded that, most roots directly affecting slope stability are about 10 mm or less in diameter.

Abe and Iwamoto (1986a) reinforced the ends of roots with epoxy resin to encourage failure in the centre, and commented that reshaping of roots to assure failure point is not sensible as annual rings, bending points and junctions greatly influence value of root strength. Ziemer, (1978) commented that tensile strength tests reflect the weakest point in the root segment, and the sample length can increase the probability of finding a weak segment. Weakness can occur on bends where individual fibres break as the root straightens, or root nodes and knots, branching or necking points or areas that have disease. The cross cut shear strength apparatus was developed by Ziemer (1978) as an alternative to laboratory tensile strength testing, because the tensile strength test allows a greater probability for testing weak points in a root. Ziemer (1981b) reported that the cross cut shear results correlated well with the tensile strength results measured with an apparatus developed by Burroughs and Thomas (1977).

The Young's modulus for a root can be measured effectively by either direct tension or static loading, used to assess beam stiffness. Young's modulus is taken from the linear portion of the stress strain plot of the tension test; however, this may prove problematic as the root can slip as the wood in the grip fails, yielding erroneous results. Static loading is an alternative method for the determination of Young's modulus, which can also yield a bending strength if the test is taken to failure. The three and five point methods, so named because of the number of point contacts along the specimen, may be employed to determine the Young's modulus without clamping the root.

However, it must be borne in mind that the Young's modulus and tensile strength of a root is dependent on the water content. Work conducted by Papa (2003) concluded that the tensile strength of roots increased after roots lost 5% of their original water content but tensile strength decreased thereafter. Rehydrated roots also had a reduced tensile strength compared to those tested at the natural water content. Therefore, the root tensile strength and stiffness determination should be undertaken while the samples are still at their natural water content and the water content should be measured and recorded along with the results. Root tensile strength can also be affected by the environment, season, age, type or species (Gray and Sotir 1996), root diameter, (Burroughs and Thomas 1977; Operstein and Frydman 2000) amount of cellulose (Commandeur and Pyles 1991; Genet *et al.* 2005; Hathaway and Penny 1975) sample preparation and the elongation rate (Cofie and Koolen 2001).

Wu *et al.* (1999) observed that, progressive failure will occur in a root system, where different roots fail at different displacements. For example a tap root system is more likely to develop the full tensile strength of the tap root while, in plate or heart shaped root systems, many of the roots would not fail in tension at shear displacements up to 400 mm. Therefore, it is implausible to count on the tensile strength of all roots when estimating the shear strength. Wu *et al.* (1999) developed an empirical relationship of one third of T_{uf} (the tensile force for the roots cross sectional area) however; they do caveat this relationship as tentative as it was based on a few tests.

4.7.2 Shear Resistance

Many researchers have preferred *in situ* shear box testing as this can accommodate whole root systems or large lateral roots. In addition the test can be carried out on a large undisturbed sample. However, studies on land slipped areas and root plates from winched or fallen trees indicate root failure occurs in the smaller diameter roots. Therefore, a suitable undisturbed sample containing the finer root portion tested in the laboratory, either in a shear box or triaxial cell, may be as informative as the large scale *in situ* tests. Waldron (1977) conducted laboratory shear tests on Alfa alfa, barley and yellow pine and fallow soil samples and recorded significant root reinforcement from the Alfa alfa and barley but the yellow pine only had a small effect on shearing resistance.

4.8 SUMMARY

To ascertain the contribution vegetation may have on slope stability it is necessary to determine the geotechnical parameters to evaluate the condition of the slope, regardless of the vegetation as discussed in Chapter 3. However it is also important to characterise the vegetation covering the slope to ascertain the beneficial or detrimental effects that may be associated with the vegetation. Although, Sutton (1969) stated that there is no such thing as an intrinsically deep or shallow rooted tree species, different types of vegetation express differences in root morphology and survival strategies (to tolerate extreme conditions or seasonal changes). Therefore, it is important to identify the functional types and determine the amount of each type present on the slope. It is also necessary to evaluate the distribution and location of the vegetation across the slope, to ascertain where the key contribution or vulnerable areas are. In addition, the spacing between trees can be an important parameter on wooded slopes to assess the potential for interweave between roots or buttressing and arching between suitably spaced trees.

To evaluate the long term contribution of vegetation to the slope stability it is also necessary to undertake a visual assessment of the age, vitality and health of the key functional types. The root reinforcement potential is dependent on the lateral and vertical extent of the root system and the size of roots. Therefore, it is necessary to ascertain the distribution of the roots either by invasive or non invasive methods and establish the amount and size class of roots within the soil, which can be done through core or trench methods. Once the amount and extent of the roots is determined it is then possible to establish zones of influence of the vegetation.

Root pull out tests can be conducted to ascertain the soil reinforcement interaction. Pull out tests have been conducted by a number of researchers with different aims, therefore the methodologies vary accordingly. Agricultural scientists have conducted pull out tests on entire specimens, while foresters and engineers have concentrated on tree stumps or tree winching tests and individual root pull out tests. The pull out test methodology varies as the roots are either pulled out parallel to the direction of growth, or through the soil perpendicular to the growth direction.

The failure mechanism depends on the soil root interface friction, the tensile strength and Young's modulus of the root along with the soil properties and normal load. The soil root composite will fail by one of three main ways: tensile failure of the root, failure of the soil root bond or soil failure around the root system. The three failure mechanisms are not mutually exclusive and a pull out test on large roots may fail by a combination of the three, as side roots fail prior to the main root or soil fails around a fibrous cluster of roots. The complexity of the failure mechanisms and soil root interaction within a root system and the variability of roots encountered during a pull out test imply that the pull out test although potentially a direct way to measure the soil root bond is not a fundamental test.

The use of pull out tests for man made reinforcement evaluation benefits from the reinforcing members being of regular dimensions with consistent properties, while root morphology is dependent on the root development and environment and the tensile strength also varies. Pull out tests have been conducted in the laboratory on specimens grown in containers (Kaul 1965; Operstein and Frydman 2000). Although such tests can give an indication of the pull out capacity required for entire specimens or individual roots, they are not without their limitations, such as the influence of boundary conditions (Palmeira and Milligan 1989) and the practicality of testing large specimens.

Comparative analysis of root permeated and fallow *in situ* shear box test results can give an indication of enhanced shear resistance of a root reinforced soil. However, there is not a standardised apparatus or methodology, and the various shear box designs are not without their problems, as with the laboratory shear box there is no control over the drainage and the shear plane is mechanically induced, however, because the *in situ* apparatus is not secured shear zones rather than a shear plane can occur increasing variability between tests. Similarly, if the shear box is pulled or pushed it may deviate from the principle direction, resulting in multiple or badly defined shear directions, this phenomenon is minimised if the box is mounted on runners to a secured frame. The problems associated with drainage, variable shear zones, direction and rotation of the sample can all be augmented by the presence of vegetation, which can provide preferential flow paths or focus zones of resistance within the sample. Therefore, the *in situ* shear box cannot be considered as a fundamental test, but is a useful index test, the results from which may be incorporated into slope stability models so long as the limitations of the test are appreciated.

Root reinforcement may be derived by one of a number of theoretical models (Chapter 2) with the use of key vegetation and soil parameters. Therefore, it is possible to model the contribution of vegetation to slope stability from the characterisation of the vegetation and root distribution and appropriate sampling of soil and roots and the soil root composite, for laboratory testing. The tensile strength and Young's modulus of the root are the key parameters for laboratory determination, however, the results of both tests are water content sensitive and should be conducted at the natural water content of the root, which ought to be recorded and reported along with the results.

This chapter has focused on the characterisation of vegetation on a slope and the testing techniques available to quantify the mechanical reinforcement contributed by the vegetation. The following chapter recognizes the influence vegetation has on the hydrological cycle and the soil water conditions, and the techniques available for monitoring the soil water conditions, either positive or negative pore water pressures, to determine the effect of vegetation on the hydrogeology of a slope.

Hydrogeological Investigation Techniques

5

Water, water, everywhere, and all the boards did shrink.
Water, water everywhere, nor any drop to drink
Samuel Taylor Coleridge (1772-1834). The Rime of the Ancient Mariner

Vegetation has long been recognised as part of the hydrological cycle, and as such it is important to ascertain the effect of vegetation on the hydrogeological parameters when characterising a vegetated slope. The hydrological cycle is the constant recycling of water between the oceans, atmosphere and the land. The continual cycle of storage and movement mainly comprises input (precipitation), storage (as ice, oceans or lakes), transfer (as rivers, groundwater flow and rain clouds) and outputs (transpiration from vegetation and evaporation from open surfaces and plants). The hydrological cycle as a global model is a closed system, therefore, the inputs and outputs may be considered as additional transfer or storage mechanisms, whereas on a local scale, such as a drainage basin, an open system prevails where rivers and runoff may be considered outputs from the system. The balance of output, storage, transfer and input on the local scale is known as the soil water balance and the interactions within affect both the growth of vegetation and the stability of slopes, therefore, components of the soil water balance are an important part of the investigation of the vegetated slope.

Agricultural researcher, Briggs, considered the connection between plant growth and the energy required to extract water from the soil in 1897 (Croney and Coleman 1961). More recently research on the effect of vegetation-induced suctions in shrinkable soils on buildings has been conducted (Biddle 1985; 2001; Blight 1997; Cameron 2001; Driscoll 1984); this research has extended to the effect of vegetation-induced suctions on slope stability (MacNeil *et al.* 2001; Marsland 1997). Vegetation can create suctions in the soil during the growing season, when transpiration exceeds precipitation. There is evidence that suctions can persist through into the winter months, below certain types of vegetation, where precipitation is not sufficient to completely recharge the soil water (Biddle 1984; Driscoll 1984; Richards *et al.* 1984). In order to assess the seasonal variability of the vegetation and its effects on the soil properties it is necessary to monitor the site throughout the year. Therefore, it is necessary to conduct vegetation surveys and water content and/or suction profiles seasonally to assess the amount and variation of ground cover, and its affect on the soil water regime.

5.1 WATER BALANCE

The soil system water balance is a model used to show the state of equilibrium between water entering, leaving or stored in the soil system. The key input is precipitation, while potential evapotranspiration and runoff are the major outputs or losses from the system (Figure 5.1). When annual precipitation exceeds the potential evapotranspiration the water budget is positive and a downward flow of water or waterlogged conditions result, while an area may be classified as arid where a negative water budget prevails. The balance of water input and output is a valuable tool for agronomists and soil scientists as it can indicate areas prone to leaching or mechanical washdown of soil or other water sensitive mechanisms such as gleying or podzolisation.

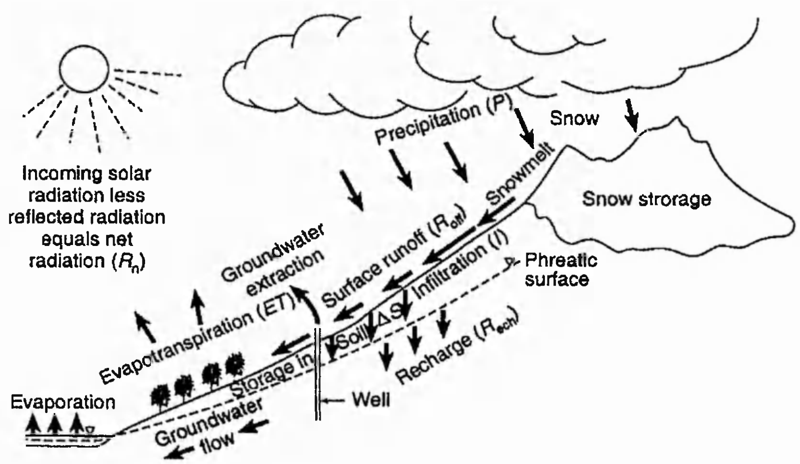


Figure 5.1 Components of soil water balance (Blight 1997)

The general equation describing the water balance for the unsaturated zone, from the soil surface to below the root zone is given by equation 5.1 (Thornthwaite and Mather 1955).

$$P - Q \pm \Delta S_w - E \pm \Delta S_s - D = 0 \quad \textbf{(5.1)}$$

Where:

P	=	Precipitation
Q	=	Runoff
ΔS_w	=	Change in water storage ponded on the surface
ΔS_s	=	Change water stored in the soil
E	=	Evapotranspiration
D	=	Deep Percolation (unrecoverable by vegetation)

In forested areas where light precipitation occurs as much as 50% can be intercepted (Tindall and Kunkel 1999) therefore, where interception (I) is a consideration it can be written into equation 5.1 giving equation 5.2.

$$(P-I)-Q\pm\Delta S_w-E\pm\Delta S_s-D=0 \tag{5.2}$$

The soil water balance system employed by Blight (2003) is totalled over the year to give an annual water balance (equation 5.3). Although evapotranspiration is considered a parameter within the equation interception by vegetation is not taken into account as a potential loss, but may be accounted for in the bucket term, losses. Therefore, infiltration or recharge to the water table is assumed to equal the amount of rainfall and water stored in the soil less the amount of runoff and water lost through evapotranspiration. Thus equation 5.3

$$\sum(R-RO)+S-\sum ET=RE+losses \tag{5.3}$$

Where:

R	=	Precipitation (measured using rain gauges)
RO	=	Runoff (measured by discharge flumes)
S	=	Water stored in the soil
ET	=	Evapotranspiration
RE	=	Recharge to water table

The loss of water back to the atmosphere through evaporation and the mobility of water within the system are influenced by the energy balance (equation 5.4). Vegetation plays an active role in the partitioning of incoming solar radiation into sensible and latent heat fluxes and the energy balance becomes more complicated (equation 5.5) the overall net effect of vegetation is a significant reduction in the diurnal temperature range (Tindall and Kunkel 1999).

$$R_n=H+L_vE+G \tag{5.4}$$

With vegetation becomes

$$R_n=H+L_vE+G+St+P \tag{5.5}$$

Where:

R_n	=	Net Radiation
H	=	Sensible heat flux
L_v	=	Latent heat of vaporisation
E	=	Mass flux of water vapour, transpiration is included in this term
G	=	Soil heat flux
St	=	Combination of sensible and latent heat stored or released from vegetation
P	=	Energy consumed by photosynthetic and metabolic activity in plants

The parameters necessary for such models may be measured, assumed or modelled. However, assumed parameters invite uncertainties and the system may only be considered a partial water balance. Unless the soil system water balance is defined, understood and measured, changes and their effects within the system cannot be fully understood, analysed or predicted (Blight 2003).

5.2 HYDROGEOLOGICAL PARAMETERS

The key hydrogeological parameters are a combination of meteorological, hydrological and geotechnical parameters. Certain parameters such as soil water, groundwater and permeability are common to both geotechnical and hydrological investigations. The parameters incorporated in the water balance model may be grouped according to the fate of the water within the open hydrological system of a vegetated slope.

- The major input parameter is precipitation, although some transfer mechanisms may also contribute to an input of water from elsewhere in the system.
- Transfer mechanisms include, infiltration, percolation, surface runoff, through flow, groundwater or base flow, through fall and stem flow.
- The key storage mechanisms are surface ponding, groundwater, soil water, interception (stored on foliage) and vegetation storage (within the plant cells, used for plant growth).
- Finally the major outputs from a system are evaporation, transpiration and runoff, although interception can influence the runoff rates, depending on the type of vegetation present.

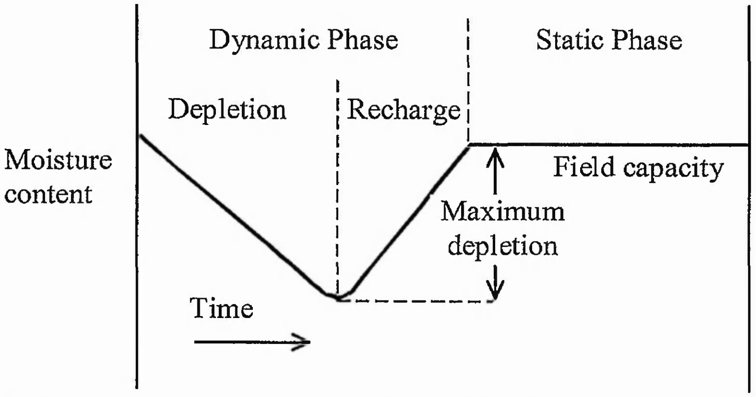


Figure 5.2 Idealised representation of soil water cycle (Bethlahmy 1962)

Dynamic and static phases may be observed within the system, depending on the season, vegetation and soil properties. A dynamic phase comprises soil water depletion and recharge due to evapotranspiration and rainfall, respectively. While in a static phase the soil water content fluctuates around field capacity (Figure 5.2). A clear cut site has a shorter dynamic phase than a forested site as depletion is smaller and recharge is more rapid (Bethlahmy 1962). Therefore, it is important to characterise the vegetation covering the slope and monitor the influence it may have on the soil water balance throughout the year.

5.2.1 Input

Rainfall is the major input of water into the soil water system and as such is a key parameter in the soil water balance model of Blight (2003). Additionally, transfer and storage mechanisms, such as ingress from further upslope or groundwater flow may also be considered as contributing factors if only a section of a slope is under investigation. Correlation between rainfall events and subsequent landslides is widely recognized (Brand 1984; Rahardjo *et al.* 2001; Tsaparas *et al.* 2002) the rainfall events are often divided into triggering and antecedent. Triggering rainfall is that which falls on the day that the landslide occurs, while antecedent rainfall is the rain that falls in the days preceding the landslide.

The significance of antecedent rainfall has been the subject of some debate and experiences from different regions of the world have resulted in different conclusions as to the significance of antecedent rainfall with regard to slope instability (Morgenstern 1992). In certain areas antecedent rainfall raises the groundwater level and plays a significant role in slope instability (Chatterjea 1998; Rahardjo *et al.* 2001; Wei *et al.* 1991) while Brand (1984) suggested that antecedent rainfall was not a significant factor for landslides in Hong Kong due to the high permeability soils. Therefore, an understanding of the initial groundwater regime, infiltration and permeability of the soil is also important.

Although it is important to determine the amount of water entering the soil system it is not necessarily appropriate to solely measure the amount of rainfall for a given area, because of the effect of vegetation on the soil water regime. Much of the rainfall may be intercepted, and run off, depending on the type of vegetation and whether the plants are in full leaf. Therefore, it is important to quantify the amount of rainfall along with interception and runoff rates for a given site.

5.2.2 Transfer

Infiltration is a transfer mechanism and is defined as the process by which water passes across the atmosphere – soil interface and enters the soil column, therefore the soil must be permeable and unsaturated (Bettess 1996). Infiltration capacity is used to determine how much of the incident rainfall will runoff or percolate down the soil profile. Three types of preferential flow patterns have been identified in unsaturated field soils macropore flow, fingering and funnel flow (Beven and Germann 1982). In addition, the infiltration process exhibits four distinct zones (see Figure 5.3) saturation, transition, transmission and wetting plus the wetting front, which is a distinct boundary between the wet and initially dry soil (Tindall and Kunkel 1999).

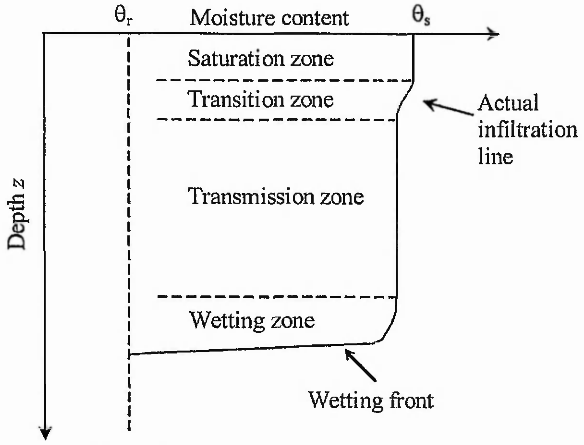


Figure 5.3 Idealised infiltration water profile distribution (Tindall and Kunkel 1999)

- The saturation zone usually extends to a depth of between a few millimetres and a centimetre. In this zone the soil is saturated apart from possible entrapped air.
- The transition zone extends a few centimetres out or down from the water source, and the water content is still very near saturation yet exhibits a slight but rapid decrease of water content.
- The transmission zone displays uniform water content, very near saturation, and lengthens with time.
- The wetting zone the water content decreases sharply and merges with the wetting front.

The infiltration rate decreases as the initial water content increases but the velocity of the wetting front advance increases; therefore, the antecedent water content is the major factor determining the infiltration rate of a given soil for the first few hours of infiltration (Tindall and Kunkel 1999). Plant roots have been observed to induce preferential flow (Kim *et al.* 2004), however, any increase in infiltration rates are part of a dynamic system where, roots grow and initially fill voids reducing permeability, then die back leaving macropores and connected voids in the soil structure, which increases infiltration (Archer *et al.* 2002). The subsequent increased infiltration capacity within the root zone can produce a hydraulic discontinuity within the soil profile, which may facilitate the build up of positive pore water pressures at depth.

Positive pore water pressures may also develop at depth if desiccation cracks have formed at the surface and progressed down the soil profile, allowing a rapid influx of water at depth, bypassing the infiltration mechanism. Desiccation cracks may form naturally in a water sensitive soil regardless of vegetation cover, however, the presence of vegetation, especially that with a high water demand, can increase the number, width and depth of the cracks present on a slope, and augment the potential for positive pore water pressure build up. Although the build up of pore water pressure may be ephemeral it is nonetheless problematic, therefore, it is important to determine the infiltration capacity and permeability of the soil and ascertain if there is hydraulic discontinuity within the profile, whether or not it has been induced by vegetation.

Permeability and water retention are fundamental properties in slope stability analysis as rainfall can lead to a maximum reaction of a slope in terms of pore water pressure development (Alonso *et al.* 2003). In general permeability may be divided into two types Primary and Secondary. Primary permeability is a function of the soil properties and depends on grain size, shape and sorting which affect the porosity, while secondary permeability is a function of fissures, fractures (including desiccation cracks) or bedding within the strata and reflects how pervious a stratum is.

The flow of groundwater through a saturated soil is governed by the hydraulic gradient, cross sectional area of the flow path and the hydraulic conductivity, and is summarised in Darcy's Law (equation 5.6). The hydraulic gradient is the rate of decrease of total head (potential) with distance in the direction of flow. The hydraulic conductivity (K) or coefficient of permeability depends on both the fluidity of the permeant and the intrinsic permeability (k) of the medium, which in turn is a function of the pore structure and geometry. Hydraulic conductivity and intrinsic permeability are related by equation 5.7.

$$Q = KAi \tag{5.6}$$

$$K = \frac{k\rho_w g}{\mu} \tag{5.7}$$

Where:

Q	=	Volumetric flow rate of water (m3/s)
K	=	Hydraulic conductivity
A	=	Cross sectional area of the flow tube
i	=	Hydraulic gradient
k	=	Intrinsic permeability of the medium
ρ_w	=	Fluid density
μ	=	Viscosity of fluid
g	=	Acceleration due to gravity

Transitions in permeability may occur at stratum boundaries or as at the limit of rooting depth and distribution, resulting in elevated pore water pressures. Alonso *et al.* (2003) reported that water pressures recorded at the Villa Blasi slope are consistent with a decrease in permeability with depth. Shiao and Doran (2000) reported that permeability declined significantly with increasing root hairiness and biomass density, however, root hairs die back as part of the root development and the dynamic system observed by Archer *et al.* (2002) whereby roots grow to fill voids and die back leaving macropores and preferential pathways, may prevail.

5.2.3 Storage

Soil water content is a measure of the water stored in the soil and may be quantified volumetrically or gravimetrically. Volumetric water content is the volume of water over the total volume (Tindall and Kunkel 1999), while the gravimetric water content is the mass of water over mass of dry soil (BS 1377-2: 1990). Soil water is a fundamental geotechnical parameter and a critical component of hydrogeology, because near surface soil water controls the partitioning of available energy into sensible and latent heat exchanges with the atmosphere, thus linking the water and energy balances through the water and temperature states of the soil (Wei 1995).

Volumetric water content is the preferred parameter for irrigation management in agricultural systems because it is readily compared with the field capacity and wilting point of the soil (Ley *et al.* 1992). Field capacity and wilting point of the soil are used to determine the available soil water, which in turn is used to determine whether irrigation is required. The determination of gravimetric water content requires laboratory analysis, which takes at least 24 hours, and in addition the bulk density of the soil is required to convert gravimetric water content into available water content. While volumetric water content may be determine instantaneously in the field by a number of devices (Section

5.3.3) resulting in a more efficient irrigation system. Gravimetric water content is considered a more accurate estimation of water content as it is not influenced by the conductivity or temperature of the soil or soil water which is an issue with some of the volumetric measuring devices.

Fine soils may remain saturated for several metres above the water table due to capillary action, while coarse soils will have a relatively thin capillary fringe. If the groundwater table is at rest the decrease in pore water pressure with height above the water table will be approximately hydrostatic (Figure 5.4), until the air entry value is reached (Powrie 1997). The air entry value is the limiting negative pore water pressure a soil can sustain without drawing in air, and will increase as soil pore size decreases.

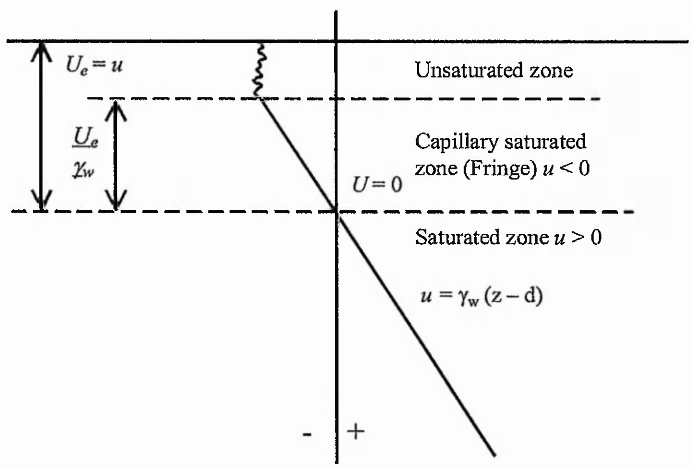


Figure 5.4 Pore water pressures in a fine soil above the water table (Powrie 1997)

Any soil near the surface in a relatively dry environment will be subjected to negative pore water pressures and natural desaturation (Fredlund and Rahardjo 1993). Croney and Coleman (1961) make the distinction between soil suction and negative pore water pressure. Historically the term soil suction was used in agricultural research and refers to a pressure deficiency measured in a small sample free from external stress, as the effect of applied stress on the soil suction has little practical significance. The term negative pore water pressure takes into account the vertical and horizontal stresses the *in situ* soil may be subject to, and so is reserved for any pressure deficiency measured *in situ* or in the laboratory with the soil subjected to the stress regime associated with the particular loading conditions under consideration (Croney and Coleman 1961). However, more recently the terms appear have become interchangeable in the literature, referring to gauge pressures relative to atmospheric pressure (Take and Bolton 2003).

Negative pore water pressures are an important factor in unsaturated soil mechanics as the effective stress can be greater than the total stress (Section 3.3). However, suctions have commonly been ignored for stability analysis where the major portion of the slip surface passes through saturated soil. Slope stability analysis may assume saturated soil conditions because it is simpler to model and the results obtained are conservative. However, this does dismiss the potential contribution from vegetation through the exertion of suctions and situations where the groundwater is deep or the concern is over shallow failure an understanding of the performance of the unsaturated soil is required (Fredlund 1987).

It has been recognised that most plants are capable of applying 1 to 2 MPa of tension to the soil water before reaching wilting point (Taylor and Ashcroft 1972), with many non drought tolerant plants reaching permanent wilting point at 1.5 MPa. The suction in the plant is limited by the osmotic pressure in the leaf cells and when the osmotic pressure in the leaf equals the external suction the plant wilts and transpiration reduces, if this condition persists the plant will fail to recover due to the high suction gradient required between the soil and the root at wilting point. The presence of vegetation has been shown to compound the de-saturation (Biddle 1984; Blight 2003; Cameron 2001; Ziemer 1981b), therefore, the affects of vegetation on negative pore water pressures can be significant enough to aid slope stability, if the suctions are maintained throughout the year.

Water content and matric potential are positively related, lowering the water content makes the matric potential more negative, which may be plotted on a soil water characteristic or retention curve. Soil water characteristic curves (SWCC) represent a continuous water content versus soil suction relationship, so it is possible to determine the water content from correlation to relative soil suction rather than gravimetrically or volumetrically. Caution must be used with this method as the existence of hysteresis in the soil water characteristic curve produces different suctions associated with the same water content, depending on whether the soil is in a wetting or drying phase (Figure 5.5). Hysteresis has been attributed to four primary causes: geometry of the pores, contact angle (differences of radii in the advancing and receding meniscus), entrapped air and shrink/ swell processes within the soil (Tindall and Kunkel 1999).

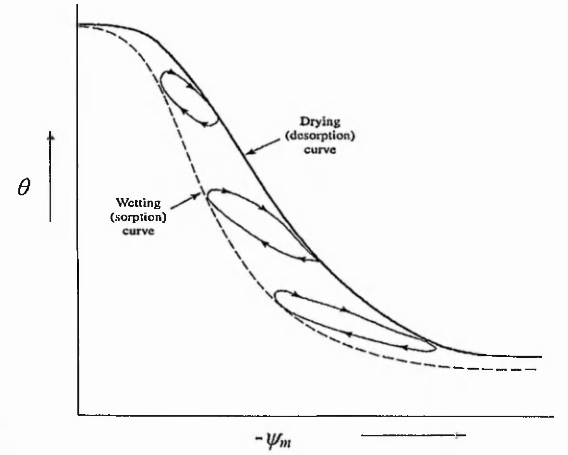


Figure 5.5 Soil Water Characteristic Curve hysteresis. (Tindall and Kunkel 1999)

The two principal laboratory methods to obtain SWCC are the pressure plate (ASTM, 1998) for low matric suctions <1500 kPa or salt solution for higher suctions >1500kPa. The SWCC along with saturated soil properties has proven to provide a satisfactory basis for estimating the permeability function and shear strength parameters for an unsaturated soil (Fredlund and Rahardjo 1993; Fredlund *et al.* 2002). Agus *et al.* (2001) comment that obtaining the SWCC is tedious so empirical relationships and regression may be used. However, as the name implies, the soil-water characteristic curve is specific for different materials. Thus, the empirical equations for the soil-water characteristic curve are limited to a narrow range of conditions (Apul *et al.* 2002). In addition, the SWCC is determined for a root free soil as a root permeated soil will have a more intricate drainage system and the roots may have to. be considered as an extra phase accentuating the complexity of the mechanisms within the sample and influencing the quality of the results.

Springman *et al.* (2003) conducted large direct shear box tests *in situ*, at natural water contents, to investigate dependence of peak shear strength on suction, and comment that most of the shear strength envelopes proposed in the literature are based on the data of tests performed following the drying branch of the retention curve, which may be higher or lower than that attainable in a wetting path due to the hysteresis.

Water that has percolated through the soil may be stored as ground water. The phreatic surface or water table is the level in the soil where the hydraulic pressure of the pore water is equal to the pressure in the atmosphere, and below the water table the pore water pressure is hydrostatic (Figure 5.4) unless groundwater flow or artesian conditions prevail, in which case the positive pore water pressures may increase. An increase in pore water pressure will reduce the effective shear strength and hence the stability of a slope. Pore water pressure may also alter as a response to changes in surcharge, either from structure or embankment construction or overburden removal or through elevation or reduction of the groundwater surface.

Comparative observations of tree and crop plantations led to the conclusion that trees had to be present to lower the water table, due to their deep rooting nature rather than shallow rooted crops (Penman 1963). Sutton (1969) concluded there was no such thing as an intrinsically deep or shallow rooted tree species; instead the root system is influenced by soil type, depth and groundwater, and it is now appreciated that the rooting depth of mature trees is usually restricted to 1–2 m depth (Dobson and Moffat 1995). Although, Burgess *et al.* (1998) reported that some vegetation compensates for dry spells by extending roots deeper, and some plants are able to redistribute deep soil water to a dry surface. The inspection of uprooted specimens of Eucalypts, studied by Blight and Lyell (1984), revealed there was no taproot and in general the roots were nearly all confined to the top metre of soil. Blight and Lyell (1984) reported that Eucalyptus and other trees have been observed to cause depressions in the water table of 19 m (Figure 5.6). It was concluded that the depression of the water table below the trees was due to the year round water demand; suctions sustained at the surface were able to draw water upward at a rate greater than it could be replenished. The groundwater was able to recharge below the annual crops, for although they are capable of maintaining high suctions during the growth period the fields were left fallow after harvesting (Blight 1997).

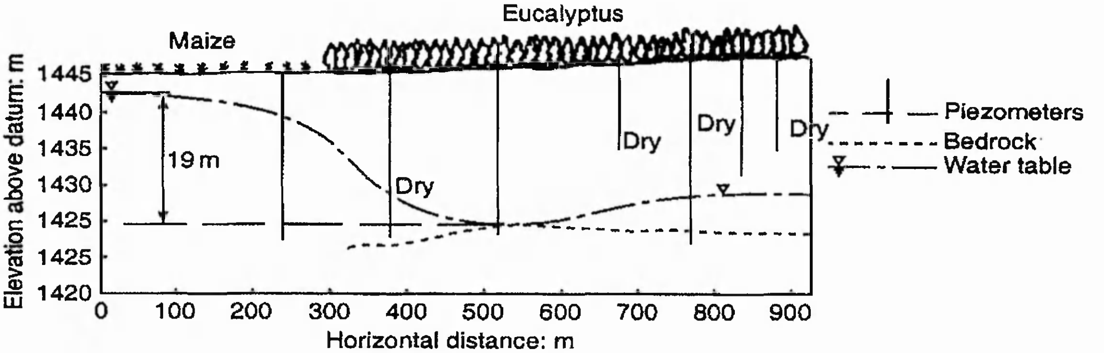


Figure 5.6 Water table depression beneath eucalyptus plantation near Johannesburg (Blight and Lyell 1984)

5.2.4 Outputs

Loss or output of water from the system is incorporated in the water balance equation and can occur in a number of ways. Runoff is a major loss of water from the system without having entered the soil. Infiltration and the storage capacity of the soil as well as the intensity and duration of the rainfall event affect the quantity, duration and distribution of runoff. Runoff estimates can be obtained from stream flow data in the drainage basin of interest or from infiltration models using precipitation, soil properties and vegetative cover data, as interception is often included as a loss in many runoff models (Tindall and Kunkel 1999). In the UK surface water run off data have been published jointly by the Institute of Hydrogeology and the British Geological Survey (Hydrogeology Group), negating the need to directly measure or monitor unless the site requires a detailed survey.

Interception can augment or diminish the runoff rate by promoting the flow of water over the surface preventing infiltration or by temporarily storing the water on the leaves; this is affected by the type of vegetation cover and whether the plant is in full leaf, rainfall intensity and duration (Section 2.3).

The other major losses of water from the system are evaporation from the wet soil surface and transpiration by the vegetation; these two losses are commonly combined and referred to as evapotranspiration. Two other potential water sinks are also incorporated in this term; they are evaporation from the moist membrane surfaces of the vegetation and of intercepted water on the foliage, and the use of water by the vegetation to build new plant tissue. Evapotranspiration is affected by several factors, including air and soil temperature, wind speed, solar radiation, vapour pressure gradients, stomatal resistance and available soil water.

Models available to determine evapotranspiration include; the Penman model (1948), the Preistely–Taylor model (1972), the Penman–Montieth model (Montieth 1965) the temperature method (Blaney and Criddle 1950), the Radiation method (Jensen and Haise 1963) or the energy balance technique (Blight, 2000), whereby soil water, temperature airflow, net radiation and other meteorological parameters are measured in order to calculate the evapotranspiration. Evapotranspiration and soil water information is issued weekly by the Meteorological office as part of the MORECS (Meteorological Office Rainfall and Evaporation Calculation System) service, which includes data on potential evapotranspiration over Great Britain.

Agricultural plants have been shown to extract water at depths beyond the effective zone of evaporation. Durrant *et al.* (1973) reported that an agricultural soil where evaporation normally affected the soil water to a depth of 0.3 m, when planted with barley that rooted to a depth of 1 m, soil water was extracted from that depth. Different species will also have different affects on the water content, Coppin and Richards (1990) reported that winter water contents below a young oak stand was 16 to 20% while below a pine stand the water content was only 12 to 16% at the same point in time.

5.3 HYDROGEOLOGICAL INVESTIGATION TECHNIQUES

An understanding of the seasonal variations of the groundwater level and pore water pressures, is accepted as an important requirement for the long term stability analysis of any slope. Methods employed to quantify the hydrogeological parameters include passive monitoring and recording of meteorological data, *in situ* testing and sampling of soil properties such as permeability and infiltration rates, laboratory testing and the installation of monitoring instrumentation to ascertain seasonal variation in the ground water regime. The majority of methodologies may be extended to include comparative analysis of vegetated plots to ascertain the effect of vegetation on the hydrogeological parameters. In addition, remote sensing techniques may be employed to assess soil water and estimate evapotranspiration rates from canopy density data.

5.3.1 Meteorological Measurements

The meteorological office collects meteorological information for the United Kingdom and publishes monthly and annual reports. The monthly weather report summarizes data from approximately 600 stations across the UK, while the annual report gives monthly, annual and seasonal rainfall as a percentage of the annual average. Alternatively automated weather stations may be located on a site to collect site specific data including rainfall, temperature, wind speed, solar radiation, net radiation, relative humidity and atmospheric pressure (Figure 5.7).

Rainfall measurements can be influenced by shelter from structures or trees or topography, so a number of gauges are recommended per site and should be sited away from obstacles. However, rain gauges may be sited below the canopy to measure the throughfall and so determine interception, small rain gauges are available to site below low canopy such as small shrubs and grasses. To avoid biased sampling, as a result of local conditions beneath the canopy, Lloyd and Marques (1988) recommend the gauge positions be changed regularly, preferably after each rainfall event. It is also recommended that rain gauges be measured promptly after each rainfall event; however, if this is not possible the water should be siphoned into a container to prevent evaporation.

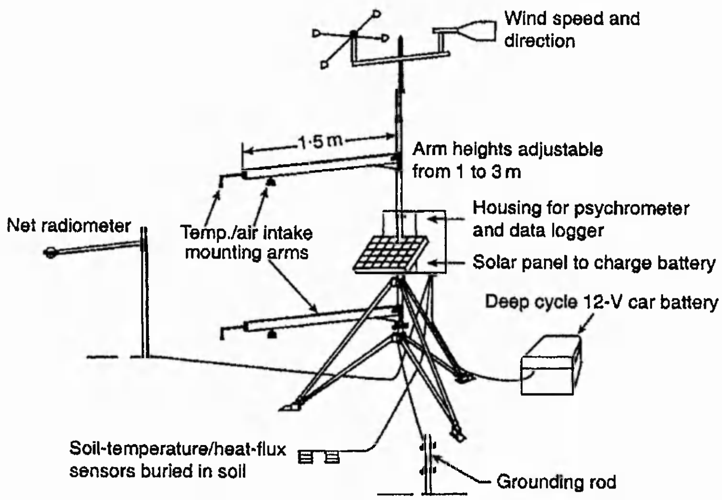


Figure 5.7 Apparatus for automatic measurement and logging of meteorological components (Blight 1997)

5.3.2 *In-situ* Tests

Rainfall simulators attempt to reproduce the characteristics of natural rainfall including drop size distribution and drop velocity as well as intensity and duration. They are typically used for infiltration and erosion measurements; however, if the rainfall intensity exceeds the infiltration capacity run off can be collected and measured on sites where drainage basin data are not available. The drip plate simulator (Bowyer-Bower and Burt 1989) uses a mesh on a frame to produce uniform raindrops; different size drops are achieved with different meshes. The small nozzle rainfall simulator (Cerda *et al.* 1997) utilises different commercially available spray nozzles placed at different heights above the soil surface to produce raindrops of different sizes.

On site rainfall simulation tests are sensitive to meteorological conditions during the tests, and should be protected from wind and not conducted in wet conditions, where ingress from upslope can affect the results, or particularly hot and dry conditions where evaporation may be a factor. Several replicates are required at different times of the year to account for seasonal variation of infiltration rates and soil water. To avoid the added complication of seasonally variable interception, the vegetation is usually removed prior to the test, giving a bare soil runoff rate.

Infiltration can be determined *in situ* utilising the rainfall simulation apparatus, a single experiment at constant rainfall intensity may be sufficient or an infiltration envelope can be determined from multiple experiments at different, uniform intensities. Alternatively, the double ring infiltrometer method (BS EN 12616: 2003) may be employed.

Permeability tests may be conducted in the laboratory on undisturbed samples; however, *in situ* permeability tests are preferable to laboratory tests as a larger volume of soil is tested and disturbance associated with sampling is avoided, Clayton *et al.* (1995) consider that accurate results are rarely obtained from specimens retrieved from normal diameter boreholes. The tests, summarised in Table 5.1, may be conducted in open boreholes or piezometer installations (section 5.3.3) or in a section of an exploratory hole sealed off with inflatable packers.

Table 5.1 *In situ* permeability tests

Test	Method	Advantage	Disadvantage
Variable head tests - falling	Piezometer tube or trial pit filled with water to assess the permeability (BS 5930:1999)	Simple to perform	May cause washout of fine material
Variable head tests - rising	Piezometer tube baled of water to assess the permeability (BS 5930:1999)	Simple to perform	Prone to sedimentation Conducted below water table
Constant head tests	Water allowed to flow into the ground under a constant head (BS 5930:1999)	More accurate results than variable head tests	Can not achieve constant head if groundwater not constant Test section can become clogged

Significant differences in results may occur between inflow and outflow tests because inflow tests can reduce the effective stress while outflow tests will increase it (BS 5930: 1999) and permeability in soils is influenced by the effective stress and stress history, therefore, this should be considered when selecting the appropriate test.

The soil water content can be can measured and continually monitored by a number of installations (outlined in section 5.3.3) or determined gravimetrically in the laboratory from samples collected from trial pits, augers or boreholes. Alternatively, ground penetrating radar (GPR) has been used experimentally to determine soil water (Charlton 2001; Galagedara *et al.* 2003; Gloaguen *et al.* 2001; Huisman *et al.* 2003a) and remote sensing has also been applied to the determination of surface soil water content (section 5.3.5). The laboratory trials conducted by Charlton (2001) tested a number of soils at various water contents and concluded that although GPR has the potential for rapid soil water assessment, site specific calibration is required. A comparative study of GPR and time domain reflectometry (TDR) conducted by Huisman *et al.* (2003b) reported that GPR is better suited than TDR for mapping large-scale features (>5 m) of surface soil water content and the data retrieved was intermediate between TDR and remotely sensed data. Galagedara *et al.* (2003) reported a good correlation between TDR and the GPR data between 0 and 1.0 m b.g.l for the 100 MHz GPR, but reported differences between the datasets for the 450 MHz and TDR. Galagedara *et al.* (2003) concluded that the differences show that the effective sampling depth of the direct ground wave of the 450 MHz data is less than the sampling depth of the 100 MHz data.

Huisman *et al.* (2003a), identified and trialled four methodologies for the determination of soil water content, these are reflected wave velocity, ground wave velocity, transmitted wave velocity between boreholes, and surface reflection coefficient. Gloaguen *et al.* (2001) correlated GPR reflection times with piezometric and stratigraphic information and concluded that estimated parameters agree very well with the measured hydrogeological data. While, Stoffregen *et al.* (2002) attempted to validate GPR water content measurements with four lysimeters, using a 1 GHz antenna and reported that only a reflected signal from the bottom of the lysimeter in the sandy loam was obtained.

Evaporation and transpiration estimates may be determined using evaporation pans, however, there is uncertainty with these measurements, particularly for short time periods (Engman and Gurney 1991) as they may be influenced by local site factors or temporal changes. Alternatively, sap flow gauges may be used to quantify the water demand of a plant to determine the transpiration rate. However, this technique may logistically be applied to a few representative specimens, and the data scaled up for the site. Therefore, these parameters may be more effectively derived from meteorological and canopy data, or extrapolated for the site from a national database source such as MORECS.

5.3.3 Instrumentation

A variety of instrumentation is available for the determination and monitoring of groundwater, soil water and pore water pressure (Table 5.2). Remote real time observations are possible through a variety of data logging systems available and may be a preferred option to the basic manual dipping and recording of standpipes.

Table 5.2 Summary of groundwater and pore water pressure instrumentation (compiled from Topp 1987, Anderson and Kneale 1987, Ley *et al.* 1994, Perry *et al.* 2003)

Device	Components	Method	Advantage /Disadvantage
Groundwater			
Open standpipe	Plastic tube 10 to 50mm diameter with perforated or slotted section at base, within response zone	Water level measured with a dip meter once water level in standpipe has reached equilibrium with groundwater	Cheap and simple to install Assumes simple groundwater regime with no upward or downward flow between strata of differing permeability Equilibrium takes a long time in low permeability soils
Positive pore water pressure			
Standpipe piezometer	Plastic pipe 10 to 20 mm diameter, with ceramic or plastic porous tip,	Tip placed at level of pressure measurement and sealed off Water level measured with dip meter	Cheap and simple to install Determines water pressure over a limited depth Slow response time Poor quality seal or backfill can affect results
Pneumatic piezometer	Porous stone containing diaphragm. Twin nylon tubes connect tip to gas supply, air pressure indicator and flow indicator at surface	Air pressure indicator is read when the gas supplied into the system ceases to flow as air pressure in equilibrium with pore water pressure	Quick response time Accurate to ± 1kPa Long term reliability questioned System can not be de-aired once installed More expensive than standpipes and requires more sophisticated read out unit
Hydraulic piezometer	Twin tubes connect piezometer tip to remote measurement point at ground surface	Tubes are flushed with de-aired water, measurement carried out with either mercury manometer or pressure transducer	Response time depends on quality of tube and de-aired water Relatively simple and inexpensive Readout equipment should not be installed > 5 m above piezometric level System often damaged by freezing
Vibrating wire piezometer	Ceramic filter with stainless steel diaphragm and electromagnets Wire strained by deformation of diaphragm	Wire is 'plucked' by electromagnets and frequency of wire is measured.	Fastest response time Accurate to 0.1 and 0.06 % Suitable where long cables are necessary Automatic data logging Tips are expensive Can be damaged by lightening
Soil Water			
Neutron Probe	Access tube Fast neutron source Slow neutron detector	Radioactive source emitted and reflected decayed neutrons detected	Radioactive source Sphere of influence affected by drying cycle Access tubes installed for repeated monitoring Cannot be left in situ for continuous monitoring
Time Domain Reflectometry	Electrode pairs or Access tubes and profile probe	Electromagnetic source emitted and reflection time recorded	Can be installed for remote continuous real time monitoring or use access tubes for repeated monitoring
Frequency Domain Reflectometry	Electrode pairs or Access tubes and profile probe	Soil completes the circuit between the electrodes and capacitance is recorded and related to water content	Can be installed for remote continuous real time monitoring use access tubes for repeated monitoring Influenced by conductivity of soil may underestimate maximum water content
Negative pore water pressure			
Heat dissipation sensor	Thermocouple and line heat source in porous ceramic plug	Heat pulse applied to heater in ceramic cup temperature measured before and after pulse by Diode bridge circuit	Flexible installation Can automate and merge with other devices Range 10-1500 kPa Not easy to remove or service Poorer results in wetter soils (0-0.5 kPa)
Porous blocks	Gypsum, ceramic or porous block containing two electrodes	Porous block installed at required depth ensuring intimate contact with soil Resistance between the two electrodes measured	Simple and cheap Resistance is affected by electrical conductivity Gypsum blocks can deteriorate in highly alkaline soils Maximum tension 100kPa may become uncoupled with soil solution in very dry conditions
Tensiometer	Twin tubes connected to liquid filled unglazed porous cup	Solution drawn out of ceramic cup to equalize with soil pore pressure vacuum created is measured with a pressure transducer or vacuum gauge	Durable but requires maintenance Can automate and merge with other devices Depth limitation of 2-5 m for most devices Works only in the moist range (0—85 kPa)
Psychrometer	Thermocouple sensing junction protected by porous cup	Soil water vapour condensates on thermocouple Wet and dry bulb temperatures recorded	Sensitive to temperature gradient Calibration of sensors and sensor readings are independent of soil type or soil particle size Suction derived from equation 5.8

Precision and price are the major factors influencing which may be the most appropriate system for a given site. However, the quality of the data obtained from any device is dependent on the quality of the installation. For example, either state of the art tensiometers or basic gypsum blocks will not give a reliable reading if there is not a good contact between the soil and the device.

Once the groundwater surface has been mapped and initial pore water pressures recorded, long term monitoring will demonstrate any seasonal fluctuations. Open standpipes and standpipe piezometers are often installed in boreholes or window sample holes (Chapter 3) and are used to give an indication of the groundwater level and positive pore water pressures, respectively. Pore water pressures in an embankment may be below the prevailing atmospheric value and in these circumstances a standpipe piezometer will be dry and likely to remain so throughout the investigation (Perry *et al.* 2003c).

Pneumatic and hydraulic piezometers comprise a tip connected to remote measuring equipment via nylon or plastic tubes. Penman (1961) reported that the response times of the piezometers are significantly influenced by the length of tube between the tip and the pressure measuring device, the introduction of 300 m of polythene tube increased the response time by a factor of 50. Frequent de airing is also required with the hydraulic system if the readout equipment is installed more than 5 m above the piezometric level as air is drawn out of the water which is under tension. The diaphragm within the pneumatic and vibrating wire piezometer tips respond to changes in pore water pressure more rapidly than the standpipe piezometer, as a smaller volume of water is required, therefore, intimate contact with the soil in the borehole is essential. The vibrating wire piezometer has the fastest response time of all the piezometers and since an AC signal is being measured they are particularly suitable when long cables between the tip and readout device are required.

The soil water content can be measured with a neutron probe, which uses a radioactive source (radium or americium-beryllium), fast neutrons are emitted, some of which collide with hydrogen atoms in the soil water, they lose part of their energy and their direction of movement is changed. A slow neutron detector inserted in the access tube then measures these slow neutrons and the reading is related to the water content (Brady and Weil 2002). As the soil dries, and the concentration of hydrogen is reduced, the probability of fast neutrons travelling further from source before colliding is higher, therefore, the sphere of influence grows as soil dries out, and the reverse applies as the water content increases.

Various time domain reflectometry (TDR) devices are available for the *in situ* measurement of volumetric water content; many are compatible with data logging devices to facilitate optimal remote irrigation systems. Time domain reflectometry measures the dielectric constant of the soil (Topp 1987). Electromagnetic signals or waves are propagated into the soil and the reflected signal is measured along with the reflection time. The propagation velocity is indicative of the volumetric water content, reducing as the water content increases. Profile probes utilise parallel pair transmission lines with discontinuities (Topp and Davis 1985), to allow the measurement of volumetric water content from an array of depths, providing repeatable soil water content profiles from the same location. Individual profile probes may be left *in situ* to allow continuous monitoring or the access tubes are installed and each location is measured manually with a profile probe.

Capacitance probes also detect changes in soil dielectric properties, which are related to volumetric water content. Capacitance sensors consist essentially of a pair of electrodes, either an array of parallel spikes or circular metal rings on a profile probe. An AC field is applied and the capacity between the two electrodes of the sensor is measured. Capacitive systems only use a single measuring frequency and are also known as Frequency Domain Reflectometry (FDR). The frequency (100 – 150 MHz) is susceptible to the influence of ionic conductivity; consequently, FDR sensors have a greater dependence on the bulk electrical conductivity or salt content and soil type than the TDR (Veldkamp and O'Brien 2000), therefore, it is important to calibrate the probe to the particular soil under observation.

Thermal conductivity or heat dissipation sensors may be used for suctions in excess of 90 kPa up to 1500 kPa, and are based on the principle that water is a better conductor of heat than air (Anderson and Kneale 1987). The temperature in a porous block is measured before and after a small heat pulse is applied to it. The amount of heat flow from the pulse-heated point is mostly proportional to the amount of water contained within the porous material. This rise or fall in temperature is measured with an accurate thermocouple in the sensor tip and calibrated to the soil water content of the medium (Ley *et al.* 1992).

Resistance between two electrodes contained within porous blocks such as gypsum, ceramic, nylon, and fibreglass is measured and correlated to water content, in some cases the conductivity of the soil water can prove problematic. The blocks are buried in intimate contact with the soil at the desired depth and allowed to come into equilibrium with the surrounding soil water tension. Gypsum blocks require little maintenance and can be left in the soil under freezing conditions, however, gypsum blocks will slowly dissolve, especially in alkaline soils and will require replacement (Ley *et al.* 1992).

Tensiometers measure suction by obtaining equilibrium between the soil water tension and a confined reservoir of water within the tensiometer system, across a high air entry porous medium and use a vacuum gauge to read the tension created (Anderson and Kneale 1987). Tensiometers allow continuous monitoring through the drying period up to suctions of 90 kPa (Cassel and Klute 1986), however calibration often occurs in the positive range and is extrapolated to the negative range (Tarantino and Mongiovi 2003). Careful installation is required to ensure the ceramic tip is in intimate and complete contact with the soil, initial saturation to remove trapped air is also important as pressure hysteresis can create errors (Take and Bolton 2003). Routine maintenance including refilling with water and hand pumping is important, as water may be lost from the ceramic cup in extreme dry conditions resulting in a loss of tension, air bubbles and erroneous readings (Ley *et al.* 1992).

Psychrometers or *in situ* thermocouple hygrometers are based on the same principle as for the determination of relative humidity in air. A thermocouple junction is enclosed and protected by a porous barrier, which maintains a cavity within the soil. The thermocouple is cooled below the dew point, causing condensation to collect on the thermocouple junction, as the condensate evaporates, the junction is cooled below ambient temperature and a 'wet bulb' versus 'dry bulb' temperature difference is obtained and related to relative humidity. Relative humidity is related to the total suction by equation 5.8 (Fredlund and Rahardjo 1993). Psychrometers are highly susceptible to thermal gradient effects and so do not perform well at shallow soil depths.

$$\psi = \frac{RT}{v_{w0}\omega_v} In\left(\frac{\bar{u}_v}{\bar{u}_{v0}}\right) \tag{5.8}$$

Where:

ψ	=	Soil suction or total suction (kPa)
R	=	Universal (molar) gas constant
T	=	Absolute temperature (273.16 + t °C)
v_{w0}	=	Specific volume of water or the inverse of the density of water
ω_v	=	Molecular mass of water vapour

$\overline{u}_v$ = Partial pressure of pore water vapour

$\overline{u}_{v0}$ = Saturation pressure of pore water vapour over a flat surface of pure water at the same temperature (kPa)

Recharge of water to the water table can be measured using lysimeters. The Suction lysimeter is primarily designed for sampling soil water under irrigated systems to monitor nutrient loss. The device comprises a porous cup; an air pressure or vacuum tube and a fluid return tube. A vacuum equivalent to the soil pressure is applied to the porous cup and both tubes are sealed off, when the pressure in the sample tube has equilibrated the water sample can be retrieved through the fluid return tube by exerting a pressure on the vacuum tube. The positive increase in pore water pressure due to recharge can be measured by the outflow from the lysimeter.

The installation of lysimeters disturbs the soil profile and can change the hydraulic characteristics therefore there is doubt as to whether the lysimeter outflow realistically represents natural recharge (Blight 2003). Lysimeters have a depth limitation of 10 m and are not easy to remove or service. Recharge may also be determined from the measured values for storage, rainfall and evapotranspiration negating the requirement for lysimeters unless it is necessary to sample and monitor the quality of the soil water.

5.3.4 Laboratory Testing Techniques

Laboratory test are used to classify the soil, and complement field observations. Although *in situ* tests are often preferred to their reduction in sample disturbance and often a larger sample size is tested in the field. However, the large body of practical experience behind many of the laboratory tests provides confidence in the results. It is important to consider the limitations of the test, sample size sample quality and conditions of the test, when assessing the quality and relevance of the laboratory test results.

Laboratory testing techniques are used to determine the geotechnical parameters outlined in section 3.3 (Chapter 3) and hydrogeological parameters such as permeability, soil suction and the soil water characteristic curve.

Permeability is determined either by the constant head or falling head tests in a permeameter or under constant head in a Rowe cell or triaxial compression which maintain confining pressures similar to the field state (BS 1377-6: 1990). The laboratory permeability test often yields results of limited value and the *in situ* tests are generally thought to yield more reliable data (BS 5930: 1999).

Soil suction may be determined by a number of methods, which may be grouped into three categories (Toker *et al.* 2004).

- Relative humidity techniques, psychrometers or the filter paper method, measure the relative humidity in the pore air and calculate the suction through thermodynamics.
- Indirect matric suction techniques, such as TDR, heat dissipation sensors or gypsum blocks correlate a suction value from a previously determined SWCC for that measurement device.
- Direct matric suction measurement may be determined by tensiometers, the combination of a tensiometer and balance facilitates automated continual monitoring allowing an entire SWCC to be obtained using the same specimen (Toker *et al.* 2004).

The gauge pressure or water potential can be measured at different water contents while continually wetting or drying the sample to produce the soil water characteristic curve. Either the wetting or the drying phase may be tested but it is important to know which test has been conducted due to the hysteresis of the results (Section 5.2.3).

5.3.5 Remote Sensing Techniques

Remote sensing uses electromagnetic radiation in one or more regions of the electromagnetic spectrum, reflected or emitted from the earth's surface to derive information about the earth's land and water surfaces using images acquired from an overhead perspective (Campbell 2002). Data can be collected remotely from satellites or aerially using passive or active sensors. Passive sensors such as photography are sensitive to variations in solar illumination so their use is constrained to time of day and atmospheric conditions, while active sensors broadcast a directed pattern of energy, such as microwaves, to illuminate a portion of the earth's surface, which is reflected back and detected by the instrument (Campbell 2002).

Remote sensing has been used to determine a number of parameters including surface temperature, surface soil water, vegetation cover and incoming solar radiation, which are employed to estimate evapotranspiration (Engman and Gurney 1991). The acquisition of data relies on the wavelength of the signal, the incidence angle, polarisation, (orientation of the vibration energy emitted and received), and the surface properties of the target area, as the roughness affects the signal reflection, which may be scattered in all directions or become diffuse or isotropic. A surface may become rougher as wavelengths become shorter, or for a given wavelength the angle of incidence increase can result in a smoothing of surfaces (Campbell 2002).

Giacomelli *et al.* (1995) used Synthetic Aperture Radar (SAR), which permits compact radar systems to acquire imagery of fine spatial detail at high altitudes, and concluded that the data compared well to sampled data on the ground using a transect but there was a significant difference where vegetation was present. Similar work was conducted by Ragab (1995) using active microwaves from the European Remote Sensing satellite ERS-1. Wang *et al.* (2004) comment that although soil water has been determined on bare plots, the surface roughness of a vegetation layer resulted in SAR backscatter and that the soil water estimation was not possible in their study. Tansey *et al.* (1999) used a surface scattering model calibrated using field data to derive estimates of near-surface soil water for seasonally vegetated and bare soil surfaces from SAR data, and concluded that good agreement between predicted and observed estimates was obtained.

The soil water content of cornfields was studied using SAR in an over flight study, AIRSAR system (Wever and Henkel 1995). Wever and Henkel (1995) concluded the attenuation coefficient of the vegetation canopy is too high for L and C band frequencies (Figure 5.8) at an incidence angle of 30°, to monitor soil water with a monotemporal dataset, however, the P band was found to be very suitable.

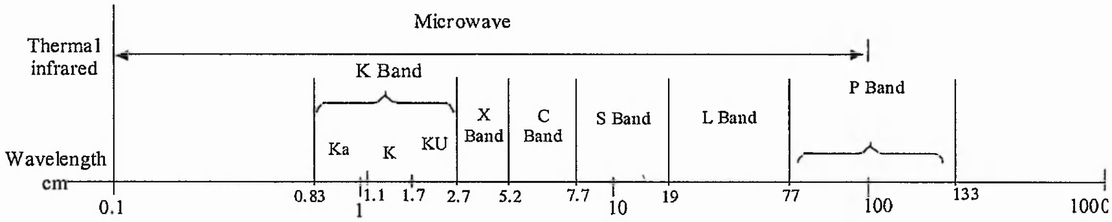


Figure 5.8 The microwave portion of the electromagnetic spectrum (Lawrance *et al.* 1993)

The Electronically Scanned Thinned Array Radiometer (ESTAR) measures brightness temperature, which can be converted into estimates of volumetric soil water. The soil moisture retrieval algorithm requires additional data layers such as soil physical temperature, land cover, and soil texture that come from different sources (Oldak *et al.* 2002; 2003). Experimental trials have also been conducted to investigate the potential of thermal satellite imagery to estimate the soil water content (Ahmad and Bastiaanssen 2003).

5.3.6 Effect of Vegetation

The effect of vegetation on the hydrogeology may be determined through comparative analysis or direct measurement of the vegetation. The influence of vegetation on shrink/swell of clay soils has long been recognised and recommendations for the determination of desiccation and building near trees on sensitive soils have been published (Biddle 1984; Crilly 1996; Crilly and Chandler 1993). Comparative analysis of soil parameters influenced by the vegetation and remote from it appear to be the most suitable approach to assessing the influence of vegetation on hydrogeological parameters. Biddle (1984) reported that the lateral extent of soil water deficit was generally contained within the radius equal to the height of the tree; however, certain species such as Poplar caused drying to a radius of over 1.5 times the tree height. Therefore, to position a borehole remote from the zone of influence is species specific (Biddle 1984). Correct positioning of boreholes is not always possible due to site restrictions, and even if sufficient spacing of boreholes is possible the quality of comparative analysis may also be limited by the lack of heterogeneity across the site. Alternatively, the water demand of representative species may be monitored and scaled up to ascertain the output of water from the system through the vegetation.

Xylem transports water and dissolved nutrients in an unbroken stream from the roots to all parts of the plant, to replace the water lost through the stomata and support tissue growth (Moore and Clarke 1995). In addition water is lost from the system by water storage for tissue growth. Miniature sap flow gauges attached to fine (3-4 mm) roots yield continuous data on water adsorption per fine root surface area (Coners and Leuschner 2002) which may be used to determine the total water lost from the system and not only that lost via evapotranspiration.

MacFall *et al.* (1990) used Magnetic Resonance Imaging (MRI) to study water uptake of loblolly pine roots in sand, this technique gives a bright image where water content is high and a dark image where it is depleted. Although this technique gives useful information it is restricted to the laboratory due to the nature of the equipment. MRI has also been used to study soil water transport in four different soils; Amin *et al.* (1996) found the main limitations were a poor signal to noise ratio, image distortions and poor spatial resolution.

The influence of vegetation on negative pore water pressures has been recognized and direct measurement of water potential change at different depths within the root zone, using tensiometers, can give an indication of the water demand of the vegetation, if monitored regularly for a suitable length of time. Alternatively, the water demand may be extrapolated from sap flow measurements and incorporated into the water balance model to determine the amount of water lost from the system. However, it is important to not put too much emphasis on the ability of vegetation to maintain suctions sufficient to increase slope stability through their water demand. The ability of vegetation to lower the ground water surface or induce negative pore water pressures is not only dependent on the water demand of the plant but also the availability of water within the system and the hydraulic conductivity of the soil. Therefore, if a particularly heavy rainstorm occurs over several days such as a one in ten or fifty year event, or there has been sufficient antecedent rainfall, and the infiltration capacity and permeability of the soil are sufficient, recharge of the soil water storage will occur and suctions will be reduced, negating that aspect of contribution from the vegetation. Consequently, it is important to ascertain the permeability and infiltration capacity of the soil, and any influence the presence of roots may have on the soil properties, along with the determination of pore water pressures to truly characterise the contribution of vegetation to slope stability, regarding hydrogeological parameters.

5.4 SUMMARY

The water balance is maintained through the input, output, transfer and storage within the system, which for a slope is an open system. Vegetation can be a major output of water through evapotranspiration and indirectly through interception and induced runoff. Vegetation also transfers and stores water and has been observed to input water into the soil system through a diurnal redistribution (Chapter 2). Therefore, vegetation is an integral part of the hydrological cycle and can influence the soil water content, pore water pressures and even cause a depression in the groundwater surface. Consequently, it is important to quantify the effect of vegetation on the soil water regime to determine the contribution of vegetation to slope stability. The level of the groundwater surface, natural water content and pore water pressures are important parameters for slope stability analysis and as such their determination forms part of a geotechnical ground investigation of a slope whether or not the slope is vegetated. The contribution of vegetation may be determined by comparative analysis of vegetated and non vegetated plots, located beyond the zone of influence of the specimen vegetation. In order to determine any seasonal variation the site should be monitored over the course of a year.

Vegetation can affect the soil water regime directly through water demand and evapotranspiration, but can also have more indirect influences on the soil water regime. The presence of vegetation can impact on the energy balance which in turn influences the mobility of water and subsequent evaporation rates, while the dynamic cycle of root growth and decay can alter the soil permeability and affect infiltration rates. Theoretical models have been developed to determine the effect of vegetation on the hydrogeology, the parameters for which can be measured directly from meteorological and soil testing techniques. Meteorological parameters include; wind speed, humidity, temperature and net radiation, which affect evapotranspiration rates. Rainfall, which is the main input mechanism, for the soil water system can be measured on site using, traps or extrapolated from published datasets. Groundwater may be another source of water for plants but there must be an equivalent recharge from rainfall for the system to maintain equilibrium, therefore, rainfall is the most significant input parameter.

Recharge of soil water exhibits a dynamic and a static phase depending on the season, covering vegetation and soil properties. The water demand of various types of vegetation will depend on the season while the rate of transfer of water from the ground surface through the soil profile is dependent on the permeability and infiltration capacity of the soil. Both the permeability and infiltration capacity can be measured *in situ* and in the laboratory, if there is sufficient undisturbed sample size to represent the massive properties of the soil, however, they are more commonly determined *in situ*. The dynamic cycle of root growth and decay can influence both the permeability and the infiltration capacity and it is important to quantify to what depth in the profile the zone of influence extends, as this can create a hydraulic discontinuity which can lead to the build up of pore water pressures at depth and reduce the factor of safety.

Negative pore water pressures are an important factor in unsaturated soil mechanics although often neglected in slope stability analysis especially where a portion of the critical slip circle passes through saturated soil. However, the ability of vegetation to exert suctions that may persist throughout the year, if the recharge is insufficient, or effectively lower the ground water surface denotes a need to determine the influence of vegetation on the soil water regime. The persistence of vegetation induced suctions may be sufficient to qualify a slope as stable without the need for remediation, however, this beneficial effect must be treated with caution, because sufficient antecedent rainfall followed by a ten year storm, or the demise of the covering vegetation may negate any contribution to the effective stress. Therefore, it may be prudent to classify vegetation induced suctions as ephemeral even if they persist through a wet season, if a design life is to exceed the probability of a rare storm event.

This chapter has highlighted the techniques appropriate for measuring hydrogeological parameters, including instrumentation and *in situ* and laboratory testing and remote sensing techniques. Site characterisation must employ a long term approach, rather than a snap shot view of the ground conditions. The instrumentation selected for monitoring will depend on the site and detail of investigation, however, the data acquired is as dependent on the quality of the installation as well as the device, and it is important to calibrate a series of devices to obtain comparable data. Comparative analysis may allow a short term assessment to be made between non vegetated and vegetated plots. However, it is prudent to monitor throughout the seasons, because the seasonal variation is an important consideration to slopes influenced by antecedent rainfall or desiccation, regardless of vegetation, although the presence of vegetation may augment the problems. Therefore, long term monitoring is essential, especially when considering the influence of vegetation on water content and ground water levels.

The following chapter discusses the investigation techniques employed during the preliminary fieldwork, which were trialled in preparation for the subsequent fieldwork, discussed in Chapter 7.

6 Preliminary Field Investigation

Experienta Docet
University of Derby Motto

One objective of this research project was to investigate the validity of appropriate field and laboratory testing procedures, to assess the contribution of vegetation to slope stability. The previous chapters have included a review of the literature and outlined the effect of vegetation and the most pertinent investigation techniques to determine geotechnical, biomechanical and hydrogeological parameters. Geotechnical and hydrogeological investigation techniques are relatively well established and have been researched and refined over the years with technological developments, and may be applied to the characterisation of slopes and incorporated into a framework to characterise vegetated slopes. Biomechanical testing techniques have been employed to demonstrate the effect vegetation has on the shear resistance of soil, but as yet have not been standardised or incorporated into a framework for the geotechnical assessment of vegetated slopes.

In order to ascertain the suitability of the biomechanical testing techniques and establish where they would fit into the overall framework, it is necessary to evaluate the practicality of the testing techniques and the quality and validity of the results. Therefore, fieldwork was undertaken to evaluate some of the botanical and biomechanical characterisation techniques. A preliminary root pull out field trial was instigated locally (East Leake, Nottingham) to facilitate the development of a root pull out procedure and evaluate the fabricated root clamps, developed for the project. Further preliminary field work was undertaken on two of the ECOSLOPES field sites (Italy and Greece) using the root pull out / *in situ* shear box apparatus (Norris and Greenwood 2003), which facilitated the evaluation of techniques outlined in the literature and the development of an *in situ* shear box procedure.

The integration of research projects within the ECOSLOPES project provided a framework in which the testing was conducted, that is the sites had been previously selected to investigate certain elements of the project and specimen plants were selected to correlate with the research of other partners. For example the root morphology of *Quercus pubescens* and *Spartium junceum* was being investigated by the Italian team on the Trivento site, hence the focus on these species for root pull out and shear box testing on that site, while in Greece the research focus was on regeneration and the contribution of roots after forest fires, therefore, a burnt site and a regenerated site were tested. The ECOSLOPES project also provided the opportunity to observe field scientists of other disciplines practice their techniques. Therefore, it was possible to observe and evaluate related techniques that may be incorporated into the framework.

6.1 SITE DESCRIPTIONS

The following sections describe the local trial site near Nottingham and the two European sites selected for the preliminary fieldwork. The experience gained from the preliminary fieldwork conducted on the following sites (sections 6.1.1, 6.1.2 and 6.1.3) was used to develop and modify the procedures for the investigation of vegetated slopes used on the subsequent field sites (see Chapter 7).

6.1.1 Nottingham, England

The site is located 2 km south east of Gotham, a small village, on the outskirts of Nottingham England (SK 545 287), at an altitude approximately 45 m above sea level. The study area comprises woodland situated along the North West boundary of a small orchard. The woodland is located near the base of an escarpment on relatively horizontal ground and is vegetated with *Acer pseudoplatanus* (sycamore), *Crataegus monogyna* (hawthorn), *Sambucus nigra* (elder), and *Salix caprea* (willow) of various ages, the ground cover is predominantly *Glechoma hederacea* (ivy) and leaf litter with occasional under story vegetation of *Cratœgus Pyracantha* and *Rubus fruticosus* (bramble).

The site is underlain by the Mercia Mudstone Group, part of the Triassic Series formerly known as the Keuper Marl (Chandler and Forster 2001). The Mercia mudstone in this locality is rich in gypsum deposits which is extracted at the near by gypsum works. The geology is overlain by an organic rich topsoil layer approximately 120 mm thick, and localised lenses of made ground. The climate is temperate with an annual average temperature of 9.4 °C and an average annual rainfall of 912 mm.

6.1.2 Trivento, Italy

The site is part of a landslide complex, located near Trivento, Molise, Italy (41° 71′ N 14° 55′ E). The study area comprises 2700 m^2 of the River Trigno catchment, which includes both north and south facing slopes, at an altitude of 575 to 600 m above sea level. The area is part of the Apennine orogenic belt and as a result suffers tectonic activity. Although the most advanced and recent thrust fronts are found offshore of the Adriatic coast (Aucelli *et al.* 2000) the area is subject to frequent high intensity earthquakes. The local geology comprises Tertiary Molasse (marl and marly limestone) and Flysch deposits of interbedded pelitic and arenaceous siliciclastic material, forming an alternating sequence of weak and competent strata.

The 'Comunita Montana Trigno Medio Biferno' manages the study area, and the dominant vegetation cover is grasses, herbs and shrubs such as *Prunus spinosa* (Blackthorn), *Quercus cerris* and *Q. pubescens* (Oak) and *Spartium junceum* (Broom). The site was divided into three areas, 1) a slide with trees, 2) a slide without trees and 3) an undisturbed slope. Although, the overall gradient of the slope in Area 1 is approximately 17°, the history of landslides in the area has formed several breaks of slope giving a hummocky topography (Plate 6.1).

Plate 6.1 Open woodland on hummocky landslip terrain, area 1, Trivento, Italy (2002)

The landslide activity in the area may develop along preferential slip planes such as contacts between strata. The variability in geotechnical and hydrological properties, such as differences in permeability and storage capacity, can result in confined or perched water tables that may lead to the build up of pore water pressures within certain soil horizons. The build up of pore water pressure may also be further amplified by the climate.

The climate is Mediterranean with the majority of the rainfall occurring between autumn and early spring and a mean annual precipitation of 680 mm. The increase in temperature and reduced rainfall during the summer generates a water deficit; this is evident on site as the stream channel at the base of the slope remains dry during summer and is replenished in the autumn. Antecedent rainfall may be considered problematic, as a contributing trigger of landslides, especially during the wet season. Therefore, the climate in combination with the seismic activity in the area produces a high risk of landslides.

6.1.3 Halkidiki, Greece

The study area is located near the small town of Metamorfosi, on the Halkidiki Peninsula of Greece (40°15′ N 23°37′ E). The natural hilly terrain ranges in altitude from 60 to 200 m above sea level, and the study areas comprise the southern aspect of one such hill, the gentle 5° gradient of which becomes steeper (22°) toward the base of the slope. The site is divided into two distinct areas; both were dominated by natural *Pinus halepensis* forest that has suffered forest fires. Area one suffered a forest fire in 2001 and only the burnt trunks of *P. halepensis* were present (Plate 6.2).

Plate 6.2 Area 1, recently burnt forest, Halkidiki, Greece (2002)

Plate 6.3 Area 2, regenerated forest, Halkidiki, Greece (2002)

Area two was not affected by the recent fire but suffered a forest fire approximately ten years before. Under storey vegetation such as *Phillyrea latifolia, Q. coccitera* and *Pistacio lentiscus* has regenerated around the scorched trunks of *P. halepensis* (Plate 6.3).

The geology of the region comprises three formations: Marbles and limestones, amphibolitic shales, and alluvial and colluvial deposits from the Pleistocene period, which are overlain by a sandy loam topsoil. However, the topsoil and fine ash crust formed during a forest fire is easily eroded when there is no vegetation, depleting the nutrient reserve, which in turn may inhibit regeneration.

Climate data recorded by the Forest Institute of Thessaloniki indicates a typical Mediterranean climate of cold winters and high temperatures in the summer with a mean annual precipitation of 416 mm, unfortunately the forested areas are particularly susceptible to wildfires during the prolonged dry summer months, due to the dominance of particularly flammable conifer species.

6.2 ROOT PULL OUT TESTING

An initial root pull out trial was conducted at a site local to Nottingham Trent University (NTU) in order to establish a methodology for root pull out testing and evaluate the competence of a fabricated root clamp (Clark 2002). Manual individual pull out tests were conducted on roots of one *Acer pseudoplatanus* (sycamore) and one *Sambucus nigra* (elder). Following the initial trial root pull out tests were conducted on the Italian site, on individual roots of one *Quercus pubescens* specimen and one *Spartium junceum*, in addition six entire pull out tests were conducted on small *S. junceum* specimens. Individual root pull out tests were conducted on the root systems of specimens of *Phillyrea latifolia* and *Quercus coccitera*, which were of a similar size to the specimens selected for the *in situ* shear box tests conducted on the regenerated area of the Greek site.

6.2.1 Apparatus

Two types of apparatus were used for the root pull out testing during the preliminary fieldwork, an assembly of equipment for manual testing and the mechanical apparatus developed for root pull out / *in situ* shear box testing (Norris and Greenwood 2003). The manual pull out apparatus included one of a selection of root clamps designed for the project a 100 kg Salter spring balance, a steel rule and a winch secured to a near by tree (Plate 6.4) a steel bar was also used in place of the winch to assist manual root pull out. The mechanical apparatus developed at NTU, from the earlier model of Norris and Greenwood (2000), comprised an aluminium frame to which a hydraulic cylinder, draw wire transducer and pulleys are attached. A steel cable is used to connect the root clamp to the hydraulic cylinder via either a 250 kg or 500 kg load cell (Plate 6.5).

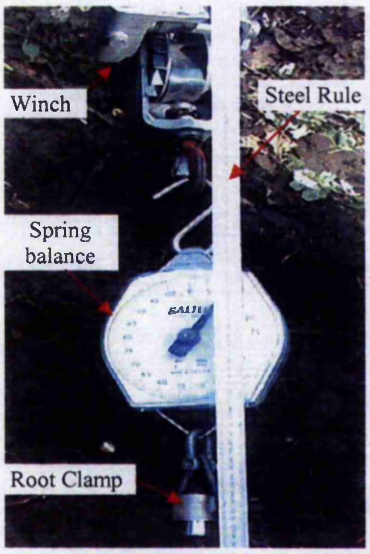


Plate 6.4 Manual root pull out apparatus

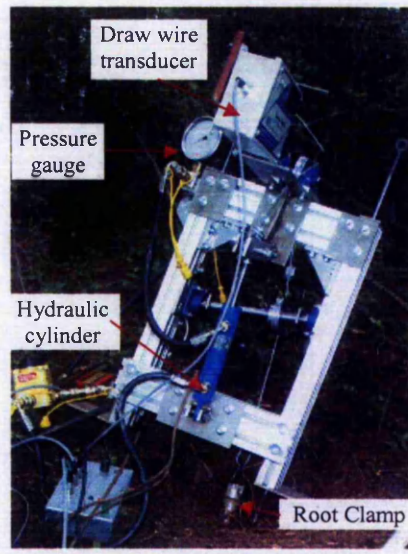


Plate 6.5 Mechanical root pull out apparatus

The load cell and draw wire transducer are linked to a lap top computer to provide continuous real time data logging. In addition, a back up manual logging system was provided in the form of a pressure gauge connected in line with the hydraulic cylinder and an LCD display on the draw wire transducer. Both the manual and mechanical assemblies allow roots to be pulled out in any direction, unlike the tripod configuration of Karrenberg *et al.* (2003), which was designed for vertical pull out testing, or the winch system of Anderson *et al.* (1989b), which was most suitable for lateral roots.

The root clamps were specifically fabricated for the project and two designs were trialled during the preliminary research (Figure 6.1). The serrated wedge collet design (Figure 6.1a) utilises three serrated wedges that form a collet, which fits around a root and slots into a tapered aperture in the inner casing. The smallest diameter root that can be secured in this clamp is approximately 5 mm, although wire can be wrapped around the end of the root to improve the grip on small roots, the maximum root diameter is limited by the internal aperture of the internal collet and wedges (20 mm). The bolt clamp design (Figure 6.1b) utilises six sections of threaded 16 mm bar to provide the grip. These threaded bar segments slot into individual housings in a low carbon steel inner casing, which in turn fit into a nylon outer casing. The nylon casing was designed to house six 12 mm bolts that tighten onto the threaded segments (studs), which close in on the root, to provide grip. The internal aperture of the inner casing limits the maximum root diameter to 28 mm although larger roots can be whittled down to fit into the clamp, while the smallest root diameter that can be gripped by this clamp is 15 mm.

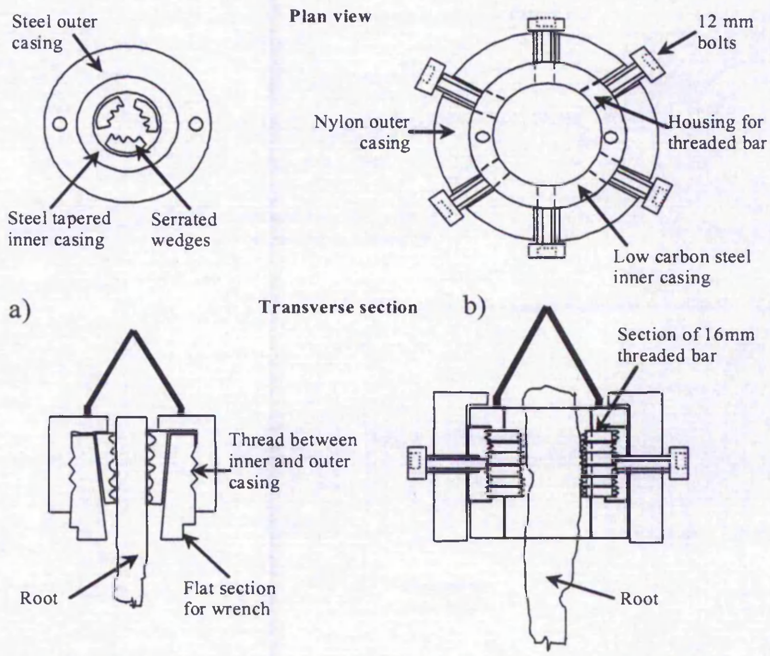


Figure 6.1 Illustration of two clamps used for root pull out testing. a) Serrated wedge collet for roots 10-15 mm, b) bolt clamp for roots 14 - 30 mm

The serrated wedge collet clamp secures the root when the external casing is screwed onto the inner casing. Flat sections on the inner casing (Plate 6.6) are provided to facilitate tightening with a wrench. The tightening action brings the outer casing down onto the collet and forces the wedges down the internal taper, which encompass and secure the root within. Unfortunately, although every effort was made to minimise disturbance, the rotation of the inner and outer casings required to secure the root caused twisting and disturbance to the root prior to conducting the test.

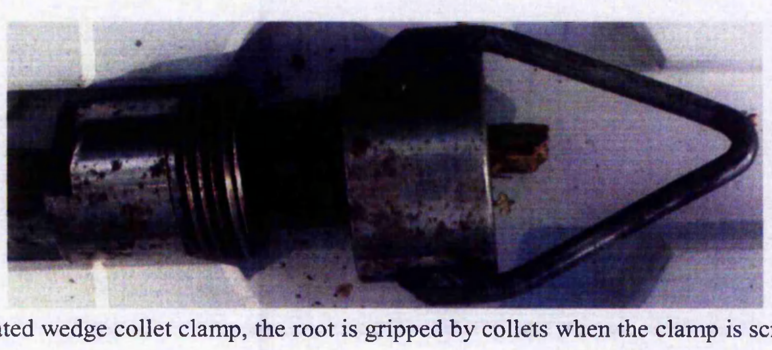


Plate 6.6 Serrated wedge collet clamp, the root is gripped by collets when the clamp is screwed together

6.2.2 Procedure

The initial root pull out field trial near Nottingham facilitated the adoption of an alternative methodology for root pull out testing to that employed by previous authors. Previously reported procedures include; a trench excavated around the sample tree (Anderson *et al.* 1989b) or a test pit excavated adjacent to the vegetation (Greenwood *et al.* 2001) following which, roots intersecting the face of the excavation are pulled. Pulling out roots that intersect an excavation wall may prove problematic when it is not possible to identify whether the roots were initially attached to the subject specimen or are still attached to a neighbouring plant. If it is not possible to identify the origin of the root the data are somewhat orphaned, but more importantly erroneous values may be recorded if the root is still attached to a neighbouring tree because of the anchorage provided from the attachment to the tree. In addition, the root morphology (tapering and branching angles) will influence the results if the direction of pull in relation to the origin of the root is reversed.

Plate 6.7 Labelled root system before bole is removed, *Q. pubescens,* (Italy, 2002)

Plate 6.8 Root bole removed facilitating pull out tests, *Q. pubescens*, (Italy, 2002)

To minimise such errors, and promote repeatability and facilitate correlation it is prudent to pull all the roots out in the same direction (opposite to the direction of growth). Therefore, the preparation procedure was modified during the local field trial. It was found preferable to excavate the root system out from the stump, in all directions around the tree. The diameter, dip and azimuth of the exposed roots could then be measured before the bole is removed, which allows room to pull out each root in turn (Plate 6.7 and Plate 6.8). This procedure facilitates the acquisition of root morphology data not attainable with the pit and trench methods but does not lend itself to root counts for root area ratio calculation.

The manual root pull out procedure proved problematic, the ratchet system in the winch determined the amount of displacement for each incremental load application, while the strain rate was not easily controlled when using manual force to pull out a root. In addition, it was not possible to record the final measurements as the root snapped without warning and it was not possible to record the displacement at failure with a rule. The spring balance returned to zero post failure, therefore, the maximum force reading dependent on the quick wits of the operator, however, this may be resolved with a different spring balance equipped with a 'lazy hand'. While continuous recording of the displacement requires the use of digital equipment attached to the root via the clamp. The mechanical apparatus, which utilises a draw wire transducer and load cell that are secured to the root via a root clamp, and connected to a laptop computer, surmounted these issues (Plate 6.9).

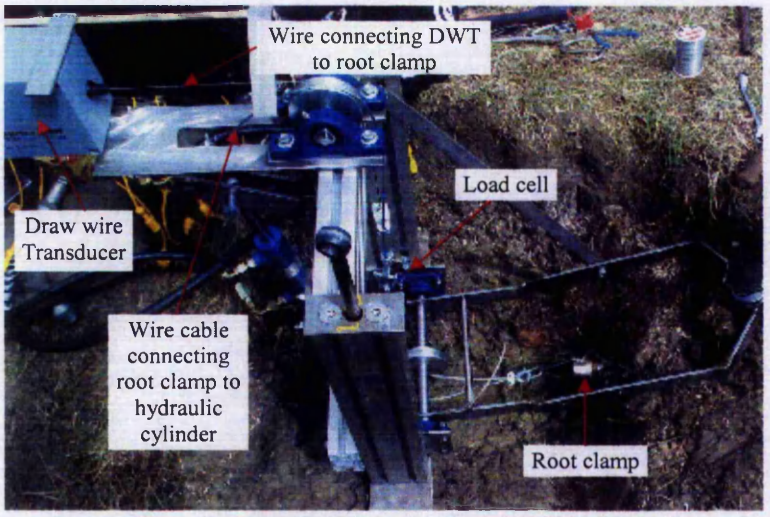


Plate 6.9 Mechanical root pull out apparatus set up on *Q. pubescens* root, Draw wire transducer is attached to root via clamp (Italy, 2002)

At each sample area the GPS coordinates and altitude were recorded along with the local slope angle. For each specimen the species name, height and diameter at breast height (DBH) were recorded. In the case of plants that were not tall enough, the diameter of the stem was recorded at three points from base to tip and averaged, in some instances the spread of the shrub uphill and cross slope were also measured. The plant was then cut down near ground level. For small shrubs a clamp was attached to the stem and the entire plant was pulled out using the spring balance and steel rule to measure the load and displacement, respectively.

For individual root pull out testing the root system was excavated from the trunk outwards to a radius of 0.2 to 0.5 m depending on the size of the plant. The diameter, dip and azimuth were recorded and the roots labelled before being cut and the bole removed. The labelling system employed the species initials followed by a letter of the alphabet for each root for the individual pull out tests, whereas a number followed the species initials for each of the entire pull out test specimens. Previous root distribution investigations have focussed on planar soils, and as such the orientation and depth of roots were recorded (Ray and Nicoll 1998). This procedure was modified by the additional measurement of the dip direction, which along with the orientation data facilitates the correlation of root distribution with the local slope angle. The root pull out procedure employed during the preliminary fieldwork is summarised in Figure 6.2.

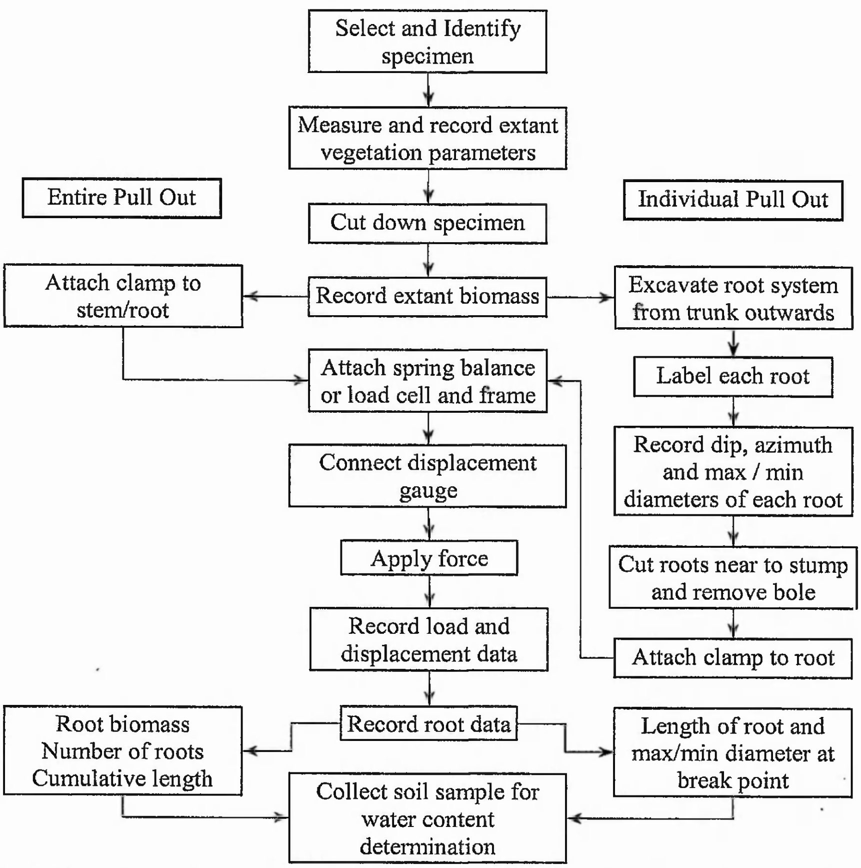


Figure 6.2 Root pull out procedure employed for both entire and individual root pull out tests.

Each root was pulled out in turn starting with the small shallow roots to minimise disturbance of the test area. Once the root pull out tests were completed the volumetric water content and undrained shear strength were measured using the portable Delta T theta probe and hand vane, respectively. The Delta T theta was used in accordance with the manufacturer's instructions to provide an instant reading of the volumetric water content and the Pilcon hand vane was used in accordance with BS 5930 (1999), where the soil conditions were appropriate.

6.2.3 Results

The local field trial was used to establish a procedure for pull out testing and evaluate the serrated wedge collet clamp, the pull out testing results were reported by Clark (2002). The procedure and the clamp were both employed during the subsequent field work.

A member of the Italian research team was investigating the influence of steep slopes on the root system development of *S. junceum*. In an attempt to dovetail the investigations six small specimens, approximately 0.5 m tall, of *S. junceum* were selected for entire pull out testing the results of which are shown in Figure 6.3. The tests were carried out manually; a technician supplied the manual force to pull the plant out via the balance and clamp. The specimens were labelled G1 to G6 due to the local name for *S. junceum* (Genestra).

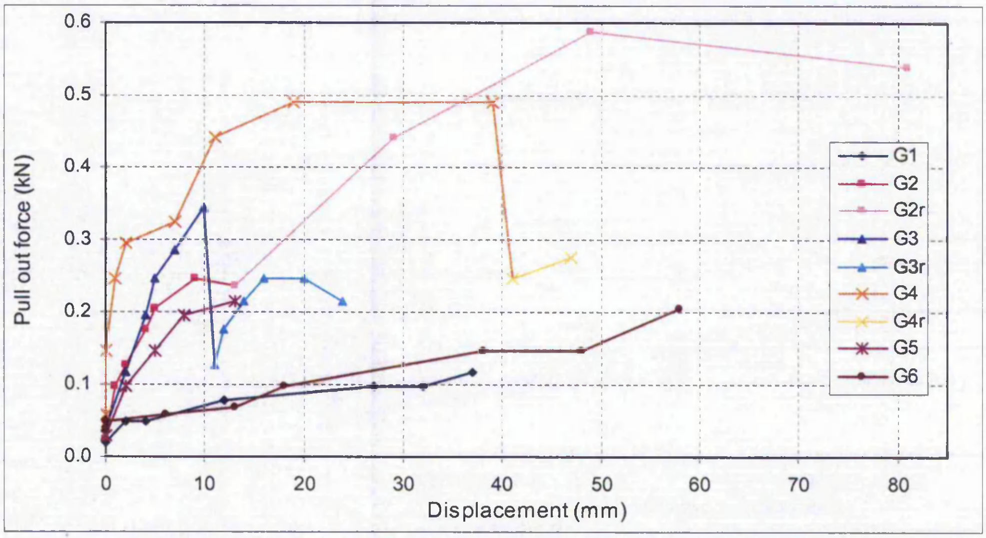


Figure 6.3 Pull out force and displacement data for pull out tests conducted on entire specimens of *S. junceum* (Italy), specimens G1 to G6 subscript r indicates a retest after the specimen had been re-clamped.

Four of the six tests (G3-G6) failed at a knot where the stem and root system joined, specimens G3 and G4 were re-clamped and the test continued (G3r and G4r), hence the trough and subsequent increase in pull out force, formed by the merged data (Figure 6.3). Similarly, the clamp slipped while testing specimen G2 this also had to be re-clamped for the test to continue as G2r. Unlike G3r and G4r which had already broken, G2r continued to resist a greater pull out force than had been subjected in the previous test attempt. The presence of such weak points in the root systems may prove problematic when analysing the results, unless a sufficient number of tests are conducted to facilitate statistical analysis.

Four of the *S. junceum* root systems were analysed at the laboratory in Italy, following the entire pull out tests. The information supplied included volume, surface area, overall length, fresh and dry weight and number of root apices (tips). These data along with the calculated tensile strength, using the diameter at the clamp and critical stress were plotted against the maximum pull out force to determine if there was any correlation between the parameters the tabulated results are shown in Table 6.1.

Table 6.1 Regression values for various root parameters and pull out resistance for entire root pull out tests

Parameter	Regression value (R^2)
Total root volume (cm^3)	0.9217
Cross sectional area at break points (mm^2)	0.568
Total surface area (mm^2)	0.4724
Dry weight (g)	0.339
Number of apices	0.3377
Fresh weight (g)	0.3299
Root length (mm)	0.1993
Cross sectional area at clamp (mm^2)	0.0392

The only correlation is between the maximum pull out force and the root volume with an R^2 value of 0.9217. The cross sectional area of the roots at the break points gives the second strongest correlation (R^2 0.568), although the regression coefficient is not optimal it is a stronger correlation than that between the cross sectional area of the root at the clamp and pull out resistance (R^2 0.0392). Furthermore, the correlation between the cross sectional area of the root break points and pull out resistance could be improved by better identification of the break points. The results from four pull out tests are not statistically reliable, due to the size of the dataset required to clarify these correlations.

Since, small shrubby vegetation was not considered to contribute to slope stability as much as tree roots, the subsequent fieldwork focused on the individual root pull out testing of tree roots rather than entire pull out tests and no further tests were conducted on small specimens during this research. However it is apparent that the cross sectional area at the clamp does not represent the root system resisting pull out, when considering the entire pull out test, which is logical, as the diameter of stem / root transition area is not necessarily indicative of the size of the attached root system. The cross sectional area at clamp would be a suitable parameter to determine the tensile strength at the break point, when the root system remains secured in the soil and the break is close to the clamp.

Operstein and Frydman (2000) measured the dimensions of the root systems of alfalfa following pull out tests and estimated the total surface area. After plotting pull out load as a function of surface area, they were able to ascertain the unit resistance to pull out of alfalfa, to be around 30 kPa (Operstein and Frydman 2000). Whereas, Karrenberg *et al.* (2003) determined the critical stress, the force per unit area necessary to induce root system failure, by dividing the maximum pull out force by the cross sectional area of the roots at the point of failure. Although, they found it difficult to identify breaking points, and usually not more than three break points were measured (this included the main root and the two largest laterals). They concluded that these data gave a good first order approximation for the critical stress in the main anchoring roots.

Manual root pull out tests were conducted on individual roots of *Quercus* species at both of the European preliminary sites. Although the manual data collection was crude, with only a few data points recorded for each test the majority of the plots in Figure 6.4 indicate a brittle tensile failure of the roots.

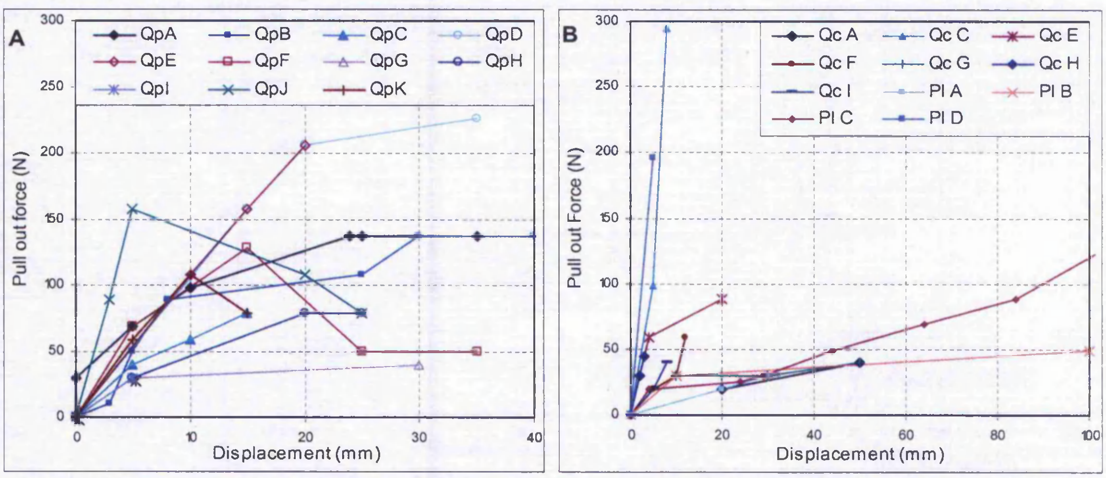


Figure 6.4 Results from manual individual root pull out tests conducted on A) *Q. pubescens* (Italy) and B) *Q. coccitera* and *P. Latifolia* (Greece)

Three of the *Q. pubescens* results (QpF, QpJ and QpK, Figure 6.4a) show a peak stress and decline in pull out resistance, which may be related to a skin friction component of the failure, as the broken root was pulled from the soil. While the remaining *Q. pubescens* roots and all the *Q. coccitera* and *P. latifolia* tested on the Greek sites (Figure 6.4b) snapped instantaneously and no measurements were recorded post failure, therefore, the plots do not exhibit the peak and residual curves.

Individual root pull out tests conducted on the larger roots employed the mechanical apparatus. The data were recorded either digitally or manually, when the digital data logging system failed. The results for the mechanical root pull out tests for *Q. pubescens* conducted at Italy and *Q. coccitera*, Greece, are shown in Figure 6.5.

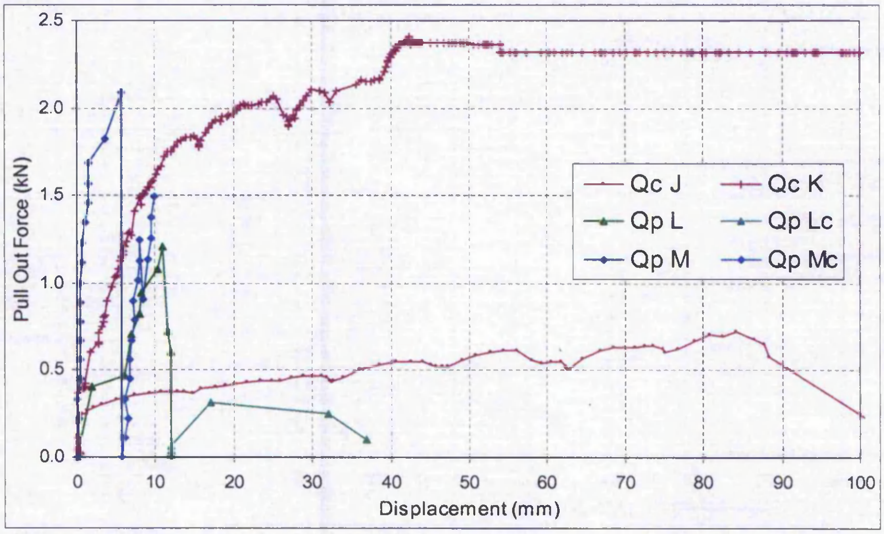


Figure 6.5 Results from the mechanical apparatus root pull out tests for individual roots of *Q. coccitera,* Greece (Qc J and Qc K) logged electronically, and *Q. pubescens,* Italy (Qp L to Qp Mc), logged manually.

The displacement and load data were recorded manually on the tests conducted in Italy (Qp L, Qp Lc, QP M and Qp Mc) while the Greek data (Qc J and Qc K) were recorded electronically. A number of minor peaks and troughs are evident on the two curves produced from the digitally recorded data (Qc J and Qc K). These steps may be associated with the failure of side roots as observed by Bailey *et al.* (2002). However, the rhythmic nature of some of these peaks and troughs is more likely to be a function of the hand jack, as discussed in section 6.3.3, while the more pronounced troughs exhibited in Qc K may be associated with the failure of secondary roots. The plateau evident in Qc K is more likely a consequence of the electronic data logging, as the 250 kg load cell used approached its capacity, rather than any indication of residual stress. Therefore the maximum pull out force for this root may have been much greater than recorded.

The clamp slipped while testing roots Qp L and Qp M, the clamp was refitted and the test continued (Qp Lc and Qp Mc, respectively). Merging the two datasets for the two roots resulted in the secondary peaks, which are a function of the loading and unloading of the root rather than side roots failing during the test. The manually recorded data were corrected to compensate for the lever arm as discussed in section 6.3.3.

Anderson *et al.* (1989b) reported significant correlation between F_{max} and the root cross sectional area at both the pulled and broken ends. Figure 6.6 illustrates the relationship between F_{max} and the cross sectional area of the root at the clamp for all the individual root pull out tests conducted during the preliminary fieldwork. All three species show a good correlation between the two parameters (R^2 of 0.95 to 0.99). This correlation is dependent on the few large diameter outliers and therefore, should be regarded with caution. However, a regression through all the data points and the origin produced a unit value for pull out resistance for the cross sectional area of the root at the clamp of 5.8 N/mm^2. This value is not the root tensile strength should not be confused with the tensile strength of the roots, as the pull out force is complex and comprises root tensile strength, soil properties and tangential friction among others.

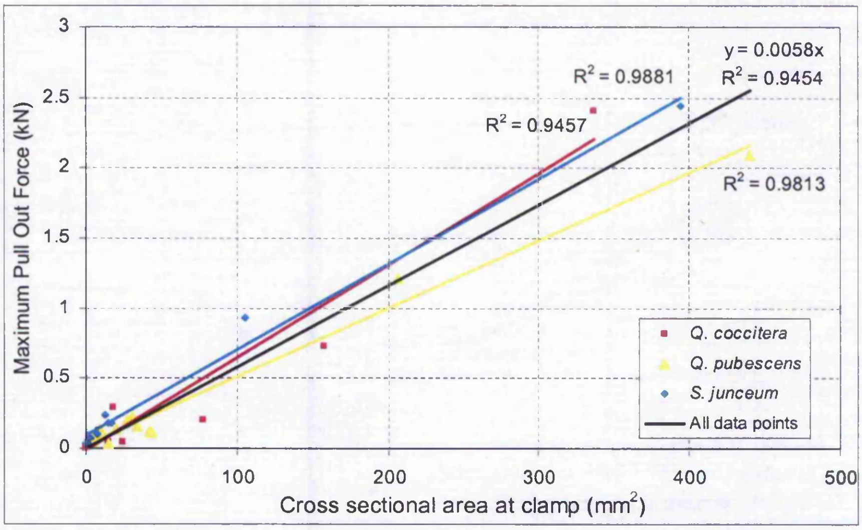


Figure 6.6 Relationship between maximum pull out force and the CSA of the root at the clamp

The individual root pull out tests conducted on the elder roots at the Nottingham site proved problematic, because the cortex and epidermis (bark), which made up 40% of the root cross sectional area, separated from the inner vascular tissue of the roots. It was possible to pull out the elder roots once the bark and cortex had been removed. Therefore, the procedure for that species was modified so that the bark and cortex were removed prior to fitting the clamp. However, this does raise the issue of whether the root CSA at clamp prior to stripping the bark and cortex is a pertinent parameter, because the load is being transferred down the length of the root through the vascular tissue and dissipates tangentially through the remaining cortex and bark to the soil, rather than simply through the entire root. Therefore, a secondary skin friction within the root is present along with the soil root interface friction. This phenomenon was not as prominent in other species and only the bark was removed prior to testing as the weakness was between the cortex and the bark rather than between the cortex and the vascular tissue. In this instance the bark that was removed was very thin and produced negligible difference to the cross sectional area of the root at the clamp.

The relationship between maximum pull out force and cross sectional area at the clamp is quite different to that evident for the entire pull out test results. This may be a function of the size of the stem/root not being indicative of the size of the entire root, whereas the cross sectional area of an individual root is better related to the size of the root. However, the root architecture may also contribute to the correlation between CSA at the clamp and maximum pull out force, or lack of it for entire pull out tests. Stokes *et al.* (1996) reported that the optimum branching angle for root pull out resistance is 90°, and the mean vertical branching angle, from the taproot, for primary laterals of the European larch was 89°. However, the branching angles of second order roots from the primary laterals averaged 66° (Stokes *et al.* 1996). Therefore, an entire pullout test may be measuring a different root morphology to that tested during an individual root pull out test, which may account for the correlation found with individual pull out tests that is not evident in the entire pull out tests.

The maximum pull out force has been used to determine the tensile strength of the roots using the diameter of the root at the clamp (Norris and Greenwood 2003). However, Easson *et al.* (1995) reported that results of pullout tests were different to the tensile test results conducted on the same wheat species. The pull out resistance is composed of tangential friction between the soil and root and is influenced by root bending, branching, root hairs, the tensile strength at breakage points (Abe and Ziemer 1991b) and the presence of stones around which roots may become entangled (Operstein and Frydman 2000). Therefore, the use of the cross sectional area of the root at the clamp and the pull out resistance is not appropriate to determine the root tensile strength as it does not account for any of the aforementioned mechanisms.

6.3 *IN SITU* SHEAR BOX TEST

Shear box testing was conducted at both the Italian and Greek sites. Three locations were selected on the Trivento site for the *in situ* shear box tests; one below the root zone of the grass cover, to simulate non-vegetated conditions, and the other two tests were conducted on *Prunus spinosa*. While in Greece three *in situ* shear box tests were conducted in the recently burnt area, both near to and remote from the burnt tree trunks, and three *in situ* shear box tests were conducted in the regenerated area; the tests were located on a non-vegetated plot, one on a *Phillyrea latifolia* and one on a *Quercus coccitera.*

6.3.1 Apparatus

The *in situ* shear box apparatus comprises an aluminium frame, hydraulic cylinder, load cell and draw wire transducer, and is shown in Plates 6.10, 6.11 and 6.12. A small steel frame, which houses a 135 mm square steel shear box on low friction rolling element bearings, was attached to the front of the aluminium frame and secured with a ground pin, while two larger ground pins were used to secure the aluminium frame (Plate 6.10). A steel cable was used to connect the shear box to the hydraulic cylinder via two pulleys and an in line load cell. A manual logging system was provided by the pressure gauge in line with the hydraulic cylinder and the LCD display on the draw wire transducer. An attempt was made to manually record the displacement using a tape measure and the front ground pin as a datum. However, this proved unnecessarily labour intensive and resulted in superfluous displacement datasets.

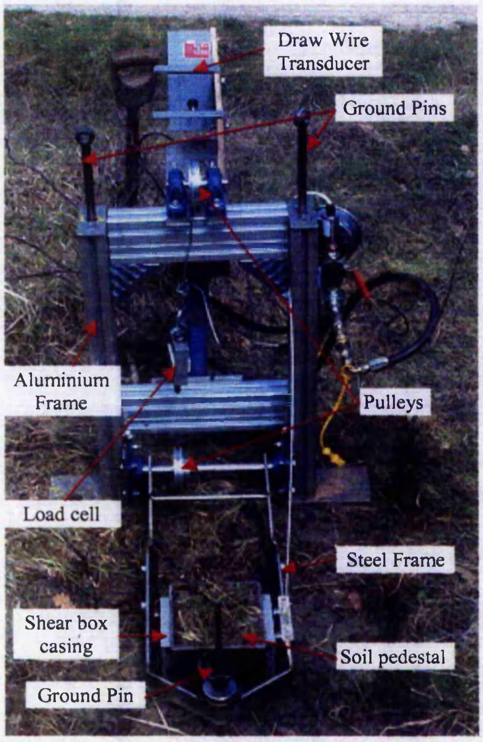
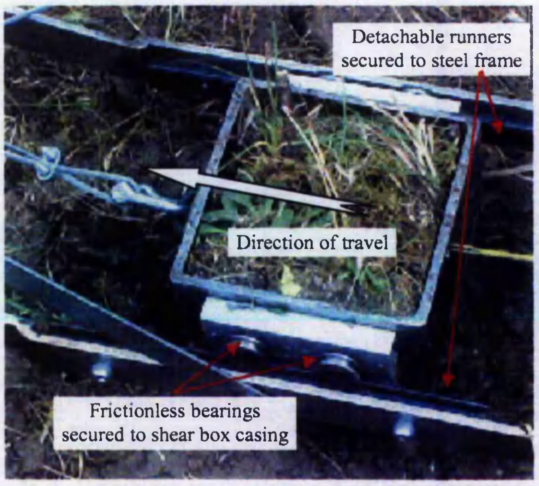


Plate 6.10 Mechanical *in situ* shear box apparatus secured by three ground pins (Italy, 2002)

A manual jack supplied the energy input required to pull the shear box toward the contracting piston. The frictionless bearings fixed to the box and the runners fixed to the steel frame (Plate 6.11), allows the *in situ* shear box to travel its entire length facilitating the measurement of both peak and residual shear resistance. Unfortunately, the steel frame did ride up the ground pin at the front of the apparatus during some of the tests, and was subsequently secured by the addition of a strengthening bar between the aluminium frame and the steel frame.



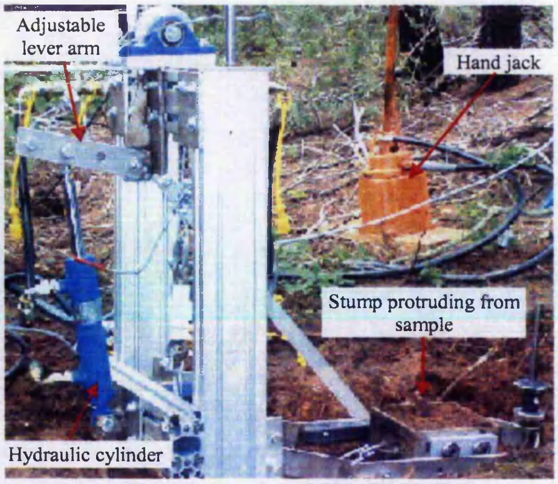


Plate 6.11 Shear box attached to steel frame via rolling element bearings and runners, (Italy, 2002)

Plate 6.12 Lever arm set-up facilitates extra travel of shear box from hydraulic ram (Greece, 2002)

The hydraulic cylinder used during the preliminary fieldwork was limited by its size to 100 mm travel, to compensate for this, and provide 100% horizontal displacement, a lever was fitted to the back of the mechanical apparatus to provide further travel of the shear box (Plate 6.12). The steel cable and hydraulic cylinder could be connected to the lever at one of three points to increase the mechanical advantage.

6.3.2 Procedure

The preparation procedure employed for the *in situ* testing was similar to that reported by Abe and Iwamoto (1986a), whereby a representative sample area was selected (either vegetated or non vegetated) and the soil around the sample was excavated leaving a pedestal of soil, over which the shear box was placed. The mechanical apparatus was then set up around the shear box, causing minimal disturbance to the sample. The procedure employed during the preliminary fieldwork is summarised in Figure 6.7.

The procedure differed from that of Abe and Iwamoto (1986a) firstly, in the selection of vegetation, as their tests focused on grasses rather than woody vegetation (shrubs and small trees). Therefore, details of the vegetation present were also recorded including species name, height, extent of canopy, diameter at breast height (DBH), or where the specimen was not tall enough to be measured at breast height, the average of three points along the stem was taken. Secondly, a normal load was applied by Abe and Iwamoto

(1986a) to replicate a reasonable overburden pressure; no additional normal load was applied to the in situ shear box sample during the preliminary fieldwork.

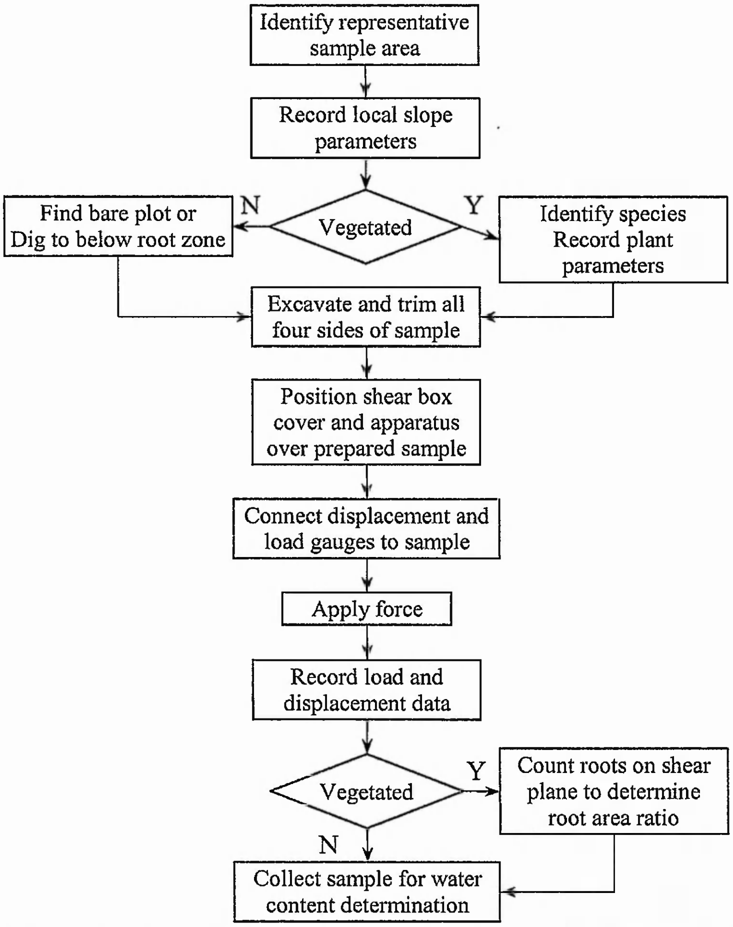


Figure 6.7 Procedure employed for *in situ* shear box testing during preliminary fieldwork.

One deviation from the methodology adopted during the preliminary fieldwork involved attaching a root clamp to the stem of a *P. spinosa* specimen, in an attempt to replicate the contribution provided by the shrub that had been removed (Plate 6.13). A drilled piece of wood and a spanner were used as spacers, between the top of the soil sample and the clamp, which secured the specimen and served to prevent the sample rotating within the shear box during the test. However, it was not possible to ascertain whether this method replicated the extant biomass or reinforced the sample further by providing the extra confinement, and was not repeated for the remaining *in situ* shear box tests. Following on from this the *P. latifolia* specimen selected for the *in situ* shear box test on the regenerated area in Greece, was tested intact (Plate 6.14). However, because the specimen was so small (0.35 m tall) any contribution to normal load would be negligible. To conduct the test on larger intact specimens could have health and safety repercussions, such as destabilising a tree with overhead vegetation. Therefore, it would be more prudent to fell the specimen and record the extant biomass, and substitute a safely balanced normal load to compensate for the missing vegetation.

Plate 6.13 Root clamp, spanner and drilled wood used to secure *P. spinosa* stem (Italy, 2002)

Plate 6.14 *In situ* shear box test on intact specimen of *P. latifolia* (Greece, 2002)

A normal load applied to the soil surface would be necessary to obtain the three datasets required to determine the cohesion intercept, and the implied improvement from the presence of roots. While a normal load applied to the stem would produce a more correct dataset as it more accurately replicates the original condition of the vegetation on that slope. If the normal load employed is to replicate the removed biomass then the load ought to be secured to the stump rather than placed on top of the soil sample, because different stress conditions are associated with the two set ups. A normal stress applied to the stump will be dissipated through the roots into the soil, whereas a normal stress applied to the sample surface will be transferred through the soil onto the root system. The difference between the two stress regimes was not investigated further in this project; however, it does require further research, which may be best achieved through finite element modelling. For the purpose of this research normal loads were not applied to either the soil or the stem and the contribution from the vegetation was obtained through comparative analysis of vegetated and fallow samples with the peak shear resistance for the vegetated samples given as a percentage increase.

6.3.3 Results

The *in situ* shear box test results for the Trivento (Italy) field site are given in Figure 6.8. Unfortunately, during the first *in situ* shear box test conducted on *Prunus spinosa* in Trivento, the electronic equipment did not record the data. Fortunately, the manual back up system of recording the pressure within the hydraulic cylinder on the pressure gauge proved a suitable substitute.

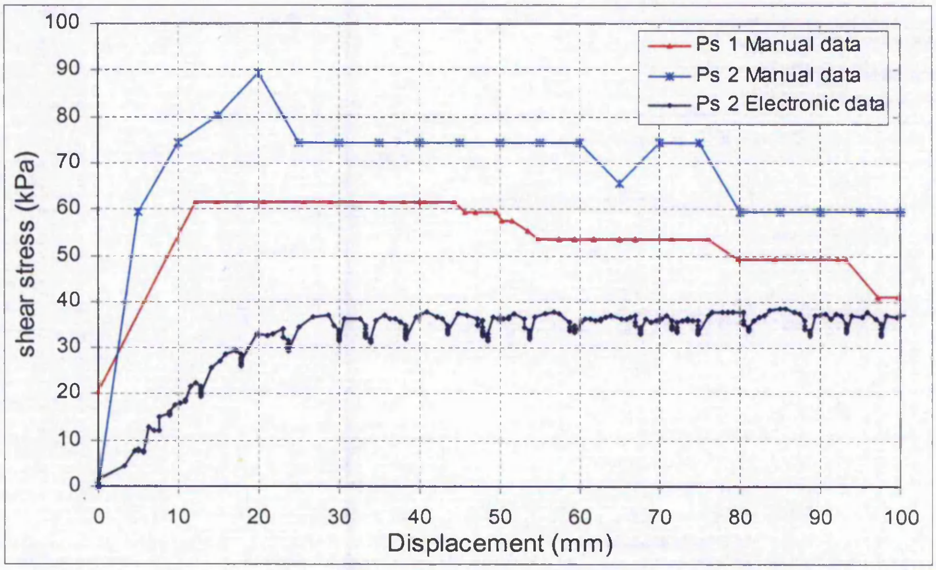


Figure 6.8 Manual and electronic data for *in situ* shear box tests conducted on the Trivento site, Italy 2002.

The data analysis required the extra step of converting pressure into force, which could then be transposed into a stress. The pressure was converted into a force using the active area of the piston in the hydraulic ram (the surface area of the annulus). This force was then considered over the area of the shear box to give the shear stress see plots Ps 1MD and Ps 2MD in Figure 6.8. However, this level of analysis proved insufficient, as the manual and electronic data for the same *in situ* shear box test (Ps 2) did not correlate. The disparity in results for the same test was due to the lever configuration on the back of the apparatus (Figure 6.9).

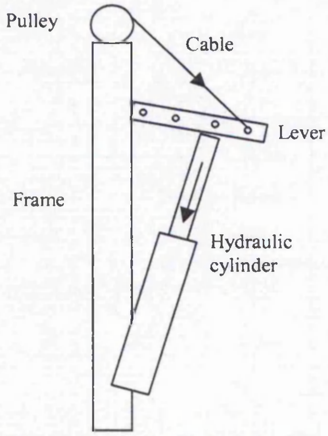


Figure 6.9 Configuration of hydraulic cylinder, lever and cable as fixed to frame

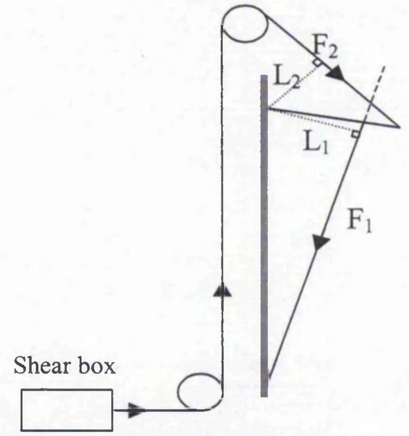


Figure 6.10 Force diagram with construction lines L_1 and L_2 taken perpendicular to F_1 and F_2

This configuration was not a consideration when using the electronic data capture set up, because the load cell was in line with the shear box and a direct reading was recorded.

Whereas, for the manual data logging system the pressure gauge was in line with the hydraulic cylinder, which was connected to the sample via the lever system. Therefore, to ascertain the actual force applied to the shear box it was necessary to resolve a force diagram of the hydraulic cylinder, cable and lever arm to compensate for the rotation within the lever system (Figure 6.10). If there is negligible friction in the two pulleys or loss of energy through the cable, it may be assumed that F_2 is equal to the force applied to the shear box; therefore, the force applied by the hydraulic cylinder (F_1) can be used to determine F_2 using equation 6.1.

$$F_2 = \frac{L_1}{L_2} F_1 \qquad (6.1)$$

The application of the correction factor to the original manually acquired data for test Ps 2 produces a plot which correlates better with the electronically acquired data for the same test (Figure 6.11) than the original data (Figure 6.8). Therefore, the same formula was applied to the data for the first *in situ* shear box test (Ps 1).

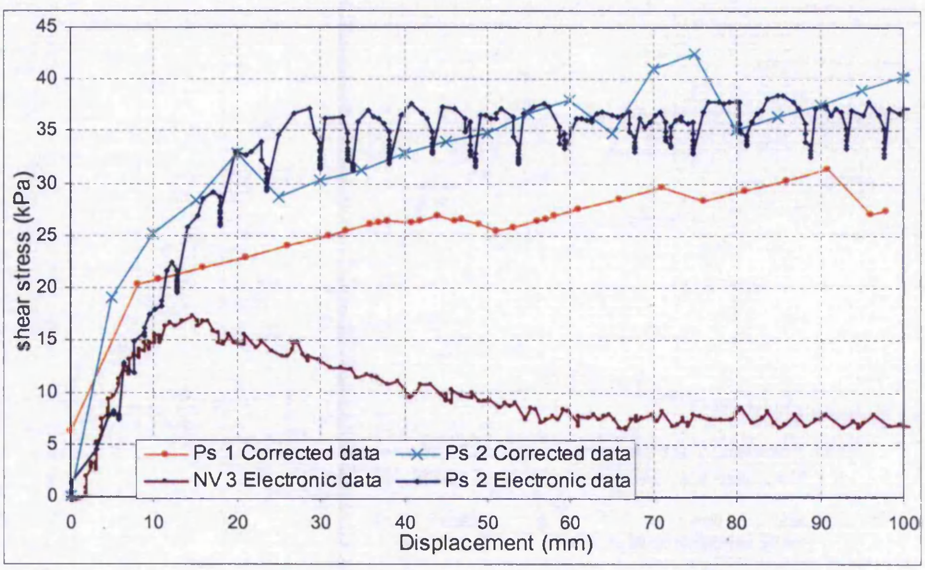


Figure 6.11 Corrected manual data for the two *in situ* shear box tests conducted on *P. spinosa* and Electronic data for one *P. spinosa* and one non vegetated sample (Italy, 2002)

Applying the formula reduces the apparent peak shear stress considerably; however, the actual shear stress determined from the manual data for the two *in situ* shear box tests carried out on *P. spinosa* is greater than that recorded for the non vegetated sample (NV 3 see Figure 6.11), which illustrates that the presence of vegetation contributes to shear resistance. A hand jack powered the hydraulic cylinder, and the cyclic nature of the peaks and troughs evident in plot Ps 2 Electronic data is indicative of the travel of the jack handle, producing a slight relaxation of load at the end of each stroke. The resolution of digital logging facilitates the capture of this phenomenon (also witnessed during the root pull out testing section 6.2).

The *in situ* shear box tests conducted in Greece were performed on both fallow and vegetated samples, and the vegetation was either alive or burnt. As anticipated the tests conducted on vegetated samples yielded a higher shear resistance than the non vegetated samples on both the recently burnt and the regenerated plots (Figure 6.12). Ekanayake *et al.* (1997) found that soils with roots undergo larger shear displacement than fallow soils prior to total failure. This trend is evident in the *in situ* shear box test results from the regenerated area, but not so with the samples from the burnt area. This phenomenon may be associated with the presence of vegetation; however, vegetated and fallow samples were tested on both plots and lateral roots were present at shallow depths beneath the shear box samples on the burnt site for both the vegetated and non-vegetated samples. Therefore, the presence of vegetation is not considered to be a direct influence on the failure mechanisms at the two sites.

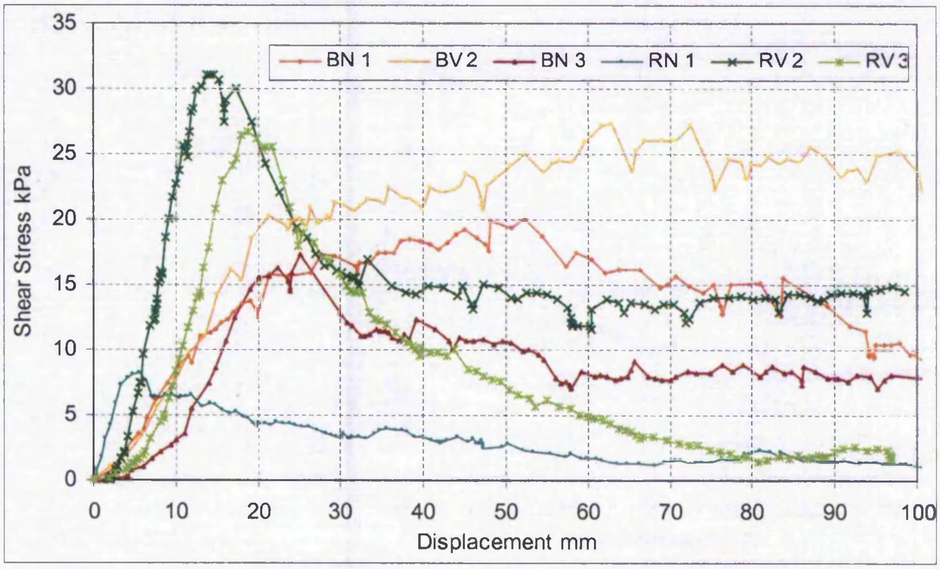


Figure 6.12 *In situ* shear box test results for the recently burnt (B) and regenerated (R) areas of the site for both vegetated (V) and non vegetated (N) samples (Greece, 2002)

The samples from the burnt area required a greater displacement to mobilise ultimate resistance than the samples from the regenerated area, regardless of vegetation. The regenerated area, curves RN1, RV2 and RV3 (Figure 6.12), exhibit a brittle failure, (with a distinct peak) while the curves for BN1 and BV2, from the burnt area, display a more ductile failure. The distinction between the failure patterns of the two areas may be coincidental and further testing would be required to confirm any trend. However, because there is no apparent correlation between the presence or lack of vegetation and the failure mechanism, the trend may be associated with the site or soil properties rather than the vegetation.

However, the six samples are a combination of CLAY, sandy CLAY, and clayey SAND, non of which correlate with the trend of ductile or brittle failure mechanisms found on the two plots. The maximum shear stress recorded for each test was plotted against the undrained shear strength (measured on site with a Pilcon hand vane), the volumetric water content (measured on site with the Delta T theta probe) and the root area ratio determined by counting the number of roots crossing the shear plane after each test. The regression lines for the three plots indicate a significant correlation between maximum shear resistance and root area ratio, with a regression coefficient of 7.951. While the undrained shear strength recorded with the hand vane showed little relationship to the maximum shear stress determined from the *in situ* shear box test (R^2 0.1509).

Surprisingly, the lowest correlation was between the volumetric water content and *in situ* shear box determined shear strength (R^2 0.0174), suggesting that the soil was not water sensitive. Therefore, it may be reasonable to assume that the recent fire has altered another soil property that was not measured during the fieldwork, which may influence the failure mechanism. Soil density/compaction is known to affect the failure mechanism of a soil; unfortunately the dry and bulk densities were not ascertained during the investigation, so it is not possible to determine if there is a correlation between the failure mechanisms and the density.

6.4 TRANSFER OF TECHNIQUES

During the preliminary fieldwork an opportunity was provided to observe other field scientists performing some of the tests outlined in the ECOSLOPES field protocol (Cammeraat *et al.* 2002). These included procedures for soil characterisation such as the excavation of test pits for soil profile descriptions based on the FAO standard (Food and Agriculture Organization of the United Nations 1990) and undisturbed sample collection. Vegetation characterisation techniques including vegetation surveys using quadrats, excavation of root systems for root morphology logging and 3D digitisation, were also observed.

As part of the vegetation characterisation two permanent plots were demarcated and sub divided into metre squares, with string and metal pegs, on the hill slopes of the Italian field site. A portable quadrat was employed to aid the estimation of vegetation cover present (Plate 6.15), using a modification of the Braun-Blanquet method (1951) in accordance with the ECOSLOPES field protocol (2002), whereby the species are grouped according to the functional types. The adoption of grouping species by functional types would appear to be a particularly useful technique to utilise for the geotechnical assessment of a vegetated slope as it can aid the evaluation of long term and seasonal contribution anticipated for particular functional types.

Plate 6.15 Quadrat used within permanent plot to conduct vegetation survey (Italy, 2002)

To increase the understanding of root morphology on hill slopes, the Italian team excavated root systems of several trees, which were then transported to the laboratory of Molise University to be digitised, using the Polhemus fastback digitiser. In addition to this large scale root architecture investigation, the root systems of small shrubs were excavated and manually assessed. Each plant was first identified and the dimensions measured before being felled and excavated. Once the small root system was exposed it was highlighted with yellow paint (Plate 6.16), to discern it from the surrounding soil and other vegetation, this technique improves the contrast in a photograph, and aids the production of a field sketch (Figure 6.13).

Root diameters were measured using callipers and whether the root was growing up or down slope was also recorded. Root pull out tests were then conducted on some of the roots while other root systems were excavated totally to identify the extent of the root system. The roots were then taken back to the laboratory of the Italian team and scanned into the computer, to facilitate the use of the specialised root morphology software package, winRHIZO (2000), which has been developed to reduce the manual labour and time required to measure all the roots within the root system, thus speeding up data acquisition and processing.

Plate 6.16 Excavated root system painted to aid visibility (Italy, 2002)

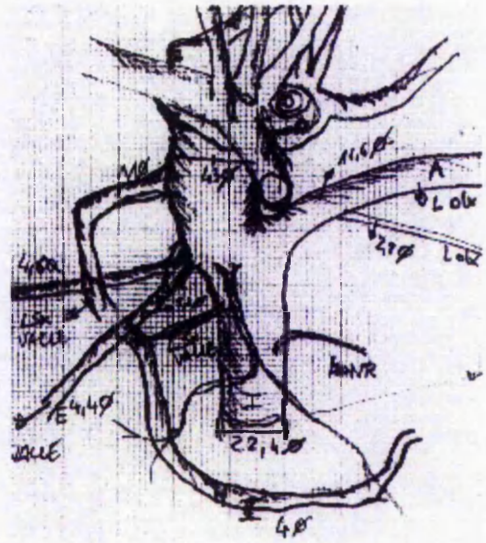


Figure 6.13 Field sketch of root system including root diameter data (Sarnataro 2002)

Detailed soil descriptions were conducted by a pedologist in accordance with the FAO guidelines (1990). The depth of each horizon in the soil profile is recorded to a much greater detail than executed with the engineering description of soil. The boundaries between horizons are detailed (gradual / abrupt, smooth / wavy) and the major horizon codes (A, B, C) are allocated along with lowercase modifiers which are designated by soil colour, chemistry, texture, structure, mottling and thickness of the layer, as these properties help identify soil processes within the soil profile, such as eluviation, illuviation, gleying, podzolisation and pan formation.

The colours of the soil in both a dry and moist condition are described using the Munsell scale handbook (1954), while the pH, cat ion exchange capacity, carbonate and organic content are tested or estimated. The texture (relative quantities of clay, silt sand and loam) and structure of the soil (platy, prismatic, blocky columnar or massive) and angularity of the peds are also described along with the abundance and size of additional constituents such as cobbles and roots. The drainage or seepage within the soil profile is recorded along with any additional comments observed while excavated and logging the soil profile.

The level of detail included in a pedology description helps to classify the soil as a resource and facilitates the mapping of soil for land use and management. However, the knowledge of soil formation required to produce such specialised descriptions to allocate the subordinate classifications would necessitate the employment of a pedologist to characterise the soil. Although, an appreciation of the soil quality is required to enhance the visualisation of root development, the level of detail does not necessarily add value to the geotechnical assessment of the soil. Therefore, for a geotechnical assessment of a vegetated slope it would be prudent to use the engineering description of soils (BS 5930: 1999), modified by paying greater attention to the topsoil horizon than is usually done in an engineering description.

6.5 LESSONS LEARNT

The preliminary fieldwork was instigated to implement the appropriate methodologies published in the literature, which led to the development of procedures for root pull out and *in situ* shear box testing. In addition, the exercise allowed an on site evaluation of the apparatus and improvements, such as bracing the frame were implemented. The preliminary fieldwork also provided the opportunity to observe field scientists from other disciplines, namely pedologists and biologists, facilitating a transfer of techniques.

The initial root pull out testing revealed that roots of different species fail in different ways. The roots of the elder tree have a very weak bond between the cortex and the stele of the root and the initial pull out tests failed with the cortex stripping from the rest of the root. This was particularly significant because the cortex of the elder formed a large part of the root cross sectional area, rather than a discrete layer of bark found in other species. Although this phenomenon was not as pronounced within the other species tested the bark of some roots was separated from the root for some of the tests, however, this did not affect the cross sectional dimension of the root to the same degree.

The collet root clamp proved straightforward to set up and secured the majority of roots sufficiently, however, for some roots tightening the clamp sufficiently was problematic. The turning that occurred when tightening the two casings resulted in unnecessary disturbance to the root, and some roots were pulled out unintentionally while tightening the clamp. Setting up the bolt clamp was awkward because the studs had a tendency to fall out of the housing while fitting it over the root and a larger excavation was required to facilitate access to the six bolts to allow tightening with an Allen key. Despite this the bolt clamp set up was less detrimental to the roots but was limited to a minimum root diameter of 15 mm, therefore, a smaller model was considered for the subsequent field work.

The use of the draw wire transducer was a preferable technique for recording the root displacement during pull out testing. The manual technique using a steel rule was problematic not only because it was not possible to take a reading at failure but for some tests the datum was obliterated as the root was pulled from the soil surface, even when a line was set up remote from the soil surface the change in direction of the root resulted in the loss of the original datum. Whereas, the draw wire transducer was connected to the root at the root clamp and the data was recorded as the wire recoiled during the pull out test, however, this was not without problems as displacement was recorded when the clamp slipped while the root remained stationary.

The maximum pull out resistance obtained from the entire pull out testing did not correlate with the cross sectional area at the clamp, unlike the results from the individual pull out tests. This phenomenon may be due to the poor relation between the stem dimension and the amount of roots in the entire root system or it may be a function of the different root architecture within the root system. However it is necessary to appreciate the difference between entire pull out testing and individual root pull out testing. Entire pull out testing is a useful technique for agricultural scientist to investigate resistance to grazing and lodging (Ennos and Fitter 1992). However, because of the complexity of the root architecture and soil interaction it is difficult to ascertain the soil root interface friction, which is one of the parameters required for evaluating the contribution of roots to slope stability. This parameter is more readily determined from individual pull out tests, therefore, individual pull out tests are preferable for the geotechnical assessment of vegetation for slope stability analysis.

Root pull out testing has been shown to measure a combination of tensile strength and the soil/root interaction (including skin friction). The maximum pull out force is not indicative of the root tensile strength unless the root has been sufficiently anchored by the soil and the root has failed some way from the clamp and the soil surface. This scenario was not encountered during the fieldwork.

The maximum pull out force may be expressed as a function of the cross sectional area at the clamp to produce a unit force, although this is only applicable to individual root pull out test results. Theoretically, expressing the maximum pull out force as a function of the surface area, as done by Operstein and Frydman (2000), would facilitate comparison with data from individual or entire root pull out tests. However, the potential for error in surface area calculations is exacerbated by the practicalities of determining accurate root dimensions. The fieldwork and subsequent analysis of results indicate that the volume of the root system should be used to derive the maximum pull out resistance. Alternatively, for entire pull out results Karrenberg *et al.* (2003) employed the maximum pull out force and the sum of the three main break points to derive the critical stress, to produce a unit value of maximum pull out resistance. However, incorporation of break points in complex root systems (i.e. greater than a single member) requires a subjective factor to be applied. Therefore, this approach is not recommended for use in isolation, and the volume of the root system should be recorded for comparative analysis.

The *in situ* shear box tests were conducted on small specimens, saplings or shrubs, due to the sample size, however, when characterising vegetated slopes it is necessary to evaluate the reinforcement contribution of trees, which is not possible with the 135 mm box unless individual roots or the finer roots occurring distal to the trunk are tested. Therefore, further testing using a larger sample size is required to assess the contribution of vegetation to slope stability. However, a large sample size is not suitable for the small sites due to the associated damage; therefore, large *in situ* shear box testing was conducted at the remote Spanish site of Almudaina, this is discussed in Chapter 7.

Analysis of the *in situ* shear box test data highlighted the need to modify the procedure that had been employed during the preliminary fieldwork. The different failure mechanisms apparent in the two Greek sites were not associated with the presence of vegetation, the soil type or water content. The soil density is also known to influence the failure mechanism; unfortunately, undisturbed samples were not collected for dry and bulk density determination. Therefore, it would be prudent to take an undisturbed sample of or near to the shear test, to determine the dry and bulk density of the soil. In addition, the recording of the extant biomass once the specimen has been cut down to ground level is required, as this value may then be used to replicate the normal load of the removed vegetation during the *in situ* shear box test, or employed in later analysis. If a normal load is to be applied to replicate the removed vegetation it should be applied to the stem of the plant rather than the soil surface, because the stress regimes are different for the two load applications.

In summary, the preliminary fieldwork facilitated a hands on learning experience, which has brought about a greater understanding of procedures and techniques that may be employed to characterise vegetation, namely the *in situ* shear box and root pull out test. Field trials of the testing procedures facilitated critical analysis and recommendations to be drawn on both the data analysis and practicalities of root pull out testing, and identification of limitations of the *in situ* shear box. In addition, the observation of other field scientists has facilitated the transfer of techniques. The use of a quadrat to assess vegetation cover and the grouping of species by their functional types are useful techniques that may be adopted into the framework for the geotechnical assessment of vegetated slopes. Whereas, the pedological description of soil is very involved and specialised and does not necessarily add value to a geotechnically biased investigation.

Lessons learnt from field testing and subsequent analysis were taken forward into the subsequent fieldwork conducted on the ECOSLOPES sites. This fieldwork also provided the opportunity to trial the fixed quadrat technique used to assess seasonal variability by monitoring vegetation cover on the M25 site, and rudimentary hydrogeological monitoring and testing was conducted on the M25 site. In addition, tree winching techniques employed on the M11 were observed, and large scale *in situ* shear box testing was conducted on the additional field site in Spain, all of which is discussed in Chapter 7.

7 Field Investigation

Errors, like straws, upon the surface flow;
he who would search for pearls must dive below
John Dryden (1631-1700), All for Love

Following the preliminary fieldwork further fieldwork was undertaken on two sites in the south of England and one site in Spain. The techniques employed during the field investigation were selected to characterise the vegetation and determine parameters relevant to slope stability analysis. The evaluation of the botanical survey techniques, biomechanical testing techniques and analysis of the results obtained are essential for the development of a framework for the geotechnical assessment of vegetated slopes. Therefore, some of the procedures pertaining to the contribution of vegetation, outlined in the literature review, were employed on the appropriate sites. Basic conventional geotechnical and hydrogeological investigation techniques were employed to characterise the sites. However, the focus of this research is to investigate the techniques employed for quantifying the contribution of vegetation to slope stability in order to produce a framework, therefore, a comprehensive geotechnical investigation was not considered a necessary part of this fieldwork, which allowed attention to be paid to the biomechanical testing techniques.

The two sites in the south of England included an embankment on the M25 and a cutting on the M11. The site work was divided between the two sites purely for logistical reasons, because it was imperative that the works did not interfere with the infrastructure as both the sites were located adjacent to a motorway. The two sites in the south of England offered a different formation, cutting and embankment, on similar geology and different distribution of woody vegetation cover (planted copse on the embankment and natural woodland on the upper half of the cutting). The additional ECOSLOPES site in Almudaina, Spain was used for a trial of a large scale (600 mm^2) shear box test, where damage of the slope or the influence of any testing on infrastructure was not an issue, due to the size and remoteness of the site. The data obtained from the fieldwork conducted on the Almudaina site was then incorporated into a modified finite element analysis package (FLAC) by van Beek *et al.* (2005) to ascertain the mechanical contribution of vegetation to slope stability.

7.1 GENERAL INVESTIGATION

The general investigation comprised approaches that are necessary to characterise any site, regardless of the ultimate research bias. Whether the investigation aim is geotechnical, botanical or hydrological it is important to determine the location, history and climate and characterise the soil and slope conditions, as all of these factors can influence the specific parameters under investigation. These aspects are usually considered in phase one of a geotechnical investigation, desk study and walkover survey. The information gleaned from the general investigation is summarised in the site descriptions for each area (Section 7.2).

7.1.1 Desk Study

Prior to the selection of the two motorway sites for the ECOSLOPES project, the suitability of the sites was assessed and rudimentary desk study information, regarding year of construction and local geology and history of failures, was provided by the Highways Agency (HA). This was followed by the provision of highways passes (courtesy of the HA) to facilitate a walkover survey, to confirm the suitability of the sites for slope, soil and vegetation characterisation. The Almudaina site has been a study area for Utrecht University and the University of Amsterdam since 1995, and as such the desk study data includes geological, geomorphological and climate data, along with the socio economic and land use history for the area, providing a detailed representation of the site.

The presence of protected species on a site or the allocation of protected areas such as SSSI (Site of Special Scientific Interest) or AONB (Area of Outstanding Natural Beauty) may also be ascertained during the desk study phase of a site investigation. Such information is critical for the effective planning of a ground investigation as potential disturbance to the ecology or protected site can prevent the execution of an intrusive investigation, and will determine the techniques employed or the time of year the investigation can take place.

7.1.2 Slope Characterisation

A topographic survey was conducted on the south bank of the M25 embankment using an abney level, tripod and staff (Plate 7.1). The site boundaries, key vegetation (clumps of shrubs and copse outline) and exploratory test locations were also surveyed in. The boundaries of the M11 site and test locations were surveyed in using hand held GPS (Global Positioning Satellite) equipment that also provided altitude data. A topographic survey was conducted on the Almudaina site to facilitate detailed geomorphological and topographic mapping of the landslide distribution. GPS equipment was used to locate key vegetation and test locations.

Plate 7.1 Topographic survey equipment used on the M25 Embankment. November, 2002

Plate 7.2 Trial pit face after disturbed and undisturbed sampling, M25. November, 2002

7.1.3 Soil Characterisation

Both the M25 and M11 sites have a history of shallow landslips and a full scale geotechnical investigation was commissioned by the HA for the north bank of the M25 to investigate a number of shallow slips. Therefore, the research project focused on the south bank of the M25 embankment along the same chainage as the geotechnical investigation and the geotechnical data were to be made available to the project. Similarly, the investigation on the M11 was restricted to the stable slope set back from the motorway rather than the slipped area adjacent to the carriageway.

Therefore, the focus was on the biomechanical testing and vegetation characterisation rather than a geotechnical appraisal. However, three trial pits were excavated on both sites to facilitate engineering soil descriptions (BS 5930: 1999), *in situ* hand vane tests and disturbed soil samples were taken at 0.1 m centres (Plate 7.2) for gravimetric water content and liquid limit determination (BS 1377-2: 1990), while undisturbed 50 mm diameter core samples were taken from each horizon for bulk and dry density determination.

7.2 SITE DESCRIPTIONS

The following sections (7.3.1, 7.3.2 and 7.3.3) describe the three study sites selected to conduct further fieldwork. The embankment and cutting near London, England and the historically terraced slope in Almudaina, Spain, were selected from the wider ECOSLOPES project to trial some of the techniques appropriate to quantify the contribution of vegetation to shear resistance, vegetation characterisation and seasonal monitoring.

7.2.1 M25 Site, England

The embankment is located between junctions 26 and 27 on the M25 and forms an approach to an overbridge where the M25 passes over the A113, in an area known as Passingford Bridge, Essex, southeast England (OS Grid ref: TQ504976). The embankment trends east west, and the investigation was concentrated on the south facing slope, because an investigation commissioned by the Highways Agency was underway on the unstable north bank. The height varies from a maximum of 11 m at the east of the site to 3 m at the western margin; however, the overall slope angle of the south bank is 26°.

The underlying geology comprises London Clay locally overlain by Taplow Gravels (BGS Sheet 257), and the embankment is constructed mainly of the locally won London Clay with some lenses of Taplow Gravel. The construction material is covered by a topsoil layer approximately 150 mm deep. An outcrop of the Taplow Gravel is evident in the stream section to the north of the site; the small stream flows from the north to south under the embankment and is culverted near the eastern boundary of the site.

The motorway was constructed in 1981-2 and opened to the public in 1983. The embankment has a history of shallow slip failures since construction. Three failures were identified in 1988-89 on both the north and south flanks of the M25. All three failures were repaired between 1989 -1991 using reinforced soil. The most recent failure occurred prior to April 2001, on the north bank, for which a geotechnical investigation was commissioned. Therefore, the field investigation was focussed on the south bank of the embankment.

Plate 7.3 M25 Embankment, vegetation includes mixed cover of grass and herbaceous plants and a copse of trees planted 10 to 15 years ago.

A planted copse of *Sorbus aucuparia*, *Betula pendula*, *Quercus robur*, *Crataegus monogyna* and *Acer campestre*, (rowan, birch, oak, hawthorn and field maple respectively) is situated toward the eastern boundary of the site while the majority of the site is covered with grasses, herbs and occasional self seeded hawthorn and rowan (Plate 7.3). The close planting of the trees in the copse resulted in a nominal under story vegetation, of moss, sparse grass and plantain, a layer of leaf litter and organic matter also covered the soil.

Plate 7.4 Desiccation crack on M25 site, 60 mm wide and 420 mm deep (October, 2003)

Desiccation cracks, approximately 60mm wide and 420 mm deep (Plate 7.4), were observed on the grass covered slope surface but were not apparent below trees.

Desiccation cracks are associated with water sensitive soils that have a medium to high shrinkage potential, a characteristic common to the London Clay.

The absence of desiccation cracks below the copse indicate that the trees have a different effect on the soil water conditions, either through water take up from deeper in the soil horizon, redistribution of water via the root system or increased permeability and infiltration capacity. Alternatively, the canopy of the copse may protect the underlying soil from excessive evaporation from the soil surface, which occurs during the summer months especially on a south facing slope. The site climate is cool temperate; displaying seasonality in temperature and precipitation, mean annual temperature 9.6°C and average annual rainfall of 584 mm (Met Office 2003).

7.2.2 M11 Site, England

The cutting is situated off the southbound carriageway of the M11 motorway, between junctions 4 and 5, near Loughton, Essex, southeast England (OS Grid ref: TQ434943). The maximum height of the cutting is 15 m, with an overall slope angle of 20°, facing northwest. The local geology consists of London Clay with a thin cover of superficial deposits of Boyn Hill Gravel and Boulder Clay (BGS sheet 257), which in turn is overlain by approximately 150 to 250 mm of topsoil. The M11 was constructed in 1976, and the cutting was re-profiled using the locally gained material to provide a restricted access slip road off the M11.

Plate 7.5 Deciduous vegetation dominating cutting slope of M11 slip road.

Plate 7.6 Shallow landslip in cutting on M11 to the south of site area

The site is covered with predominantly deciduous vegetation (Plate 7.5 and Plate 7.6), including grasses, shrubs and mature trees. Among the species of trees identified are *Betula pendula*, *Quercus petraea*, *Crataegus monogyna*, *Acer pseudoplatanus*, and *Pinus sylvestris* (silver birch, oak, hawthorn, sycamore and pine, respectively). The vegetation is dense woodland toward the crest of the slope, opening into grass and shrub dominated cover toward the toe, near the access road. Shallow landslips have occurred on the south of the site in the cutting shouldering the M11 (Plate 7.6). This slipped area was not investigated as part of the research fieldwork due to the close proximity of this section of cutting to the M11 carriageway. The area studied was adjacent to the slipped section but was sufficiently set back from the motorway to allow biomechanical testing without interfering with the infrastructure. The site climate is cool temperate, displaying seasonality in temperature and precipitation, with a mean annual temperature of 9.6°C and an average annual rainfall of 584 mm (Met Office 2003).

7.2.3 Almudaina, Spain

Cultivated terraces have been formed along the valley slopes of the Baranco del Mollo, a tributary of the Rio Serpis, which flows through the Valles de Alcoy within the municipality of Almudaina, Alicante, South East, Spain (GPS 38°76' N, 0 °36' E). The gradient of the terraced slopes vary in angle, the levelled areas average 10° while the slopes are in excess of 40°. The local geology comprises Mesozoic Limestone, which has undergone structural deformation during the Tertiary period resulting in large scale folds and faults, overlain unconformably by Neogene Marl and local fluvial deposits (van Beek 2002). The village of Almudaina is located near the spring line of the Mesozoic Limestone hills above the Neogene marls, which are the focus of the study area.

Plate 7.7 Cultivated terraces and natural successive vegetation on the Neogene marl hill slopes below the village of Almudaina, which is located around the spring line from the Mesozoic limestone hills behind.

Some terraces are still cultivated with cherry, almond and olive groves, while others have been abandoned and natural succession is evident (Plate 7.7). Aleppo pine trees, *Pinus halepensis*, with an under story vegetation system of grasses and perennials including *Ulex parviflorus*, *Thymus vulgaris* and *Erica multiflora*, dominate the natural vegetation. The site climate is continental and Mediterranean, displaying a strong seasonality in temperature and precipitation; the mean annual temperature is around 12–18°C with a difference of 16° between the summer and winter temperatures (van Beek 2002). The rainfall in this area is irregular, distributed mainly in spring and autumn, with peaks in April and October (Figure 7.1).

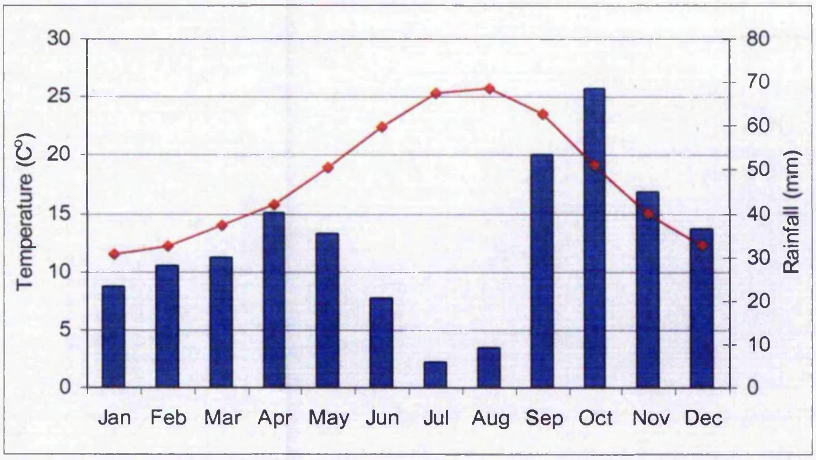


Figure 7.1 Average climate data for southeast Spain derived from GCHN data for 468 months between 1951 and 1990 (Hoare 1996)

7.3 BOTANICAL INVESTIGATION

A botanical investigation is necessary to characterise both the above and below ground vegetation, so must form an integral component of a geotechnical investigation of a vegetated slope. The botanical investigation comprised vegetation characterisation techniques observed during the preliminary fieldwork, including fixed quadrats to estimate vegetation cover and excavation to determine root density and distribution.

7.3.1 Vegetation Cover

A permanent 9m^2 plot was randomly selected and marked out with string and pegs within the grassed area of the M25 slope, to facilitate the cover estimation, which was conducted each season to assess the seasonal variability. The fixed plot was subdivided into a 1 m^2 grid; three of these squares were used to survey the vegetation with the aid of a 0.5 m^2 quadrat frame, with 0.1 m^2 intervals. However, the sample size will vary depending on the size of the site, type and distribution of vegetation, and the entire copse was used to ascertain the density of vegetation cover within. The aim of the vegetation survey is to give an indication of the cover and seasonal variation rather than a detailed population study; however the Jaccard index was used to compare similarities between the plots.

The ECOSLOPES field protocol (Cammeraat *et al.* 2002), modified the Braun-Blanquet method for cover estimation, to speed up the field assessment, with the introduction of functional types. However, it was still necessary to identify the individual species present in order to classify them into the correct functional type. Therefore, the cover estimation was not speeded up by the method, as anticipated, but introduced another stage to the data handling. The use of functional types to group species may not necessarily aid or speed up the estimation of cover in the field, but it does benefit the end user who will be able to appreciate the type and amount of vegetation covering the site. The classification of annual, perennial, deciduous or evergreen will facilitate the evaluation of the contribution of the vegetation through the seasons, even if the user is not familiar with correct botanical terminology or a particular species.

To determine the overall contribution of the trees to slope stability it is necessary to ascertain the density and distribution of trees over the slope, similarly the leaf area index is an important parameter for evapotranspiration and interception determination. However, quadrat frames are only suitable for cover estimation of small herbaceous plants and grasses, as the quadrat should be of a suitable size to contain an average of four individuals (Curtis and McIntosh 1950). Therefore, a different methodology is necessary to assess tree and shrub cover. Fixed area plots are used to characterise forest stands, whereby density per unit area, stem diameter and height of an even aged plantation are ascertained (Adlard 1990). However, fixed plot selection requires a large area from which to select a representative sample area of suitable size. This was not practicable for the M25 site, therefore, the key species within the copse on the M25 were identified and the edge of the copse was surveyed in during the topographic survey. The stand density was readily determined, as the trees had been planted in a 2 m grid formation.

The ground cover was estimated for each species as a percent of the quadrat, however, because in a multilayered system the total can add up to more than 100 the results were normalised to plot the data. Figure 7.2 illustrates the results from the six visits to the M25 site, for the same 1 m^2 quadrat. Chart A illustrates the species cover, however, when considering the overall contribution of vegetation to slope stability Chart A contains unnecessary detail, therefore, to reduce the noise the same data have been grouped into corresponding functional types, from bare soil through to the evergreen herbaceous perennials (Chart B). The concentric circles represent the data from each season, with the initial monitoring data, summer 2002, at the centre of both charts.

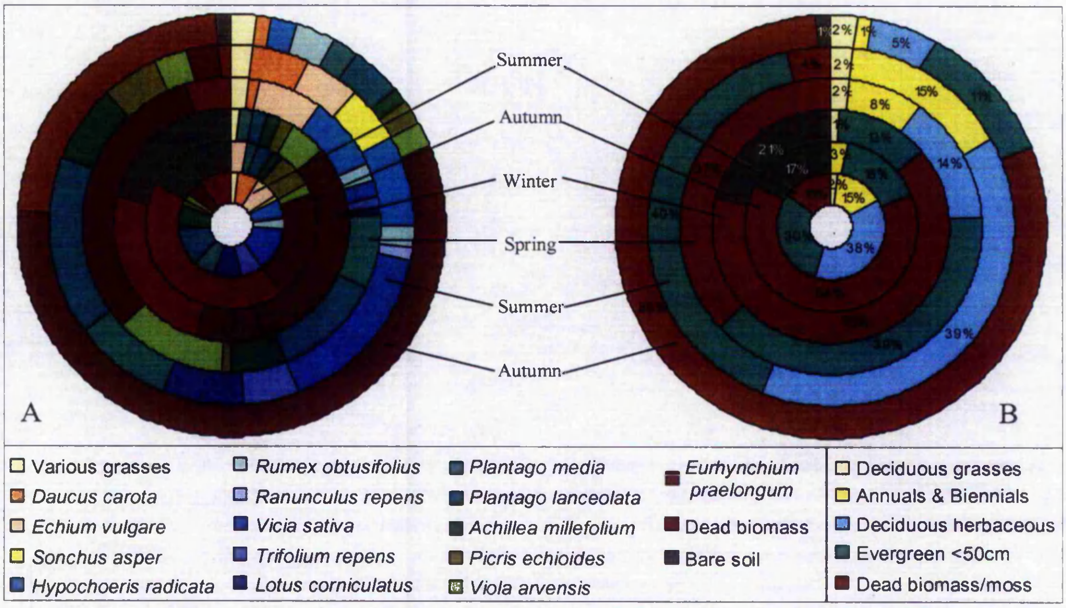


Figure 7.2 Compilation of results from six visits for the same 1m^2 fixed quadrat. Chart A illustrates species cover for each season monitored while Chart B illustrates the functional types

The plot of functional types (Chart B Figure 7.2) facilitates a general comparative analysis of the vegetation cover and seasonal variation, with up to 96% of the surface covered by vegetation during the summer (although only a few percent cover is actual grass) dieing back to 14% cover, revealing bare soil, in the winter. It is also possible to see the difference in cover from year to year; summer 2002 has the same amount of deciduous grasses (2%), annual and biennials (15%) as summer 2003 and a similar amount of deciduous herbaceous cover (38% and 39%, respectively). However, the evergreen vegetation has grown over the year resulting in an increase of evergreen vegetation cover (from 30% to 40%) and a reduction in dead biomass/ moss cover.

The autumn 2002 survey was conducted in November and the results are quite similar to the winter survey that was conducted in January. Whereas, the following autumn survey was conducted in September so has much less bare soil exposed and still has annuals and deciduous herbaceous cover. Therefore, because of the variability anticipated with vegetation cover it may be preferable to conduct a survey each month, at regular intervals to produce a comparative analysis. However, if this is not possible a seasonal survey ought to be carried out in the same month, chosen to represent each season, as it is important to minimise the variables.

The Jaccard index (Section 4.2) was employed to compare the similarity of species between the grassed plot and the copse on the M25 and also the seasonal difference exhibited in the grassed plot (Table 7.1). As anticipated there is a strong similarity, indicated by the result being close to unity, between the species present on the same plot over the two summer surveys (0.94). While the disparity between species during the winter and summer is evident (0.43) it is not as significant as the difference between the grass plot and the copse (4.29), which only had four species in common between the two plots.

Table 7.1 Jaccard index for comparative plots on the M25 site

Comparative plots	Jaccard Index
Grass Plot Summer 2002 vs. grass plot Summer 2003	0.94
Grass Plot Summer vs. Grass Plot Winter	0.43
Grass Plot vs. Copse	4.29

The Almudaina site has been studied for several years (van Beek, 2002) and the vegetation over the slope has been meticulously characterised, by recording herbaceous cover with quadrats and mapping tree locations. Each tree taller than 2 m was located and the height, DBH, canopy extent and foliage density were recorded. The vegetation data for the Almudaina site was then grouped into two categories, of sparse and dense, to facilitate slope stability modelling using FLAC (van Beek *et al.* 2005). The data acquisition proved to be a very labour intensive procedure, especially for a large or densely populated site, and it may be more efficient to randomly or systematically select a representative sample area rather than recording data for the entire site, again sample size and selection depends on the size of the site, and type of vegetation.

7.3.2 Root Density and Distribution

The trial pits excavated for soil sampling and characterisation were also used to count the number of roots exiting the pit wall, to assess the root area ratio and ascertain the vertical extent of the roots. This was done with the aid of a 0.5 m^2 quadrat frame on the M25 site while the on the M11 site the roots were counted per soil stratum so that they may be included in an engineering soil description, because the arbitrary boundaries produced by the quadrat did not correspond with the horizons. This method was also employed for the vertical sides of each pit following the open sided *in situ* shear box tests conducted in Almudaina. In addition, the sample block was excavated in 0.1 m layers down to the shear plane (van Beek *et al.* 2005), and the roots intersecting the horizontal surface were counted following the large scale *in situ* shear box tests.

For all three methods the roots were classified by size, and the number of roots for each size class recorded. The number of roots and average diameter for each size class were used to calculate the root area per unit area of soil, A_r or root area ratio (using equation 4.2, Chapter 4). At present the root size classes are only used to determine the total root area ratio, which can be used to characterise the root density and employed in a slope stability analysis, to indicate zones of root influence. However, further research may produce a distinction between the reinforcing contribution of different sized roots. Therefore, further understanding of the mechanics of root reinforcement may lead to the categorisation of root reinforcement potential for the different size classes, and provide a valuable empirical relationship.

To expedite the root counts the root diameters were generally estimated for roots smaller than 6 mm diameter, roots larger than this were measured with vernier callipers. To accurately count all the very fine roots (≤1 mm diameter) the aid of a hand lens would be necessary and the time required to produce the extra precision was unfeasible. The root counts were conducted with the naked eye, rather than with the aid of a hand lens because requirement for a precise assessment of the number of very fine roots within the profile wall was outweighed by the time constraint and the overall contribution of these data to the investigation. The arbitrary size classes, used for the field work, are given in Table 7.2.

Table 7.2 Root size classes used for root counts

Size class	Diameter (mm)
Very fine	<1
Fine	1 to 2.9
Small	3 to 4.9
Medium	5 to 10
Large	10 - 15
Very large	> 15

The trial pit in the copse on the M25 revealed fine to medium roots penetrated to a depth of 1 m b.g.l., while large roots were only observed to a depth of 0.5 m b.g.l. Similarly, fine and small roots penetrated to 0.8 m b.g.l, while medium roots were recorded to a depth of 0.6 m b.g.l., and only one large root was recorded (between 0.2 and 0.3 m b.g.l) in the trial pit excavated in the grassed area.

A fixed quadrat frame is suitable for root counting in a homogeneous soil, but in a stratified soil, especially for engineering horizons, it may be preferable to group the root counts per stratum rather than the arbitrary intervals of a quadrat frame. This method is also preferable if the data are to be incorporated into a slope stability model, which uses the parameters of the individual horizons to calculate the factor of safety.

For the trial pits on the M25 site a quadrat frame was employed to facilitate root counts while for the M11 site the roots were counted for each soil horizon. The roots were counted by size class to calculate the root area ratio (A_r/A); although the results are small they can be given as a percent of the unit surface area. Figure 7.3 is a graphic log of the soil strata and root area ratios for trial pits excavated on both the M25 and M11.

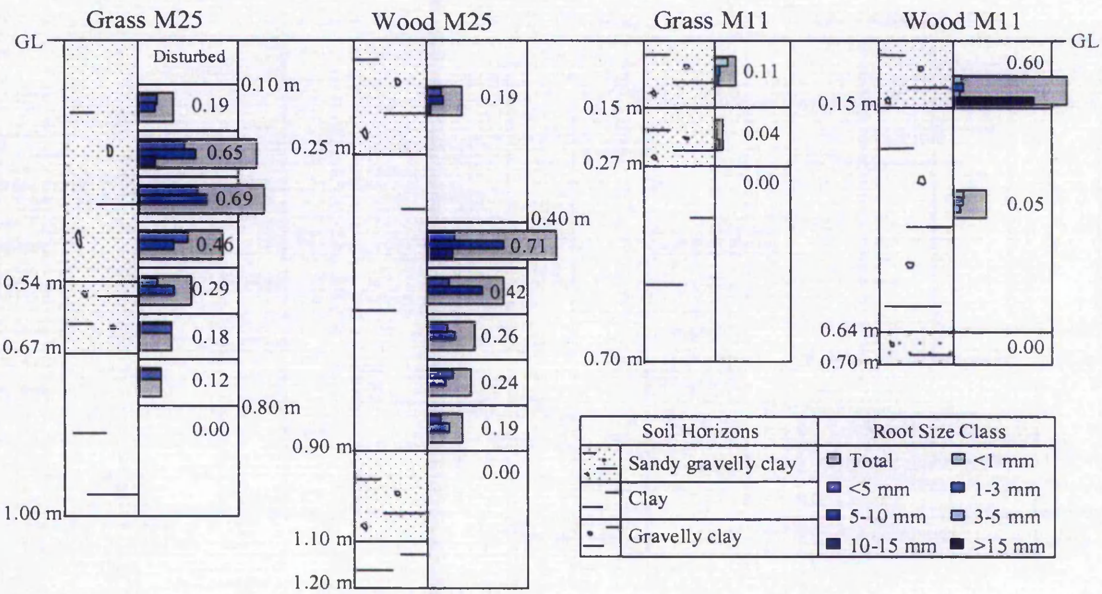


Figure 7.3 Graphic logs of the trial pits excavated on the M25 and M11 sites, along with root area ratio data given as a percent of the total area

The total root area ratios are included beside each bar chart, which represents the root area ratios of the particular size classes that make up that total. The vertical distribution of roots on the M25 is quite different to that on the M11 for both the grass and woodland plots. The roots in the M25 trial pits range from below 5 mm diameter up to the 10 – 15 mm diameter size class and extend down to 0.80 m and 0.90m b.g.l. Whereas, the roots in the grassed plot of the M11 do not exceed 5 mm diameter and only extend down to

0.27 m b.g.l, and the pit located in the M11 woodland, 1 m away from the nearest tree, shows a gap grading of roots up to 5 mm diameter and in excess of 15 mm diameter, in the top 0.15 m, with only roots less than 5 mm diameter extending down to 0.64 m b.g.l.

The maximum total A_r/A values calculated for the M25 are around 0.7% for both the grass and woodland plots, while the M11 shows a difference between the grass and woodland vegetation with maximum A_r/A values of 0.1% and 0.6%, respectively, indicating a greater reinforcement potential to a greater depth on the M25 when compared to the M11. This may be a function of a number of factors such as nutrient and water availability, soil or slope conditions or the species present. The M11 site has a topsoil horizon in which the majority of roots are concentrated, while the M25 site is lacking a topsoil horizon, therefore, root systems on the M25 site may have to extend further to acquire the appropriate nutrients. In addition, the M25 site has a southern aspect which can affect water availability during the summer months, also encouraging deeper root penetration, while the M11 site has a north eastern aspect so is not as exposed to the drying influence of the summer sun. However, the two sites have quite different vegetation cover both in the wooded and the grassed plots. The grassed area on the M25 site mainly comprised deciduous and evergreen herbaceous plants with some annuals and perennials with occasional grasses, whereas the grassed plot on the M11 site was mainly covered with grasses with only a few herbaceous plants.

The choice of root size classes depends on the type of roots present, the range of roots on the M25 site allowed for the small, fine and very fine roots to be grouped as <5 mm, while on the M11 all the roots present below the grass were up to 5 mm diameter, therefore, the group was subdivided. The boundaries of the root size classes are arbitrary as they mainly serve to determine the root area ratio and prevent skewing of the dataset that will result from taking the mean of the root diameter range for the total number of roots to calculate the total root area (A_r).

The division of the trial pit surface area by quadrat or by stratum for counting roots have their merits and drawbacks, and the employment of either technique will depend on whether the stratigraphy or root morphology is the most dominant feature. The quadrat method illustrates the root distribution with depth at arbitrary intervals, which may not correspond with the soil strata. However, roots counted per soil strata may illustrate the propensity of roots to exploit a particular horizon but does not clearly illustrate the distribution of roots with increasing depth or define the limit of root depth. Therefore, it would be prudent to combine the two methods and use the quadrat frame, and re-align it to the top of each new horizon, thus providing the definition of the quadrat survey, which will correspond to the strata boundaries.

Assessment of the lateral root distribution was conducted on the M11 site using the 'airspade' to excavate the roots of specimens selected for root pull out tests and one specimen which was selected solely for root morphology investigation (Plate 7.8). The 'airspade' comprises a metal hose connected to a compressor, and is used to direct a jet of compressed air to the soil surface, and removes the soil without damaging the roots, even fine roots remain intact.

Plate 7.8 Hawthorn root system excavated by D. Barker. 'Airspade' in background (M11, 2002)

Although the 'airspade' proved an effective tool it was also necessary to use a trowel to remove the spoil from the deeper part of the excavation. The jet of air from the 'airspade' scattered the soil, resulting in a lack of spoil available to back fill the hole after excavation and the burial of surrounding vegetation, and so may not be the most suitable tool for some sites. However, this technique is ideal if the requirement is for a pristine root system, with intact fine and very fine roots, for root architecture analysis. The root morphology investigation revealed a shallow, plate like root system (with no taproot) that was confined to the uppermost soil horizon, which correlates well with the trial pit data. Similarly, the roots excavated for the root pull out tests (see section 7.5.2) were confined to the top 0.3 m b.g.l. near the tree, although some were found to grow downwards approximately 0.6 m. out from the stump. The azimuths of the roots selected for root pull out tests were recorded and may be presented on a stereographic projection or rose diagram to illustrate directional growth trends, as done by Riestenberg (1994, Section

4.4). Riestenberg (1994) used an equal area projection net, which is distorted to facilitate contouring of the data points and subsequent statistical evaluation of the angular relationships, and a rose diagram

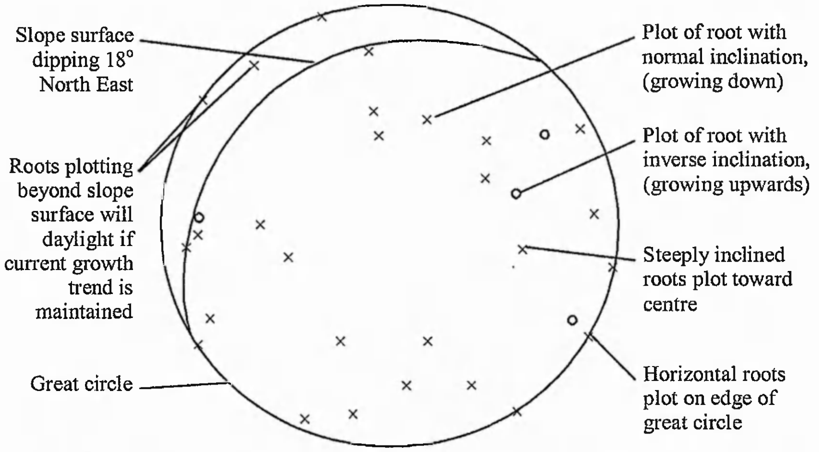


Figure 7.4 Equal angle stereographic projection of a hawthorn root system recorded 0.30 m from stem, illustrating the lack of taproot and dominance of lateral roots

An equal angle net is geometrically correct and used by geologists to visually solve angular relationships; therefore, this plot was chosen, as an alternative, to represent the hawthorn root systems, from the M11 site, in relation to the slope surface (Figure 7.4). Points plotted near the perimeter or great circle, are close to horizontal whereas those plotted at the centre are vertical, the specimen plotted in Figure 7.4 has no taproot, but has many lateral roots which do not display preferential up or down slope growth. Although there was no preferential growth with regard to the slope evident, four roots were growing upward from the root system, these along with the roots that are plotted beyond the slope surface line would daylight if they maintained that azimuth, indicating that the root direction must change out from the stump as there were no roots exposed at the surface prior to the investigation.

All three of the aforementioned plots are suitable to represent the root data obtained prior to pull out testing; this method may also be used to collate data from a number of trees to represent the trend of principle root growth across the site. In addition, it is not necessary to fell the tree or excavate the entire root system to ascertain the direction of principle root growth, with regard to the slope. Therefore, a reasonable amount of data can be obtained to help characterise the distribution of roots on a slope, which must be established to conduct a slope stability analysis incorporating vegetation. However, whichever method is chosen, to represent the root data, should be used with caution as the plots represent a snapshot of the roots at a given depth and distance from the stem, which is likely to change if an obstruction is encountered or the soil properties vary.

7.4 BIOMECHANICAL INVESTIGATION

The biomechanical investigation included tree winching, root pull out and *in situ* shear box testing to assess the mechanical reinforcement contribution of vegetation. Tree winching was conducted on the M11 site on a number of trees; some of the winching tests were conducted to destruction while other trees were left intact to allow subsequent root pull out testing in an attempt to correlate the results of the tree winching and pull out tests. However, the complexity of the influencing factors for both tests prevented such a correlation.

In situ shear box tests were conducted using the 135 mm shear box apparatus (Norris and Greenwood 2003). During the preliminary fieldwork and the main field investigation it became apparent that the sample size was insufficient to ascertain the contribution of tree roots, as only small saplings or shrubs were selected for testing. Following the test it was found that on some specimens the roots did not penetrate the shear surface, or the test was conducted in the topsoil to encapsulate the roots and the properties of the engineering horizons were not tested. A large scale *in situ* shear box trial was conducted at the Almudaina field site, to obtain shear resistance data for tree root reinforcement. Unfortunately, the two results from the small *in situ* shear box testing were not suitable for comparative analysis with the large scale *in situ* shear box results (Section 7.5.3).

7.4.1 Tree Winching

Tree winching is a technique used by foresters and arborculturalists to assess tree and stand stability. The longitudinal strain, stem stiffness and Young's modulus are determined by the test, which are then used to ascertain the dissipation of wind forces from the stem into the soil. Tree winching tests were conducted on most of the ECOSLOPES sites, by the team from Laboratoire de Rheologie du Bois de Bordeaux (L.R.B.B.), to collate sufficient data to validate biomechanical models developed during the project, which provided an opportunity to observe the technique in practice. Tree winching tests were conducted on two silver birch and three hawthorn trees on the M11 site. The natural open woodland located a distance away from the M11 proved most suitable for the test, whereas the close planting of the copse and nature of the M25 site proved less suitable; therefore, tree winching was not conducted on the M25 site.

The trees were winched sideways (in the up, down and cross slope directions) and the force required to displace the tree a certain distance was measured to determine the stiffness of each tree. The two silver birch trees were tested to failure (Plate 7.9) whereas, the three hawthorn trees were not winched to failure, to facilitate subsequent individual root pull out testing (Section 7.5.2) for comparative analysis. Therefore, care was taken to not damage the root system of the hawthorn trees during the winching process, by limiting the displacement angle to 15°, as noticeable movement of roots within the soil starts with a trunk displacement of 20 – 30° (Crook and Ennos 1996). Measurements of strain and displacement in the principle lateral roots were measured using strain gauges and digitiser sensors fixed on individual roots in line with the four winch directions around the tree (Plate 7.10). The principle roots were excavated near to the trunk and the bark was removed to facilitate a close bonding of the strain gauges and digitiser sensors to the roots and trunk.

Plate 7.9 Destructive tree winching of silver birch (M11, 2002)

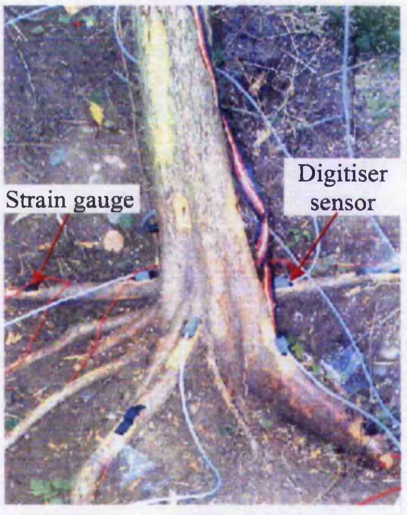


Plate 7.10 Hawthorn with digitiser sensors and strain gauges attached to the roots (M11, 2002)

The destructive tree winching test is used to determine the maximum resistive bending moment and the critical bending moment obtained from the test must be corrected to compensate for the mass of the crown and stem that has been removed (Papesch *et al.* 1997). The critical bending moment is derived from the force applied by the winch and the geometry of the test (Figure 7.5) which changes throughout the test as the tree moves about the centre of rotation, the position of which is influenced by the root morphology and soil properties. Unfortunately, flexural bending of the stem can create a complex geometry, therefore, inclinometers are positioned at the top and base of the stem, and the Young's modulus of the stem is determined during the early phase of the test. Although the complexity of the failure mechanisms may appear prohibitive, the test is relatively well understood and several models use the data to determine the susceptibility of tree stands and individual trees to wind throw (Cucchi *et al.* 2005).

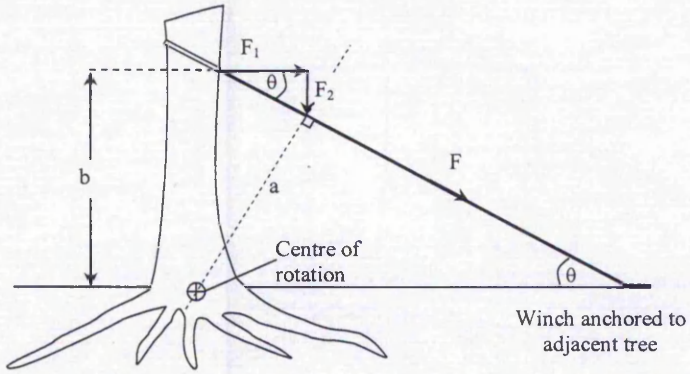


Figure 7.5 Geometry and force diagram for tree winching test

Strain gauge data for the principle roots of the hawthorn trees were supplied by Berthier *et al.* (2002) and the data for two lateral roots of one hawthorn tree are plotted against the load applied to the stem in Figure 7.6. The load applied to the stem to winch the hawthorn trees can only be used as an indicator of load, because the complex nature of the dissipation of stresses through the stem and entire root system impedes the determination of a direct load to any particular root.

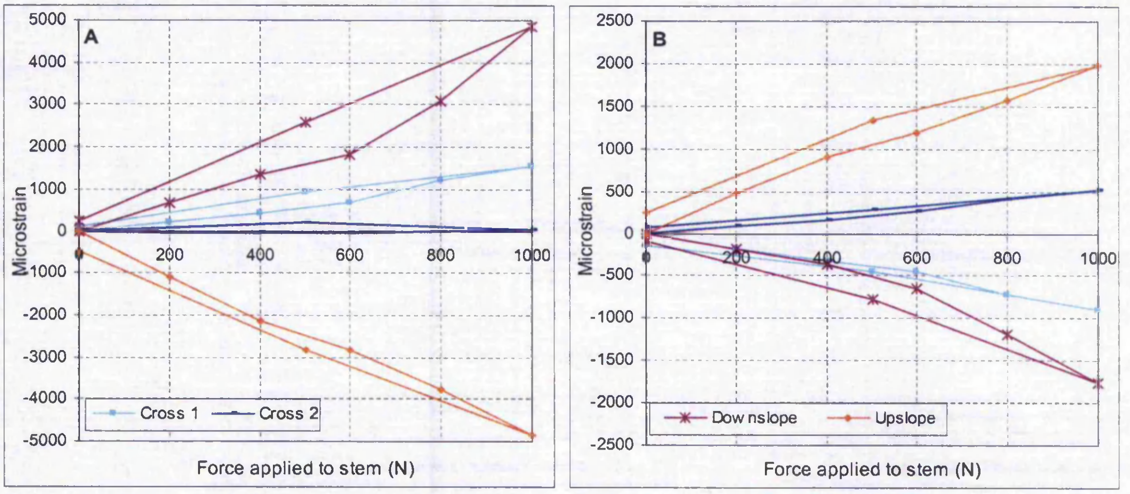


Figure 7.6 Strain response for principle roots winched in four directions A) up slope root and B) down slope root.

However, the test revealed the behaviour of the lateral roots during stem loading. When the trunk was pulled in the upslope direction compression of the upslope root occurred (indicated by the negative strain values, Figure 7.6a) and tension was evident in the principle upslope root during the down slope winch and one of the cross slope winches (positive strain values), while the root was not affected by the other cross slope winch. Similarly, compression was evident during the down slope winch, and tension during the upslope winch for the principle root growing in the down slope direction (Figure 7.6b). Although the strains induced in the down slope root are much less than those in the upslope root is evident in both roots, where the hysteresis loop does not return through the origin. Therefore, even though care was taken to minimise disturbance to the roots, partial factors were inevitable. However, the test was representative of natural conditions (strong winds) and the permanent deformation recorded is very small, and may therefore, be considered negligible when evaluating the root pull out data.

The difference in strain between the two roots may be due to the difference in root size, rather than growth direction, although the size may be intrinsically affected by the growth direction. The down slope root had a diameter five times that of the up slope root which can influence the strain recorded in one of two ways, either the strain is not as easily recorded over larger surface area, or the larger root associated with the diameter provides better anchorage which does not yield under the same load as the smaller root system. The pull out force for the down slope root exceeded 5 kN, while the extraction force for the upslope root was only 0.33 kN, however, the diameter of the down slope root was 35.33 mm while the diameter of the upslope root was 7.06 mm, giving an extraction force per cross sectional area at the clamp of 8.43 MN/m^2 for the up slope root and 6 MN/m^2 for the down slope root. The tension and compression evident during the cross slope winches is most likely related the root not being at 90° to the direction of winching. The tensile and compressive response of the roots to the movement of the trunk is complex, as a directional force is dissipated throughout the root system in every direction. Research on maritime pines (Stokes *et al.* 1998) has demonstrated that trees subjected to a prevailing wind (static load) have an asymmetric root system to compensate, and improve tree stability.

Although tree winching is an important test to determine stand stability and the propensity of trees to up root during gales, the data does not directly correspond with any slope stability analysis. The uprooting force obtained from destructive winching is the product of stem and root stiffness, soil root interaction, the turning moment of the trunk and root ball, the compressive and tensile strength of the roots and the soil strength. These factors are not readily separated for use as slope stability parameters, but the results are useful as an indirect input to an overall assessment of a vegetated slope. Overturned trees can alter the dynamic of the vegetated slope and allow water into the soil profile, and removal of the roots from the system may reduce the reinforcement contribution *etc*. Therefore, an appreciation of stand stability is necessary to assess the overall stability of a forested slope but tree and stand stability are complex to model and the raw data cannot be directly used for slope stability modelling.

7.4.2 Root Pull Out

Individual root pull out tests were conducted soon after the tree winching tests on two of the three hawthorn trees that were winched (CM 1 and CM 2). One of the winched hawthorn trees (CM 3) was subjected to root pull out testing the following year, along with a tree that had not undergone tree winching (CM 5), as a control. Figure 7.7 illustrates the results from the root pull out testing of all four hawthorn trees.

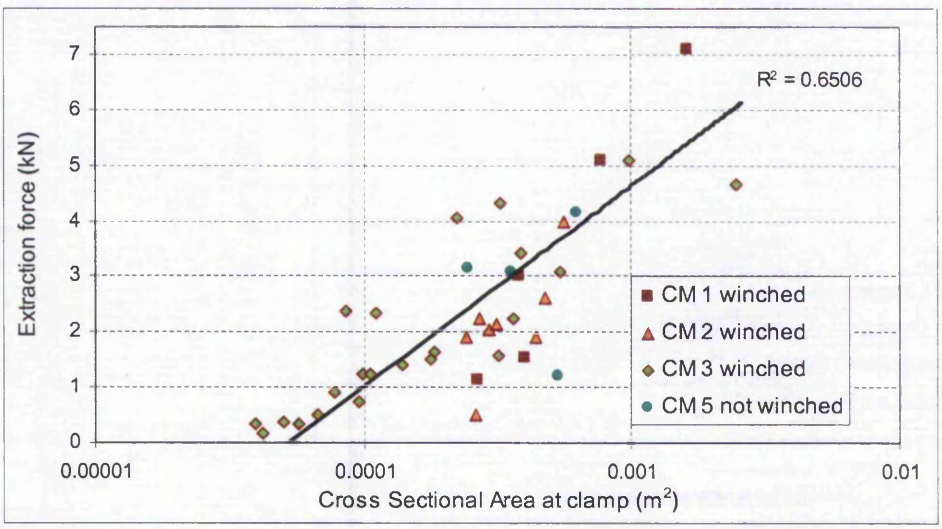


Figure 7.7 Individual root pull out test results for the four hawthorn trees (CM 1 to CM4) on the M11 site. CM1 and CM2 were tested directly after tree winching (September 2002) CM3 and CM5 tested May 2003

The majority of the roots pulled directly after the tree winching tests yield at a lower extraction force than the specimens tested the following year. However, this may be related to the seasonal variability and soil water content rather than the pre test stress application, which was intended to replicate natural wind loading. The average gravimetric water content taken in September 2002 was 27.37 % whereas the result for May 2003 was 22.95 %.

The individual root pull out tests were conducted on the principle lateral roots, some of which had strain gauges attached (Plate 7.11). Therefore, an attempt was made to correlate the pull out and tree winching data, however due to the complex nature of the factors involved in both tests the correlation was not successful. Some of the principle roots were too large for the root clamps so were pulled directly by a sling made of wire cable, which self tightened with tension. The sling was looped over the root and a notch was cut into the root to prevent the cable slipping until the slack was taken up (Plate 7.12). This is not the most suitable alternative to a root clamp as the cable severed the root under high loads and the test had to be reset, however it did prove sufficient for many of the roots beyond the capacity of the large root clamp.

Plate 7.11 Root pull out test with strain gauge attached to root (M11, 2002)

Plate 7.12 Large root of hawthorn gripped by self tightening sling (M11, 2002)

Following the preliminary fieldwork a third root clamp was fabricated. The additional root clamp utilised a similar design to the bolt clamp (Plate 7.13) but is smaller, facilitating its use on smaller diameter roots (from 2 mm to 15 mm). The Allen headed bolts are spaced at 120° around the outer casing making it easier to access the bolts to tighten the clamp. The small bolt clamp facilitated sufficient tightening of the clamp on the root without excessive twisting and disturbance of the root, which was observed with the serrated collet clamp (Section 6.2.1).

Plate 7.13 Screw bolt root clamps used in Spain, 2002

Nylon had been selected for the outer casing of the large bolt clamp to reduce the overall weight of the clamp; however, consistent tightening of the bolts stripped the thread in the casing. Therefore, both the inner and outer casing of the small bolt clamp were fabricated from steel, which prevented the thread wear observed in the nylon outer casing. The large bolt clamp lasted for the duration of the field testing, however, to improve the durability of the clamp the nylon outer casing would require sleeved threads, or the outer casing ought to be fabricated from steel and the inner casing from nylon, as the inner casing only houses the studs and is not threaded.

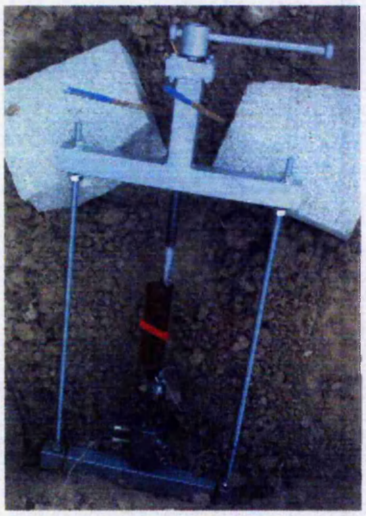


Plate 7.14 Manual root pull out frame with spring balance and small bolt clamp (Spain, 2003)

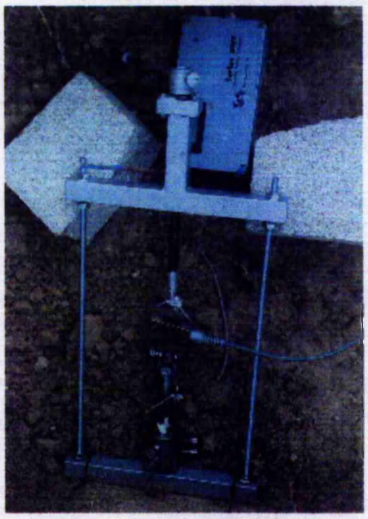


Plate 7.15 Manual root pull out frame with load cell and displacement transducer (Spain, 2003)

Several individual root pull out tests were conducted on the Almudaina site, on *Pinus halepensis* roots that remained in the ground following the large scale *in situ* shear box tests, either intercepting the shear plane or side of the pit. The root pull out equipment used was a manual apparatus, which rather than relying on brut force to pull the root utilised a threaded screw drive in which either a load cell or spring balance could be connected (Plate 7.14 and Plate 7.15).

It was possible to ascertain the displacement by counting the number of turns of the handle; however, a draw wire transducer was connected to the root clamp for several of the tests. Although the root pull out apparatus may vary the most important influences on the extraction force recorded are the root and the surrounding soil. The digital data acquisition may record more data per test and ascertain the peak pull out force with greater precision, but manual logging can give a reliable indication of the pull out force if the equipment is set up correctly.

It is important to avoid setting the apparatus up on top of the underlying root, especially when testing a lateral root, as the reaction of the frame required to conduct the test may contribute to an elevated extraction force. Similarly the draw wire transducer should be secured remote from the rig; again the reaction can pull the apparatus toward the root influencing the displacement data if it is attached to the rig. It is also prudent to fabricate a datum for recording the displacement data manually, rather than relying on the soil surface, as this usually becomes displaced during the test, annihilating the original datum.

Riestenberg (1994) reported three general categories of root failure based on the root morphology, which were correlated to the force displacement relationships. The root pull out results from the tests conducted on the hawthorns on the M11 exhibited all three failure categories reported by Riestenberg (1994), in addition a fourth failure category has been identified (Figure 7.8). All three categories of Riestenberg (1994) show an initial increase in force with little or no displacement, Category I roots are generally long and poorly branched and the initial peak of pull out resistance is followed by a gradual reduction in force. Category II roots maintain the high extraction force and display an abrupt drop in force characterised by generally short highly branched roots. Whereas, Category III produces a force displacement plot with several peaks, reported by Wu *et al.* (1999) as successive tensile failure. The root morphology associated with Category III forks into two major branches (Riestenberg 1994). Many of the failure patterns of the roots tested on the M11 correlated with the three categories of Riestenberg (1994).

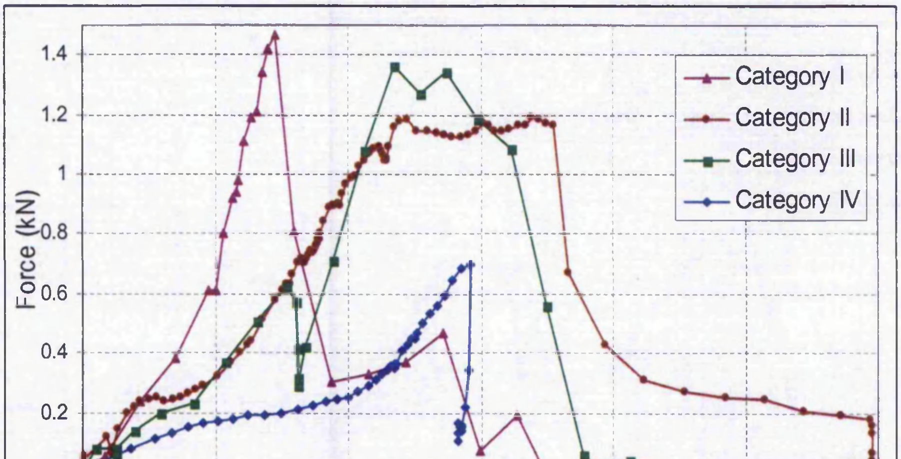


Figure 7.8 Selection root pull out testing results from hawthorn (H3) to illustrate the three failure categories of Riestenberg (1994) plus a fourth category.

However, the requirement for an additional category was also evident. The failure curve of Category IV (Figure 7.8) exhibits a gradual increase in force over a relatively large displacement, rather than the steep increase reported by Riestenberg (1994). This gradual increase in force over a large displacement may be attributed to sinuous or obliquely oriented roots (Figure 7.9), which are straightening during the test.

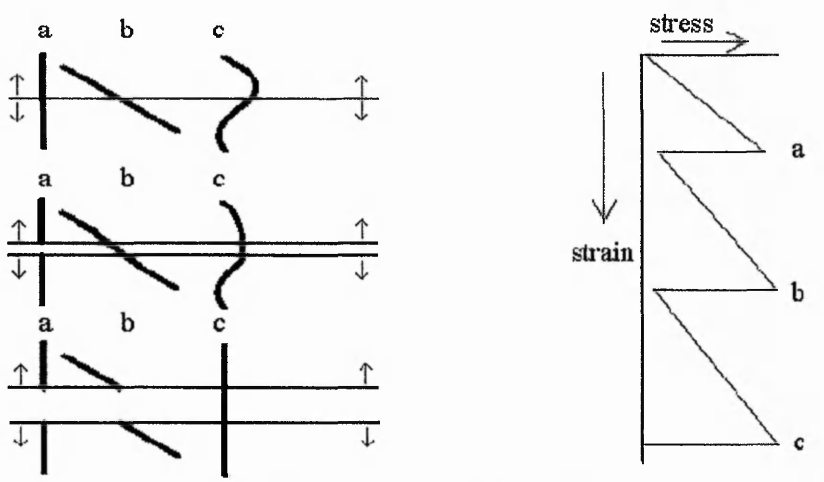


Figure 7.9 The stress strain and failure of a) straight, b) oblique and c) sinuous roots (Krogstad 1995)

Krogstad (1995) reported that straight roots oriented parallel to strain (a) begin to strain immediately and can break, while more sinuous roots (c) or obliquely oriented roots (b) are still straightening out. Roots often change direction so that an initial straight pull out can become oblique during the test, or if one root fails the force is transferred to secondary root resulting in an oblique pull. The sinuosity of roots can also be problematic when analysing the data produced from the root pull out test, as it is difficult to distinguish between extension, elongation and displacement, whereby the root may stretch, straighten out or move from its original position, respectively. Therefore, unless the original position and morphology of the root is known the displacement recorded can only be taken as an indication of strain. It is important to record any supplemental observations during the test and record key elements of the root morphology (such as sinuosity and branching) after the test to elucidate idiosyncrasies within the data. However, failure of a slope will incorporate all the roots at a range of angles to the shear plane, and the maximum reinforcement potential is not the sum of the different failure strengths, but some fraction of this total (Krogstad, 1995).

Hamza *et al* (2005a) are currently investigating the root mechanics during root pull out testing, using Particle Image Velocimetry (PIV) and a variety of different shaped model root analogues. The sequential digital photographs taken during the pull out of root analogues, which are manufactured to provide known mechanical properties, facilitates the measurement of soil and root movement, and the radial and axial strain. Therefore, the effects of root morphology on the load distribution and deformation behaviour can be evaluated (Hamza *et al.* 2005a). Although this procedure can increase the understanding of biomechanics during root pull out testing it is not a technique that can be used in the field, to improve the *in situ* root pull out test. However, the system does provide a way to verify theoretical models of root system anchorage, and will allow a more detailed analysis of the root soil bond and failure mechanics (Hamza *et al.* 2005a).

The maximum pull out resistance obtained from individual root pull out tests can be used to determine the interface friction between the root and soil, or employed directly to characterise the reinforcement potential. However, the root tensile strength, soil root interface friction and the anchorage of the root produced by the embedment length and root morphology are all variables which influence the maximum pull out resistance. Furthermore, the root tensile strength can vary with water content and cell structure, which in turn can be influenced by the environment, creating inter and intra species variability. In addition, the diameter at the point of rupture or at the clamp may correlate well with the extraction force (Anderson *et al.* 1989b; Norris 2005), but either parameter does not determine the true stress distribution before ultimate failure occurs, as the radial strain is unknown (Hamza *et al.* 2005b). The stress distribution is influenced by the root morphology, soil properties and the strain rate of the test, which are unique for each test conducted. Therefore, the root pull out test can only be classed as an index test, and the resistance data obtained should be employed as such when conducting a slope stability analysis to ascertain the contribution of vegetation to slope stability.

7.4.3 *In situ* Shear Box

The mechanical root pull out/*in situ* shear box apparatus was modified following the preliminary fieldwork. The modifications included the fabrication of a split sample box to reduce sample disturbance, also the hydraulic cylinder was replaced with a larger one, and the lever arm was removed. The front steel frame was also modified to house two ground pins rather than one (Plate 7.16), these were set at an angle rather than vertical, to secure the frame and prevent the sample riding up during the test. Although these modifications improved the equipment and quality of the data acquired there was still a concern about the sample size (135 mm^2) being sufficient to represent root reinforcement of anything other than grasses and small shrubs, whose roots are generally confined to the topsoil horizon further limiting the value of the data obtained.

Plate 7.16 Ground pins securing the steel frame (Spain, 2002)

The *in situ* shear box employed during the fieldwork was not large enough to test trees, therefore, small saplings and shrubs were selected, unfortunately, following the *in situ* shear test it was discovered that the root systems of some specimens did not penetrate below the shear plane (Plate 7.17). In this case their potential contribution is considered negligible as the roots are confined to the topsoil. Larger specimens were too big for the shear box (Plate 7.18) and boundary conditions became a consideration. Therefore, it seemed appropriate to employ a larger sample size for testing vegetated slopes. In order to investigate the *in situ* shear box further a large shear box 0.60 x 0. 60 x 0. 40 m was fabricated and trialled on an additional ECOSLOPES site in Almudaina, Spain, where it was possible to conduct *in situ* shear box tests on trees rather than saplings and shrubs.

Plate 7.17 Root system of *P. latifolia* contained within the shear box sample.

Plate 7.18 Limit of sample size evident as *P. halepensis* trimmed to fit into shear box.

The additional field trial was conducted in Almudaina, Spain, where the lack of infrastructure and size of the site made it the most suitable location for the large scale shear box trials. Eight large in-situ shear box tests were carried out on square samples of 0.6 x 0.6 m in plan and at 0.4 m depth to encompass a sufficiently large volume of rooted soil. The soil sample was prepared by excavating the surrounding soil and the shear box casing was placed over the remaining block. The sample was wetted several hours before the shear test to replicate worst case conditions. Concrete blocks were used to apply a normal load and the two normal stresses achieved were 3.3 and 4.1 kPa.

Plate 7.19 Large scale shear box with four sides and cable at front to pull sample (Spain, 2003)

Plate 7.20 Large shear box with two sides, pins on both sides and jack at rear (Spain, 2003)

Two tests utilised the four sided box configuration (Plate 7.19) where the sample is isolated from the surrounding soil and shearing resistance could be mobilised along the basal plane only. For six tests the box had a front and back plate only, so additional shearing resistance could be mobilised along the sides and by any uncut roots extending through the sample. Strain in the adjacent soil was monitored by locating 10 pins on either side of the shear box and recording their start and end positions (Plate 7.20). The shear box was mobilised either by winching from the front or pushed by extending a bottle jack at the back, the shear box procedure for both tests is summarised in Figure 7.10. The winching method was only possible for the four sided shear box configuration, and when there was a suitable tree nearby to winch from. The bottle jack method could be used on either the two or four sided configuration but required a suitable pit wall to jack against. Displacement was recorded with a draw wire transducer attached to the back of the sample. The load was recorded with a load cell for the pulled tests and a proving ring was used for the jacked tests.

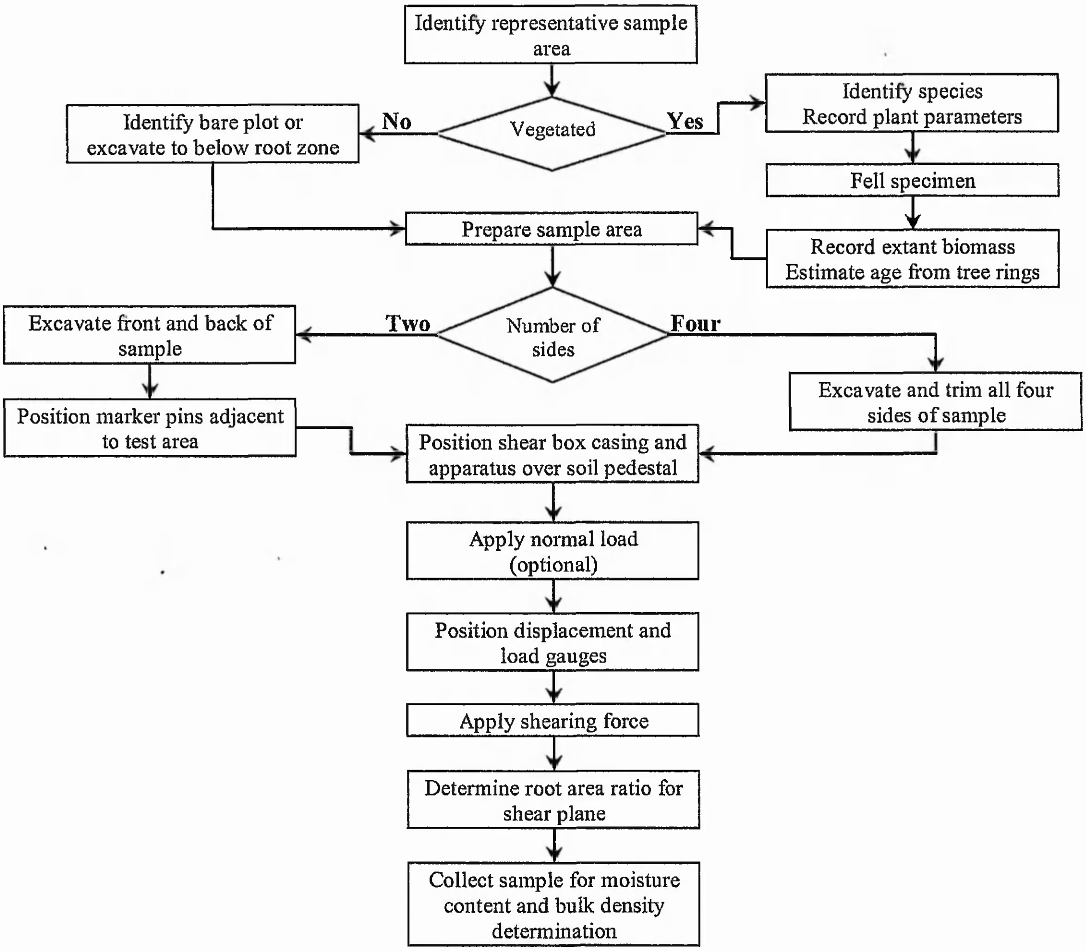


Figure 7.10 Procedure for two or four sided large *in situ* shear box testing employed in Almudaina (2003)

Tilting of the sample occurred during some of the tests, which was minimised by appropriate location of the jack below the centre point of the back plate. The strain rate targeted for testing was 4mm/min. This was considered as suitably slow to prevent the build up of excess pore water pressures within the clayey silt materials tested (van Beek *et al.* 2005). Following each test root counts were conducted at 0.1 m centres down to the shear plane, root counts were also conducted on both side walls after the two sided tests. The results for the investigation conducted on the Almudaina site along with the slope stability analysis and FLAC modelling results have been reported by van Beek *et al.* (2005), and is contained in the appendix.

The large *in situ* shear box facilitated the testing of larger trees, both as a four sided test to ascertain the contribution of roots along the horizontal shear plane and as a two sided test to determine the contribution of lateral roots. However, the large sample size requires a large excavation around the sample and as such may not be the most appropriate test for some sites.

To monitor the long term soil water conditions within the M25 embankment, Delta-T Theta Profile Probe access tubes, 1 m in length, were installed at fourteen positions on the southern slope. The tubes were installed on a grid system within the copse, and a row of three tubes were installed approximately 10 m to the west of the copse within the grassed area, positioned near the crest, centre and toe of the slope. The Delta-T Theta Profile Probe is a capacitance probe and is sensitive to the electrical conductivity of the soil (Delta T 2000), therefore, it was necessary to calibrate the probe to the soil conditions. The theta probe was calibrated against time domain reflectometry (TDR) equipment (by Rens van Beek at the Utrecht centre of Geosciences) using an undisturbed block sample collected from the M25 site.

Soil water within the embankment is dominated by the seasonal variation, with winter and spring exhibiting the highest soil water contents for both the grass and tree covered parts of the slope. Figure 7.11 illustrates the averaged seasonal data for an installation within the copse, and at a similar mid slope position within the grass covered part of the slope. The overall volumetric water content of the soil is considerably higher beneath the trees than the grass cover, especially during the summer and autumn months, which correlates well with the occurrence of desiccation cracks concentrated within the grass covered part of the slope.

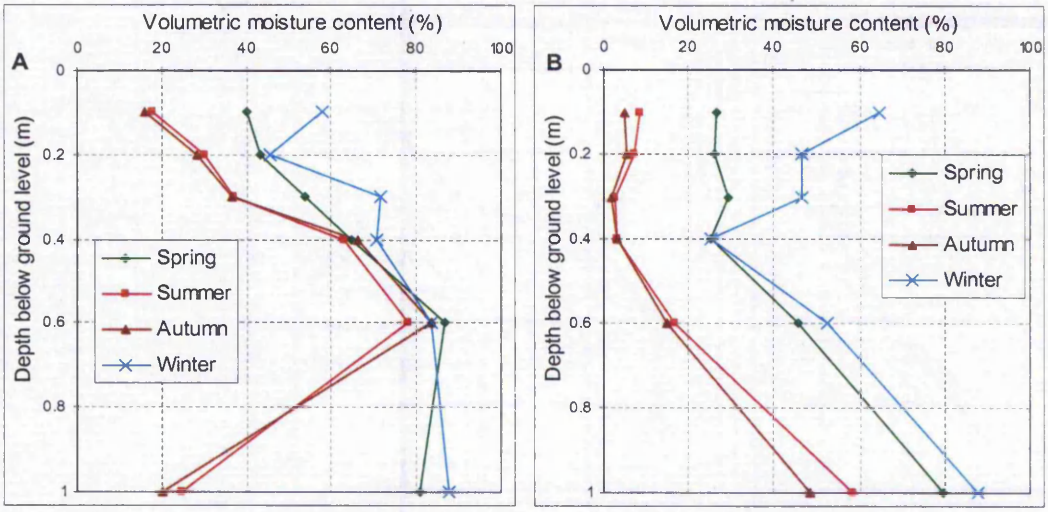


Figure 7.11 Seasonal volumetric water content data for A) installation within the copse and B) installation within the grass area (M25 site)

Water content depletion is greatest during the summer and autumn for both types of vegetation; however, the water content is consistent all year round between 0.4 and 0.6 m b.g.l below the trees (Figure 7.11a), which may be due to hydraulic lift (Burgess *et al.* 2001; Emerman and Dawson 1996). A redistribution of water from further down the soil profile is a feasible assumption being that the water content at 1 m b.g.l. is depleted, and roots were recorded to a similar depth within the copse (Section 7.3.2). Conversely, the maximum water content depletion below the grass covered plot occurs between 0.3 and 0.4 m b.g.l. (Figure 7.11b) indicating the zone of greatest water demand from the herbaceous roots. The similar increase in water content for all four seasons, below the grass cover from 0.6 m b.g.l may be due to abiotic seasonal variability, and therefore, indicate the limit of the root zone.

Suctions were not recorded during the fieldwork, as pore water pressure measurements are considered an integral part of the conventional ground investigation, for which there is a variety of proprietary devices. Research conducted on the effect of vegetation on seasonal pore water pressures on a vegetated slope of London Clay near Newbury, by Clarke *et al.* (2005), revealed that the soil water contents remained almost constant during the summer below 0.6 m b.g.l. while the water potentials increased to between -50 and -70 kPa (Clarke *et al.* 2005), demonstrating the importance of pore water pressure measurements for quantifying the effect of vegetation on slope stability.

In situ falling head tests were carried out on the M25 site to determine the permeability of the soil and ascertain any variation between the grass and tree covered plots. *In situ* tests were conducted in preference to laboratory tests as the sample size of the laboratory permeability test was considered inappropriate because there were several desiccation cracks and weak fissures observed in the soil mass. In addition, the saturated hydraulic conductivity can be influenced by preferential flow paths induced by the root systems, therefore, *in situ* tests were selected to give a representative sample size and minimise disturbance to the root system and soil structure. The holes were manually augured to a maximum depth of 1 m, using a 0.1 m diameter auger. Three tests were conducted within the copse and six tests were conducted in the grassed area due to the presence of desiccation cracks that were anticipated to affect the results, the saturated conductivity determined from each test is given in Table 7.3.

Table 7.3 Saturated hydraulic conductivity from *in situ* falling head tests conducted on M25 site (2002)

Test ID	Grass 1	Grass 2	Grass 3	Grass 4	Grass 5	Grass 6	Copse 1	Copse 2	Copse 3
K_{sat}	4.52^{-7}	3.99^{-8}	N/A	1.30^{-7}	1.81^{-7}	1.97^{-7}	3.05^{-7}	1.05^{-7}	7.89^{-7}

The overall permeability of the soil is very low across the site ranging from 4^{-8} to 8^{-7} m/s. There was no significant trend observed between the copse and the grass covered parts of the site. However, the test provides a crude approximation of hydraulic conductivity as the hole is not cased and relies on the saturated walls remaining stable throughout the test. In addition, the determination of hydraulic conductivity was simplified by assuming isotropic permeability and the employment of a shape factor (Barnes 2000). It was not possible to fill the hole for test 'Grass 3', to allow saturation or any subsequent measurement as it was connected to a fracture of some sort below the surface, therefore, no data was obtained for that test.

7.6 DISCUSSION

The fieldwork conducted provided an opportunity to evaluate some of the techniques deemed appropriate for characterising the vegetation on a slope and quantifying the contribution to shear resistance. General site description parameters are relevant to any site investigation, although climate data for a site is often overlooked; however, climate influences the vegetation and hydrogeological properties of a site both directly and indirectly. Seasonal variability is also an important consideration when characterising a vegetated slope, however, such data should be used in context with the climate data to ensure the conditions monitored are in keeping with those anticipated for that time of year.

Much of a site investigation of vegetated slopes depends on comparative analysis, either of the relationship between vegetated and non vegetated plots or seasonal variation. Therefore, a geotechnical investigation of a vegetated slope must be conducted over a suitable time period, of at least one year, to fully appreciate the impact of the seasonal variability on the vegetation and the subsequent effect that has on the slope. The successful collection of useful data depends on proper planning of the investigation, to synchronise non destructive and destructive sampling, or the allocation of discrete sampling areas that are comparable but do not damage the monitoring plots.

To characterise a vegetated slope it is necessary to ascertain the type of vegetation, its location and distribution. These principles were put into practice on the three sites, the M25 site was divided into deciduous wood (copse) and herbaceous (grassed area) functional types, while the Almudaina site was divided into sparse scrub (mainly herbaceous) and dense cover (containing *P. halepensis*) to facilitate finite element modelling of the slope and vegetation (van Beek *et al* . 2005). In addition, to the extant vegetation identification and distribution, it is necessary to determine the root density and vertical and lateral extent of the roots to ascertain the limit of root reinforcement contribution, which was done successfully by counting the number of roots of a particular size class to calculate the root area ratio. Two methods of segregating the pit surface were trialled and the most useful procedure for a geotechnical evaluation of the root distribution is a combination of the two methods, whereby the roots are counted per strata and a quadrat is used to subdivide each stratum. It is then possible for an engineer to establish the rooting depth and evaluate any zones of reinforcement potential within the soil profile.

The water demand of certain types of vegetation can influence the soil water content and pore water pressure beyond the root zone. Therefore, it is important to understand the characteristics of the vegetation and monitor the water content and pore water pressure of a vegetated slope both within and beyond the root zone, to establish the hydraulic zone of influence. However, the effect of vegetation on the hydrogeology of a slope may be ephemeral. Therefore, it is necessary to conduct seasonal monitoring of the vegetation cover and the water conditions for at least a year, and evaluate the data against climatological information, in case that season was particularly dry.

The botanical investigation phase and water content monitoring conducted on the M25 site facilitated comparative analysis of the seasonal variation of the vegetation cover and the volumetric water content. Seasonal variability of the soil water content was apparent as was the different effect of the two different vegetation types. Suctions were not monitored as part of the field work as pore water pressure measurements are considered an integral part of a geotechnical site investigation for slope stability analysis. However, pore water pressure measurements have been monitored on a vegetated slope of London Clay by Clarke *et al.* (2005) the results of which have demonstrated the sensitivity of suctions to vegetation and seasonal variability, and indicates that pore water pressure measurements ought to be an integral part of a geotechnical investigation of a vegetated slope. For negative pore water pressures to persist into the wet season is not only dependent on the water demand of the vegetation but the infiltration capacity and permeability of the soil along with the amount of interception, intensity and duration of the precipitation events throughout the wet season. Therefore, it is also important to develop a holistic approach to the geotechnical characterisation of a vegetated slope, and thereby determine the meteorological, hydrogeological geotechnical and botanical characteristics of the slope.

Many roots within the soil may undergo a dynamic cycle of die back and regeneration, however, the structural roots are likely to be present within the soil throughout the year. Therefore, root reinforcement is thought to be a longer lasting contribution than the effect vegetation may have on the water content and pore water pressures. Root reinforcement is even reported to continue for a number of years after tree felling, if the stumps and roots are left to decay naturally (Ziemer 1981b), therefore, it is important to determine the mechanical contribution of vegetation. The biomechanical testing techniques employed during the fieldwork have verified that the techniques are suitable to provide an indication of the relative contribution of vegetation to slope stability. Tree winching tests are suitable for assessing the stability of individual trees or stands and their resistance to wind throw, which can affect the long term stability of a slope, while root pull out testing can be conducted to ascertain the root interface friction and extraction force. However, the complex nature of the failure mechanisms, root morphology and stress dissipation associated with the root pull out test render it an index rather than a fundamental test, which is affected by the inter and intra species variability of the tensile strength and the heterogeneity of the soil properties through which the roots permeate.

In situ shear box tests can be used to determine the relative contribution of vegetation to the shear strength of a soil by comparative analysis of both a rooted and a fallow soil. However, fallow soil is not readily available on a vegetated slope within the same horizon as the root permeated soil, making comparative analysis problematic. The selection of a representative sample, size and number of tests is also problematic as the variability of both abiotic and biotic factors such as soil heterogeneity, species cover and individual plant variability, influence the quality of the data obtained, while selection of the test location will influence how representative the data is for comparative analysis. Therefore, a suite of tests would be required to give an indication of any trend apparent between the root permeated and fallow samples, assuming comparable samples may be located for testing.

The number of tests will depend on the size and variability of the site and whether a set of three tests are required to determine the cohesion intercept and internal angle of friction. The increase in shear strength due to root reinforcement is often referred to as apparent cohesion (Coppin and Richards 1990) and an increase in the cohesion intercept c' is assumed to represent root reinforcement for effective stress slope stability analysis (Greenwood *et al.* 2001). However, the determination of the cohesion intercept assumes a linear relationship of the Mohr Coulomb failure envelope and requires predetermined drainage conditions. Unfortunately, the lack of control over the drainage of an *in situ* shear box test is problematic.

To conduct a shear box test sufficiently slowly to facilitate the dissipation of pore water pressures in a low permeability sample would require the test to be conducted over a number of days, which exposes the test to environmental variability such as weather and diurnal changes in temperature. Similarly, the introduction of a preconsolidation stage to ascertain the most suitable strain rate necessary to facilitate drained or undrained conditions will extend the duration of the test and will incur the same variability issues, along with the lack of depth information necessary to calculate the consolidation. The introduction of a preconsolidation stage will not necessarily add value to the *in situ* shear box test as the sample is not confined to a known depth and the heterogeneity within and below the sample of root permeated soil may produce erroneous results. Therefore, the *in situ* shear box test commonly lacks a preconsolidation stage and employs a strain rate that facilitates the execution of the test within a reasonable time frame to minimise external environmental factors, but results in a lack of control of the drainage.

Even though the *in situ* shear box test is acceptable for comparative analysis, with suitable sample location selection, there is still potential for variability within the dataset due to the lack of control of the shear zone depth. The test relies on adequate excavation of the soil pedestal and surrounding soil to facilitate free movement of the shear box during the test. This can result in a pronounced column of soil between the base of the shear box and soil surface, producing an unconfined shear zone. Alternatively, the base of the shear box may run flush with the soil surface, whereby the soil is either confined by the shear box or the surrounding soil, thus creating variability of shear zone thickness between samples. Shewbridge and Sitar (1989) reported that the reinforcement and associated increase in strength are affected by the thickness of the shear zone. A thin shear zone is associated with a large increase in soil strength by reinforcement, while a thick shear zone will produce a low increase in shear strength through reinforcement (Shewbridge and Sitar 1989). Therefore, to produce comparative results in the field it is important to control the thickness of the shear zone.

The small shear box may have less impact on the site but is restricted to testing small specimens of vegetation or individual tree roots at a distance from the tree. However, this may be considered more appropriate as the large diameter roots will fail further along their length at a lesser diameter (Anderson *et al.* 1989b). The large scale shear box is able to test a representative sample size, but this involves the excavation of a large amount of soil, and if a site is small or the ecology quite sensitive it may not be possible to conduct a sufficient amount of tests for statistical analysis, in which case it is important to be able to minimise the amount of testing. Alternatively, it may be considered preferable to collect undisturbed samples of root reinforced soil to test in laboratory apparatus under controlled conditions. Laboratory tests were conducted to characterise the soil, roots and root permeated soil, which are discussed in Chapter 8.

8 Laboratory Investigation

The real voyage of discovery consists not in seeking new landscapes but in having new eyes.
Marcel Proust (1871 - 1922)

Laboratory testing is an integral part of a geotechnical site investigation as it facilitates the determination of various soil parameters. Classification tests are used to characterise the soil, while advanced laboratory testing can be used to determine sophisticated soil parameters required for finite element modelling. Soil classification tests were conducted on samples collected from the M11 and M25 sites following field investigation to characterise the soil and a selection of roots from the M11 site were also characterised by laboratory testing. In addition, undisturbed root permeated soil samples, taken from the M25 site, were tested to determine the strength properties of a root reinforced soil.

The laboratory tests conducted to classify the soil included saturated and dry bulk density, gravimetric water content and the plastic and liquid limits, which were conducted in accordance with the British Standard (BS 1377-2: 1990). The plasticity index and gravimetric water content profiles were also employed to determine the onset of desiccation to illustrate the influence of vegetation on the hydrogeological properties of the soil.

The root tensile strength is an important parameter as it can be incorporated into theoretical reinforcement models such as the one developed by Wu (1976). The stiffness of the root is another important parameter as it can influence the thickness of the shear zone of a root reinforced soil (Shewbridge and Sitar 1985) and can affect the depth of the shear plane (Kassif and Kopelovitz 1968). Therefore, root tensile strength and stiffness testing was conducted, using the direct tension apparatus and the static bending frame to determine the most appropriate test methodology.

The *in situ* shear box test has been a successfully employed to illustrate the reinforcement potential of roots. However, a study of the literature revealed the variability of the *in situ* test apparatus and procedures employed by the various researchers (Chapter 4). In addition, the heterogeneity encountered on site makes comparative analysis difficult, unless a suite of tests is conducted from which a trend may be extrapolated. The amount of testing necessary for comparative analysis may be considered excessive for what is ultimately an index test. Therefore, shear strength determination under laboratory conditions may be the preferred option. Thus undisturbed samples were collected from the M25 for laboratory shear strength determination.

Unconsolidated undrained triaxial tests were conducted on the undisturbed (U100) samples taken from both the copse and the grass covered plots of the M25 site (Section 7.2.1, Chapter 7) to ascertain how useful such a test is to quantify the contribution of roots to reinforce soil. Following each test the sample was split and the roots retrieved to determine any correlation with the recorded undrained shear strength and root density. Unconsolidated undrained triaxial tests were conducted on reconstituted re-compacted clay without the roots for comparative analysis. In addition, laboratory shear box testing was also conducted on undisturbed and remoulded samples. A supplemental laboratory trial was conducted using the small *in situ* (135 mm) shear box, set up in the laboratory to explore the effect of shear zone depth on the peak shear strength.

8.1 SOIL CHARACTERISATION

Laboratory index tests were conducted on the soil samples collected from the M11 and M25 sites to aid characterisation. Small 'undisturbed' core samples (100 cm^3) were used to determine the saturated, bulk and dry density of the soil horizons sampled. While, small disturbed samples taken at 0.1 m centres from the trial pits were used for plastic index and gravimetric water content determination. Unconsolidated undrained triaxial tests were undertaken on the ten undisturbed (U100) samples and shear box testing was conducted on an undisturbed block sample recovered from the M25 site (Section 8.3).

The classification tests were conducted on the disturbed samples, taken at 0.1 m centres from three hand excavated pits on both the cutting and embankment sites, in accordance with the British Standard (BS 1377-2: 1990). Roots were removed from the soil prior to the gravimetric water content and plasticity index determination, to facilitate characterisation of the soil matrix and minimise variability that may be introduced by the heterogeneity of the root inclusions. However, a recent study by O'Kelly (2005) reported that the true water content for organic soils (<60% organic content) corresponded well with an oven temperature of 86 °C. Therefore, if the gravimetric water content of the root soil composite is required an oven temperature of 86 °C is considered more suitable than the 105 °C recommended in the British Standard (BS 1377-2: 1990).

The Atterberg limits tests were conducted on samples in the 'as received' condition, the British Standard (BS 1377-2: 1990) states that wherever possible the test shall be carried out on soil in its natural state, and that with many clay soils it is practicable and shall be permissible to remove by hand any coarse particles present. Consideration was given to undertaking the Atterberg limits tests on the samples retrieved from site complete with the roots. However, when attempting to characterize a natural soil the variability of the inclusions will compound the heterogeneity of the samples and diminish the quality of the results by producing irregularities. Therefore, it was considered prudent to remove roots and coarse particles as recommended in the British Standard, prior to conducting the Atterberg limits tests.

The dry and saturated bulk densities were determined from undisturbed samples taken from each horizon in the trial pits. The density determination utilised proprietary 50 mm diameter steel cylinders, with which an undisturbed core sample is taken and carefully trimmed with a sharp knife to provide a sample of known volume (100 cm^3). After the initial weight was recorded one end of the sample was protected with a fine mesh and stood in a water bath until the sample was saturated. The saturated sample was weighed again and then oven dried at 103 ± 2 °C and weighed again, to provide data from which the bulk, saturated and dry densities may be calculated. The small cores are not considered suitable for stony soils, in which case a large undisturbed block sample should be taken, to minimise the influence of large particles on the density determination, and similar consideration should be taken for a heavily root permeated soil.

Soil classification data, the gravimetric water content profile and liquid limits, obtained to characterise the soil were also employed to determine the onset of desiccation. The natural gravimetric water content and liquid limit can be used to determine the onset of desiccation thus (Crilly 1996):

$$w < 0.4 w_L \tag{8.1}$$

Where:

w = Water content

w_L = Liquid limit

Crilly (1996) states that it is unwise to base an assessment of desiccation solely on this criterion and recommend that the comparison of index properties to gravimetric water content should be used only as a rough guide. Ideally, desiccation would be detected through a profile of the *in situ* pore water pressures in a clay soil (Crilly 1996), which should extend beyond the zone of influence of the roots. Therefore, this indirect assessment for the onset of desiccation may be employed as an initial guide to facilitate the location of monitoring positions.

Figure 8.1 shows the profile for the trial pits excavated in the copse and grass covered area of the M 25 embankment. Figure 8.1a, indicates the onset of desiccation from 0.6 to 1 m below ground level (b.g.l.). This potentially desiccated area corresponds well with the greater root area ratios recorded in that trial pit (see section 7.4.1, Chapter 7). Conversely the gravimetric water content profile and index tests from the trial pit excavated in the grass (Figure 8.1b) indicate the onset of desiccation from the surface to a depth of 0.7 m b.g.l. Again this corresponds well with the root area ratio data, as roots were not recorded below 0.8 m b.g.l. in that trial pit. Therefore, although vegetation may induce desiccation regardless of functional type, the zone of influence of the vegetation may vary with functional type.

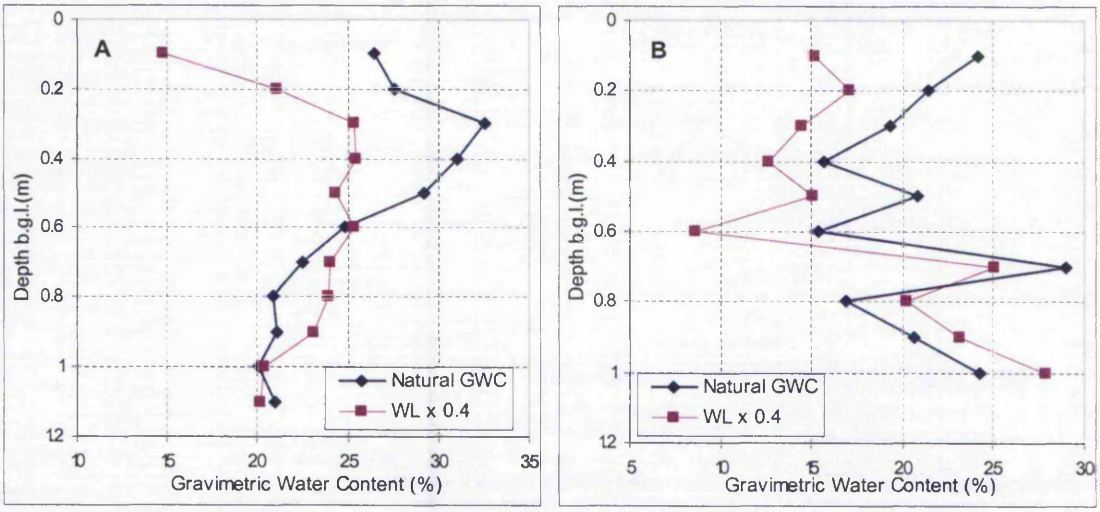


Figure 8.1 Gravimetric water content profile for trial pits excavated on the M25 site in A) the copse and B) the grass covered area.

8.2 ROOT CHARACTERISATION

Tensile strength is the most common parameter used by researchers to characterise roots and the deterioration of strength with root decay (Burroughs and Thomas 1977; O'Loughlin and Watson 1981; O'Loughlin and Ziemer 1982; Stokes and Mattheck 1996;

Watson *et al.* 1999; Wu *et al.* 1979; Ziemer *et al.* 1982; Ziemer and Swanston 1977). Root stiffness and elastic modulus along with the soil root bond and density of roots affect the width and shape of a shear zone, which influences the shear strength (Shewbridge and Sitar 1985). Therefore, root stiffness and elastic modulus are also important parameters that may be used to characterise the behaviour of a root permeated soil. The tensile strength is derived from the peak stress while the modulus of elasticity is the linear relationship between the stress and strain and the stiffness is directly equivalent to the modulus of elasticity within the elastic range of the sample. These root parameters may be ascertained using direct tension apparatus such as the Tensometer or Instron, providing the specimen is adequately secured so that strain may be recorded, to facilitate determination of the stress strain ratio. The three and four point static loading methods, commonly used for beam stiffness determination are alternative methods for the determination of the modulus of elasticity. Both static loading methods can also yield a bending strength if the test is taken to failure.

8.2.1 Direct Tension Testing

Following the site work conducted on the M11 (Section 7.5.), which focused on the hawthorn species, due to its abundance on site and throughout the UK infrastructure. A representative selection of the hawthorn roots were collected and taken to the laboratory where the tensile strength and natural gravimetric water content were determined. Some of the remaining roots were used for further investigation into the affect of water content on tensile strength, conducted by Papa (2003). The tensile strength was determined using a direct tension apparatus the Monsanto Tensometer 20 (Plate 8.1) following which the water content was determined by the constant mass method using an oven set at 80 ^{o}C.

Plate 8.1 Tensometer 20 used to determine tensile strength of some roots collected from M11 site.

Although, Abe and Iwamoto (1986a) rewetted the root specimens prior to tensile strength testing, because the increased flexibility minimised stress concentration and failure at bends and root knots. A study conducted by Papa (2003) reported that root samples that were rehydrated demonstrated a decrease in mean tensile strength, while specimens that lost 5% of their original water content exhibited a higher in tensile strength. However, specimens that were dehydrated further became weak and brittle (Papa 2003). Therefore, the tensile strength is influenced by the water content and to obtain a realistic result the test should be conducted at the natural water content, before water loss occurs or subsequent rehydration is required. If this is not possible any departure from testing at natural water content should be reported along with the results.

Clamping the roots in the Tensometer 20 proved problematic on occasion for a number of reasons. These included bark stripping from the root during the test, resulting in the root slipping from the clamp (Plate 8.2); the self tightening clamps were unable to grip the tapered section of a root sufficiently which would then slip from the clamp. Alternatively, as the strain increased the clamps tightened crushing the root promoting premature failure, similarly the stress concentration at the edge of the clamp often promoted failure at one end, rather than in the centre of the specimen. Genet *et al.* (2005) reported the use of thin slices of cork between the jaws and the root improved the grip, but only 33% of the tensile tests were successful because the roots either failed at the jaws or slipped from the clamp.

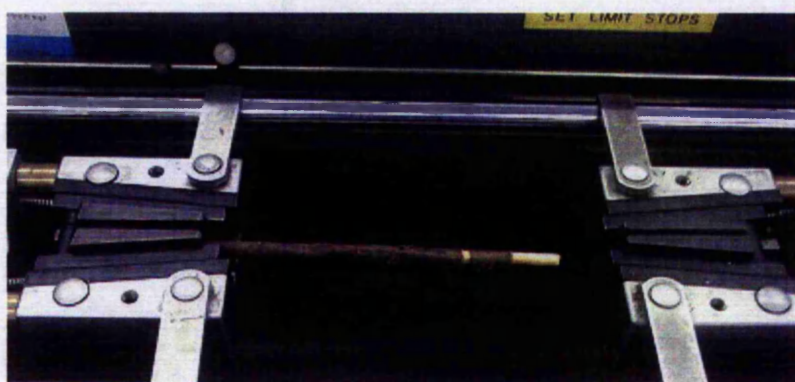


Plate 8.2 Bark stripped off root during tensile strength test.

To resolve these issues the roots were bound with wire and set in resin (Plate 8.3), however, this was not the most suitable solution as the extra stage in the procedure allowed roots to dry out. The drier root proved to be more brittle, sometimes yielding lower results than may be anticipated for roots tested at their natural water content. Hamza *et al.* (2005b) evaluated various approaches to gripping roots including super glue, medical adhesives and fast setting araldite and reported that these either failed to grip or damaged the root tissue by desiccation and heat stresses. Papa (2003) reported a further limitation of the resin method to be a maximum sample diameter of 5 mm.

Samples with a diameter greater than 5 mm often slipped during the test, and shaving the ends to size altered the root properties (Papa 2003).

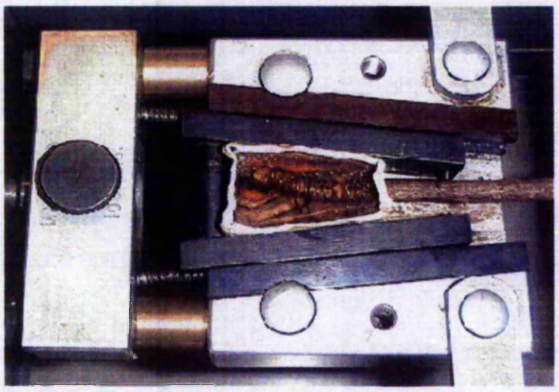


Plate 8.3 Root end bound with wire and set in resin to aid clamping in Tensometer 20 (Papa 2003)

The successful clamping of roots for direct tension testing is an issue that has yet to be resolved. Different researchers have employed various techniques to improve grip from adaptation of the jaws (Genet *et al.* 2005) to the modification of the root ends, either by bark removal (Hathaway and Penny 1975) or the use of resin (Hamza *et al.* 2005b; Papa 2003). Although modification to the root ends may improve the grip of the clamp it may also affect the root properties and impinge on the quality of results. However, if the root ends are not modified with resin there is a propensity for the root to fail near to the clamp due to stress concentration. Therefore, it may be preferable to characterise the root properties using a static loading technique, which does not require the root to be clamped.

8.2.2 Static Bending Tests

The three and four point static load tests, which are used in the timber industry to ascertain strength and stiffness of boards (BS 373: 1957), were trialled as alternative methods for determining both the strength and stiffness of roots. Root analogues were employed to minimise the variability evident in root systems. Balsa and spruce samples were selected for the experiment as they represent two different strength and stiffness classes. To determine the elastic modulus the samples were loaded and unloaded, the incremental loading was then continued to sample failure in both the three and four point loading methods to determine the strength. Similar samples of spruce and balsa were tested in the Tensometer for comparative analysis (Section 8.2.1). Following the initial assessment with the balsa and spruce samples the three point loading test was used in conjunction with the direct tension test on a selection of roots. The modulus of elasticity was determined using the central loading method, within the elastic range of the specimen and then tested to failure in the direct tension apparatus.

The three point test is so named because the test specimen is supported at each end while a static load and displacement gauge are located at the centre of the beam forming three points of contact (Plate 8.4). The four point loading test utilises the same apparatus but the static load is applied to each end of the beam, equidistant from the supporting points (Plate 8.5). The displacement gauge remains in the centre of the beam to record the deflection. The four point loading method is the preferred set up where a more accurate determination of the modulus of elasticity is required (BS 373: 1957) because the bending moment is constant along the test length and does not encounter shear deflection. However, the four point loading method requires the modification of the ends of the test specimen, to prevent the load hangers slipping off the ends during the test. The intermediate stage of setting the root ends in araldite may affect the root properties (section 8.2.1), which can negate the improved accuracy, gained from this methodology, and so does appear to be a preferable method for testing roots.

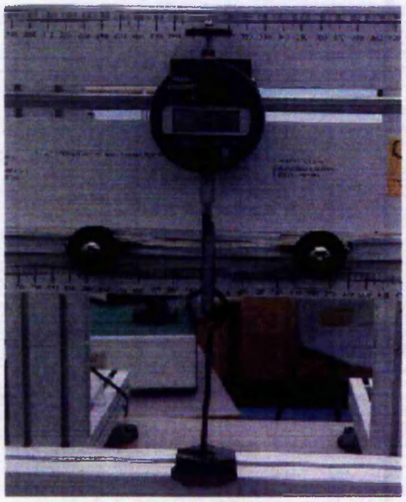


Plate 8.4 Three point loading on balsa wood

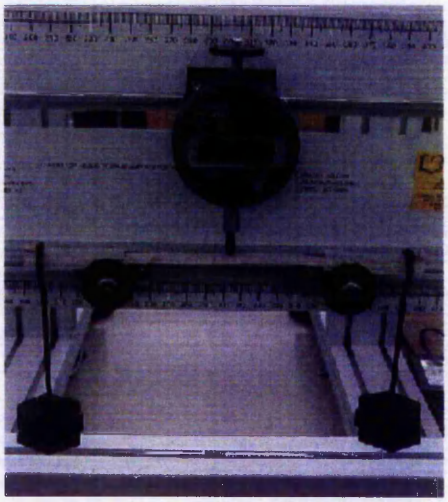


Plate 8.5 Four point loading on balsa wood, sample ends reinforced to secure load hangers.

The three point or central loading test is regarded as sufficiently accurate for testing of timber for the comparison of different species (BS 373: 1957), and does not require a modification of the sample ends. Therefore, root samples may be tested intact at the natural water content, giving the most representative strength and stiffness determination of the three methodologies.

8.2.3 Results

The strength and stiffness of roots may be determined by the three methods discussed above (sections 8.2.1 and 8.2.2). The three methods were trialled using five samples of spruce and balsa wood for each test methodology. Balsa and spruce were used as root analogues to minimise the variability associated with roots to ascertain the most appropriate method for determining the root strength and stiffness. Following the initial trial with root analogues, a second trial was conducted using real roots at three different water conditions; soaked, air dried and at natural water content (55, 5 and 27% gravimetric water content, respectively). Although the four point loading method produces a more accurate determination of the modulus of elasticity (BS 373: 1957) the test was not used in the second trial due to the modification of the root ends necessary to secure the load hangers potentially affecting the root properties. Therefore, the second trial employed the three point loading methodology to determine the modulus of elasticity then tested the sample to failure in the direct tension apparatus to determine a comparative modulus of elasticity and the tensile strength of the roots.

Commandeur and Pyles (1991) conducted tensile strength tests on the roots of Douglas fir, in direct tension. Two types of failure mechanism were observed producing either a sigmoid or hyperbolic stress strain plot (Commandeur and Pyles 1991). The sigmoid curve was associated with sinuous roots, whose tortuosity was calculated over the gauge length of the specimen, while the hyperbolic curve was associated with straighter roots. From these results Commandeur and Pyles (1991) put forward two types of elastic modulus (Figure 8.2), a form modulus (E_F) which is a function of the root straightening and the material modulus (E_M) which is a function of the material properties.

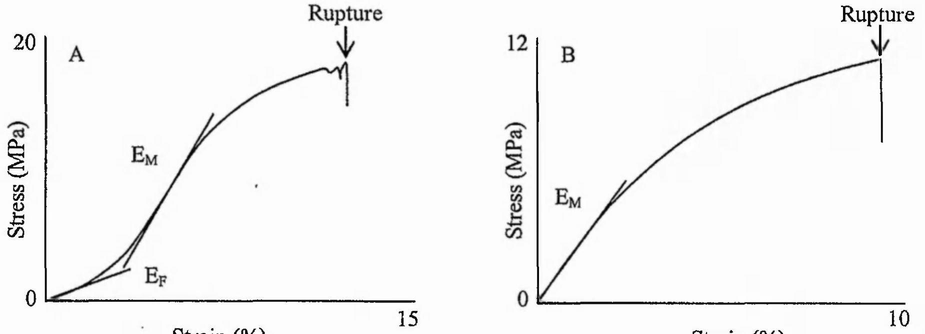


Figure 8.2 Two types of failure mechanism reported by Commandeur and Pyles (1991). A) sigmoid failure of a sinuous root displaying both form (E_F) and material (E_M) elastic modulus and B) hyperbolic failure.

However, the direct tension tests conducted on the straight samples of spruce and balsa wood specimens displayed a similar sigmoid curve (Figure 8.3) to that reported by Commandeur and Pyles (1991). The results indicate that the 'form' modulus can also occur when straight specimens are tested and as such may be a function of the initial tightening of the jaws around the specimen and the subsequent biting of the jaws into the sample. Therefore, the form modulus is not necessarily uniquely correlated with the sinuosity of roots but may also be a function of the test apparatus.

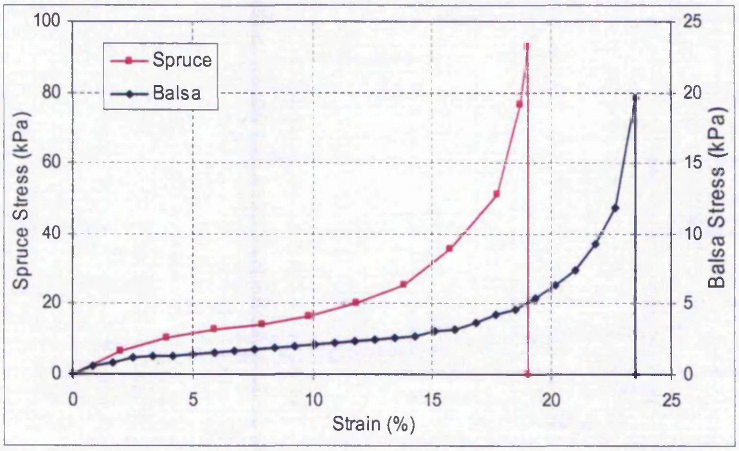


Figure 8.3 Sigmoid failure of straight balsa and spruce samples

The strength and stiffness of the spruce and balsa wood determined by the three and four point loading methodologies produced linear plots (Figure 8.4) rather than the sigmoid or hyperbolic plots reported by Commandeur and Pyles (1991) from the direct tension apparatus. Therefore, both the three and four point methodologies appear to be more appropriate for the determination of the modulus of elasticity.

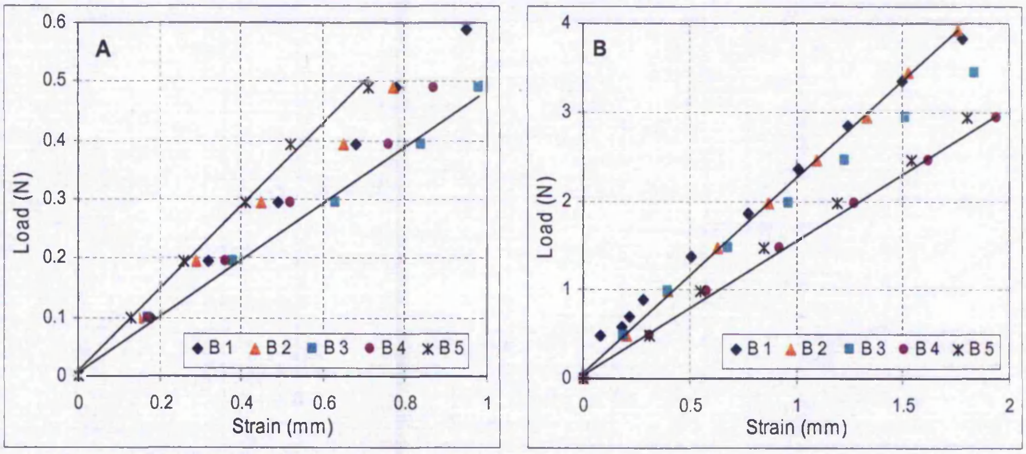


Figure 8.4 Linear relationship of load against displacement for the balsa root analogues from A) the three point loading methodology and B) the four point loading methodology.

The modulus of elasticity is derived from the three point loading methodology data using equation 8.1 (Ryder 1971).

$$E = \left(\frac{W}{\delta}\right)\frac{l^3}{I48} \tag{8.2}$$

Where:

E	=	Modulus of elasticity
W	=	Load applied to the centre of the beam
l	=	Length of beam between supports
I	=	Second moment of area
δ	=	Displacement

While the modulus of elasticity (E) is derived from the four point methodology data thus:

$$E = \frac{RM}{I} \tag{8.3}$$

Where:

R	=	Radius of beam
M	=	Bending moment between the two supports
I	=	Second moment of area

The failure plots for the balsa and spruce specimens facilitated the determination of the form and material modulus of elasticity. In addition, the secant and peak modulus of elasticity were determined along with the tensile strength for the balsa and spruce root analogues tested by direct tension. These data are tabulated along with the results determined from the three and four point methods (Table 8.1). Commandeur and Pyles (1991) reported the material modulus to be almost three times the form modulus for the Douglas fir roots. A similar correlation is evident for the spruce samples, with a three fold increase, however, the balsa wood exhibits an eleven fold increase, indicating that the stiffer samples are less sensitive to the apparatus induced form modulus.

Table 8.1 Mean strength and stiffness data for balsa and spruce determined by the three test methodologies

Test	Direct Tension					3 Point		4 Point	
Sample	E_F MPa (StD)	E_M MPa (StD)	Peak E MPa (StD)	Secant E MPa (StD)	Peak Stress kPa (StD)	E MPa (StD)	Peak Stress kPa (StD)	E MPa (StD)	Peak Stress kPa (StD)
Balsa	0.10 (0.04)	1.12 (0.53)	0.34 (0.07)	0.24 (0.05)	7.48 (2.11)	5.03 (0.70)	20.43 (3.22)	5.99 (1.23)	26.71 (7.41)
Spruce	3.05 (1.72)	9.52 (2.04)	5.12 (1.31)	4.70 (1.46)	86.82 (15.46)	25.17 (2.34)	110.78 (35.09)	24.22 (2.42)	173.59 (15.43)

The three test methodologies yield different results for the two types of wood. The three and four point loading test results are similar while the results from the tensometer are considerably lower. The low results obtained from the tensometer may be explained by the concentration of stresses near the clamp (where most samples failed). To overcome this problem fabricated material samples such as plastics and metals are designed with a narrow section to encourage failure remote from the clamp, and the radii between the narrow section and the ends of the samples are designed to dissipate the stress focus. However, the optimum specimen shape does not naturally occur in roots, and although resin blocks improve the grip and minimise the stress concentration at the clamp, setting the root in resin can affect the properties of the root (Hamza *et al.* 2005b).

The four point test is considered to give the most accurate determination of the modulus of elasticity and strength as the bending moment is constant and there is no shear force within the sample or undue concentration of stresses. However, the four point loading method is not the most suitable method for testing roots as a modification of the ends of the specimens is required to secure the load hangers, which can affect the root properties. The three point test provided a rapid determination of strength and stiffness without the need to modify the ends of the specimens, and the results obtained from the three point loading were similar to those determined by the four point loading. Therefore, the three point loading method was selected for the subsequent trial on real roots. However, because the direct tension test is commonly used for the determination of root tensile strength the three point loading method and direct tension test were used in combination to determine the strength and stiffness of a selection of roots at three different water conditions.

Nineteen roots were selected to be tested in the second trial, to minimise variability straight roots of similar diameter were selected. The roots were separated into three groups, six roots were soaked for 48 hours and six roots were air dried for 48 hours while seven roots were tested soon after harvesting, to represent the natural water content. The soaked samples had an average gravimetric water content of 55%, whereas the air dried specimens had a gravimetric water content of 5% and the natural specimens had a gravimetric water content of 27%.

The elastic modulus of the roots was determined by the three point loading method and then tested to failure in the direct tension apparatus. The three point loading produced linear failure plots from which the elastic modulus was determined while the failure plots from the direct tension test exhibit the sigmoid and hyperbolic curves (Figure 8.5). The two extreme water conditions (soaked and air dried) illustrate the influence of water content on the root strength and stiffness. The soaked samples (Figure 8.5a) fail at higher stress and strain values than the air dried roots (Figure 8.5b). The drop in stress prior to failure of Root S4 (Figure 8.5a) was coincident with the cortex of the root failing prior to the stele failing shortly after.

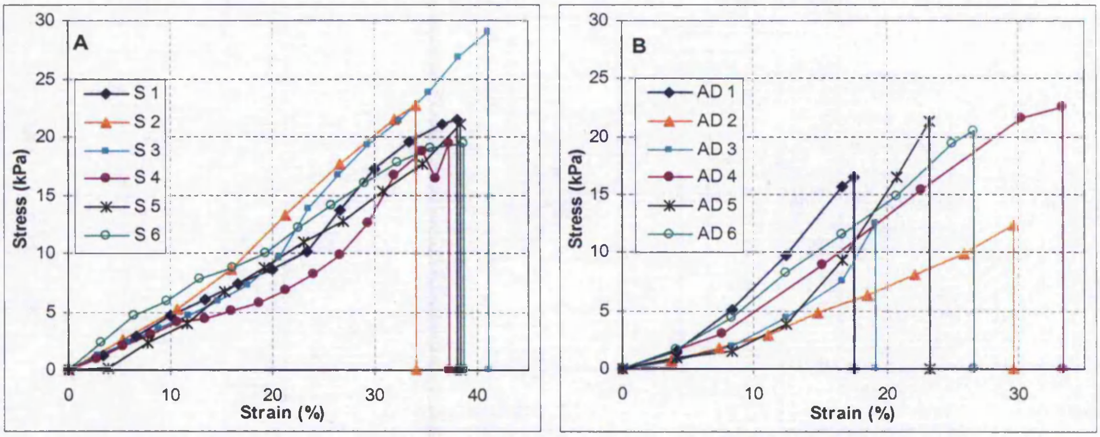


Figure 8.5 Stress strain plots for A) soaked roots and B) air dried roots tested by direct tension

The results obtained from the tensometer can be influenced by the quality of grip the clamp has on the sample, which in turn is affected if a root is tested with the bark intact or if the root is tapered inversely to the clamp. Commandeur and Pyles (1991) tested roots with and without bark and reported that removal of the bark was not shown to affect the modulus of elasticity of the Douglas fir roots. However, they removed the bark at the edges of the intact samples to facilitate clamping so they did not have a pristine sample set for comparative analysis from which to draw this conclusion. It is difficult to study the bark- stele -clamp interaction as leaving the bark intact can impinge on the quality of the grip as observed when testing the hawthorn roots (Plate 8.2). Hathaway and Penny (1975) commented that the overall diameter of the root cannot be used as a reliable indicator of tensile strength as the cortex of some species is very weak. Therefore they put forward that it is preferable to ascertain the amount of stele present and its specific gravity, and only conducted direct tension tests on the stele of roots (Hathaway and Penny 1975). However, the cortex is the part of the root that is in direct contact with the soil and as the weakest part of the system is an important parameter as it can influence the root pull out resistance.

Although, Hathaway and Penny (1975) stripped the roots of their cortex, air dried the stele and set the ends in resin it has since been reported that the change in water content can influence the results (Papa 2003). The results for the roots at natural water content fell between the two end groups as anticipated (Table 8.2). The root stiffness increased with reduced water content while the tensile strength increased with water content. Papa (2003) reported a loss of tensile strength for rehydrated samples rather than the increase exhibited in this investigation. However, the root samples tested during this investigation were soaked immediately and did not suffer dehydration. The loss of strength may be associated with dehydration, which is not regained by subsequent rehydration. Therefore, it would be prudent to store samples in a moist environment to prevent dehydration prior to laboratory testing, if the tests can not be conducted while the specimens are still fresh.

Table 8.2 Mean stiffness and tensile strength data for the three root sample groups

Test	**Direct Tension**						**3 Point**
Sample	E_F MPa (StD)	E_M MPa (StD)	Peak E MPa (StD)	Secant E MPa (StD)	Strength kPa (StD)	Strain (StD)	E MPa (StD)
Soaked	0.37 (0.05)	0.81 (0.21)	0.59 (0.08)	0.60 (0.10)	22.25 (3.59)	37.21 (2.32)	0.67 (0.23)
Natural	0.28 (0.07)	0.87 (0.35)	0.67 (0.12)	0.71 (0.15)	20.41 (3.21)	30.82 (5.12)	0.86 (0.14)
Air Dry	0.30 (0.12)	1.02 (0. 38)	0.73 (0.19)	0.74 (0.21)	17.65 (4.48)	24.94 (6.11)	2.18 (0.75)

The material and secant modulus of elasticity obtained from the direct tension data correlate reasonably well with the three point loading determination for the soaked and natural samples. However, the direct tension tests of the air dried samples yielded approximately half the *E* value determined from the three point loading methodology, indicating a disparity in the results from the two procedures.

The potential stress concentration near the clamps and the propensity for the self tightening jaws to damage the root ends amounts to the direct tension test not being the most suitable apparatus for root characterisation. However, it is currently used for root characterisation (Genet *et al.* 2005; Norris 2005; Papa 2003) and does yield results that may be incorporated into a theoretical model and may be used as long as the limitations of the test are appreciated. To successfully measure the strength and stiffness of a root specimen in a direct tension apparatus a sensitivity analysis is required to ascertain whether stress concentration in an unmodified specimen is more significant than change in water content. Alternatively, the static loading test may be a more appropriate technique for determining the elastic modulus of straight or sinuous roots.

Norris (2005) reported the tensile strength of the hawthorn roots from the M11 to be 15.5 ± 6.8 MPa, and stated that the pull out stress recorded for the hawthorn roots to approach 50-70% of the tensile strength. This is interesting because the root pull out strength was anticipated to be greater than the tensile strength, due to the interaction with the surrounding soil, such as interface friction, obstructions and overburden. The higher tensile strength may be explained as a function of the sample size, because the samples used for the tensile strength tests were of a standard length (approximately 150 mm), therefore, the propensity for weakness is less than for the entire root length, which is tested *in situ*. However, the difference may also be explained by the disparity of comparisons. The pull out stress was calculated from the cross sectional area of the root at the clamp rather than the break points, which may have a significant effect on the result when considering a tapered or branching root. The tensile strength is derived from the failure cross sectional area, which would correspond more readily with the cross sectional area at the break points rather than the cross sectional area at the clamp. In addition, the strain rate may also affect the results, so unless the laboratory tests were conducted at a similar rate to the *in situ* pull out tests the evaluation is not comparing like for like.

Unfortunately, the additional loading, required to fail the samples, deflected the beam beyond the range of the displacement gauge so it was not possible to record the complete stress strain curve to facilitate direct comparison with the direct tension methodology. In addition, the maximum load at failure is only as precise as the increment of loading, which was between 10 and 50g. However, proprietary systems are available to improve both the displacement and load increment facilitating continuous recording.

8.3 SOIL ROOT COMPOSITE CHARACTERISATION

Abe and Iwamoto (1986b) dismissed the triaxial test because the sample size was too small to shear tree roots in a soil, which justified the requirement for *in situ* shear box testing. However, the *in situ* shear box test is not necessarily an ideal solution due to the intrinsic variability, associated with both the test methodologies implemented and the apparatus employed. The *in situ* shear box test is problematic as the drainage and shear zone thickness can not be controlled. The 100 mm diameter sample size may be insufficient for large tree roots but the test may still be suitable for soil containing fine roots. Therefore, the triaxial test was revisited as a laboratory method for testing root permeated soil, using 'undisturbed' samples collected from the M25 site.

In addition, one large block sample was taken from the M25 to be tested in the laboratory shear box, to provide an alternative method for the assessment of root reinforced soil. The variability evident within the natural 'undisturbed' samples retrieved from the M25 site led to a laboratory trial utilising the 135 mm *in situ* shear box set up in the laboratory to investigate the influence of shear plane thickness and root density on shear strength.

8.3.1 Unconsolidated Undrained Triaxial Testing

To ascertain whether triaxial testing may give an indication of the contribution of roots to reinforcement, unconsolidated undrained triaxial tests were conducted in accordance with the British Standard (BS 1377-7: 1990), on ten U100 samples taken from the M25 embankment site. Following shearing each sample was split to enable root and water content determination. The tests gave an apparent cohesion intercept (c') of 31 kPa and an apparent angle of internal friction (ϕ') of 24° with an average root area ratio of 0.15%. Although sample collection allowed a set of shear box tests to be conducted under laboratory conditions, the size of the sub samples retrieved is possibly not appropriate for testing root reinforced soil.

The unconsolidated undrained test was selected to represent the *in situ* testing that has been undertaken. Therefore a low cell pressure of 20 kPa was chosen to replicate the shallow nature of the root zone and the *in situ* test conditions. Although, effective stress testing would be more appropriate for slope stability analysis, the complex nature of the drainage pathways created by the presence of roots within the soil and the potential for volume change renders this technique a subject for further investigation. The initial investigation was to ascertain whether the 100mm diameter triaxial size was suitable to determine the root reinforcement within some naturally occurring samples. Because root reinforcement is only apparent when comparing both root reinforced and non rooted samples, the results from the undisturbed samples were compared to the results of control samples.

The control samples were reconstituted and remoulded to a representative dry density and gravimetric water content, without root inclusions. The gravimetric water contents determined from the undisturbed samples ranged from 15.95 to 28.86% and the dry densities ranged from 1.43 to 1.75 Mg/m^3, therefore, the remoulded samples were fabricated within this range. Following the triaxial tests the undisturbed samples were split for root characterisation, a sub sample was taken for the determination of gravimetric water content (BS 1377-2: 1990). The root assessment analysis took three forms number, volume and biomass, the roots were separated from the soil by wet sieving and the roots were then divided into a size class and counted (Plate 8.6). The volume of roots for each size class was determined by water displacement using a graduated cylinder; finally, the roots were blotted dry and weighed to determine the biomass.

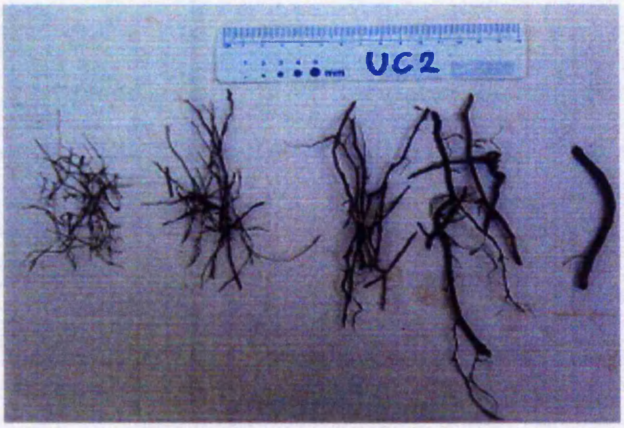


Plate 8.6 Roots taken from a U100 sample following the UU triaxial test. The roots were divided into size classes used on site (Chapter 7); <1 mm, 1-2.9 mm, 3-5 mm and >5 mm

A membrane correction was applied (BS 1377-8: 1990) and the results for the triaxial testing are summarised in Table 8.3. The average undrained shear strength obtained from the control samples is one third greater than the shear strength of the rooted samples either from the copse or grass plots.

Table 8.3 Unconsolidated undrained triaxial test results.

Sample plot	Test ID	S_u (kPa)	GWC (%)	Dry density (Mg/m^3)	Root density (kg/m^3)	Mean S_u (kPa) (StD)	Mean GWC (%) (StD)	Mean Dry Density (StD)	Mean Root Density (StD)
Grass cover	UG1	43.08	15.95	1.75	3.50	35.04 (7.27)	22.56 (4.36)	1.60 (0.11)	3.74 (2.08)
	UG2	26.85	27.46	1.50	7.30				
	UG3	34.97	20.94	1.69	3.06				
	UG4	28.85	24.49	1.55	1.88				
	UG5	41.46	23.95	1.52	2.97				
Copse	UC1	22.31	28.86	1.43	13.94	34.34 (9.39)	25.37 (2.35)	1.48 (0.05)	13.37 (11.15)
	UC2	34.98	25.40	1.54	3.01				
	UC3	48.41	22.70	1.53	7.13				
	UC4	31.31	26.07	1.45	10.83				
	UC5	34.70	23.84	1.47	31.92				
Control	LC1	42.45	24.93	1.59	0.00	45.95 (4.95)	22.75 (3.08)	1.62 (0.04)	0.00
	LC2	49.46	20.57	1.65	0.00				

The results may indicate that the roots do not reinforce the soil but actually reduce the shear strength. The weaker results obtained for the 'undisturbed' samples may be a function of sample disturbance prior to, during, or after sampling, that was not experienced by the reconstituted remoulded samples. Alternatively, the reconstituted re-compacted samples may not be directly comparable with the natural 'undisturbed' samples, despite the gravimetric water content and dry density being within range. One possible explanation is a different structure of the 'undisturbed' root permeated samples compared to the reconstituted re-compacted fallow samples, even though the water content and dry density are within range.

The compaction methodology employed a standard 2.5 kg rammer dropped 300 mm (BS 1377-4: 1990) and the sample was compacted in three layers. The 50 mm diameter foot of the rammer remoulds the sample during compaction producing a stronger sample than would be achieved through full surface plate compaction (Frost 2000) and natural samples containing discontinuities. Discontinuities occurring in the 'undisturbed' samples may be a function of the sampling technique or mechanisms that occurred *in situ* prior to sampling such as the placement of the embankment material forming preferential slip planes, previous instability within the area sampled or the occurrence of fissures or desiccation cracks.

An initial comparison of the 'undisturbed' samples grouped the results from the two plots of different vegetation cover. The root density was calculated from the biomass and sample volume, the grass plot samples yielded a mean biomass of 3.74 kg/m^3 compared to 13.37 kg/m^3 for the samples from the copse. Although, there is a significant difference in root density between the copse and the grassed plot, this does not appear to have influenced the undrained shear strength as the mean S_u from the copse is 34 kPa compared to 35 kPa for the grassed plot with significantly less root biomass. However, the variability in gravimetric water content and dry density within the ten samples may mask any correlation between root density and undrained shear strength.

Comparison of two samples from the grassed plot with similar gravimetric water contents and dry densities (UG4 and UG5, Table 8.1) revealed a 44% increase in undrained shear strength for a 58% increased root density. Similarly, samples UC2 and UC3 taken from the copse show a 38% increase in undrained shear strength for over double the root density. However, sample UC5 yielded a similar undrained shear strength to UC2 with approximately ten times the root density, while UC4 yielded a lower undrained shear strength than UC2 although it contained 3 times the root density of UC2.

The most likely explanation for the reduction in shear strength between the densely rooted samples and the sparsely populated samples, from the copse, is sample disturbance that most likely occurred during sampling. A steel cutting shoe and cap were attached to either end of a plastic U100 tube; the assembly was kept vertical by an adapted tripod, and driven into the ground with a hammer. Sample UC1, which yielded the lowest shear strength (22 kPa), was taken from the copse area and had a couple of medium sized lateral roots that were cut manually because the cutting shoe was not sharp enough to progress through the root, and the root formed an obstruction. Therefore, movement of the lateral roots caused by the cutting shoe being driven down on to the root but not cutting through it would loosen the sample. The subsequent sample disturbance was probably sufficient to reduce the shear strength significantly.

Sample UC3 yielded the highest undrained shear strength (48 kPa), although it had fewer roots than the majority of samples from the copse. Sample UC3 did not contain any roots over 5 mm diameter, and so suffered less sample disturbance associated with root movement. Similarly, the samples from the grass plot did not contain roots over 5 mm diameter (Figure 8.6) reducing the potential internal disturbance associated with root movement, which may account for the similarity in mean undrained shear strength obtained for the two sample plots. Although the total number of roots counted from the samples taken from the copse yielded a similar total number to the samples taken from the grass plot (Figure 8.6), the number of the roots within the various size classes differed. The samples taken from the copse contained more of the larger roots than were found in the samples from the grass plot, which corresponded to a greater root density recorded for the copse samples.

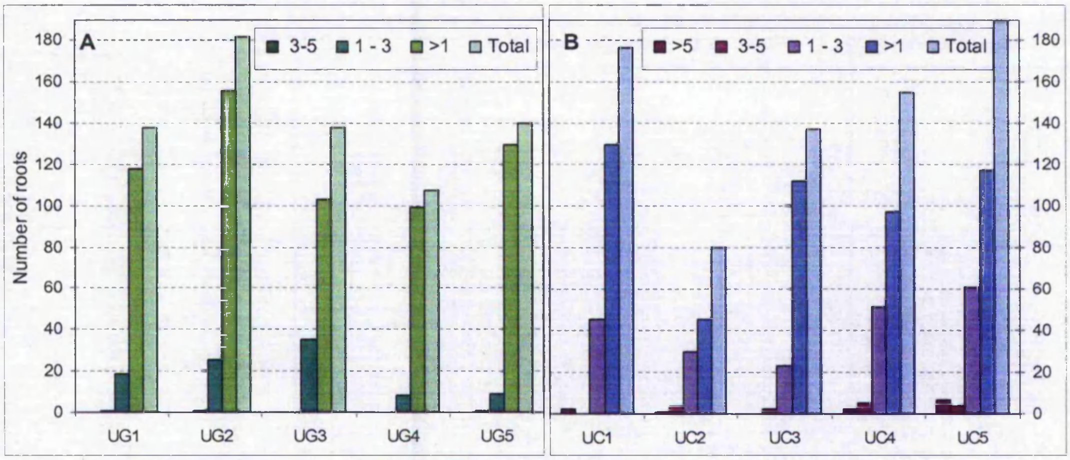


Figure 8.6 Root counts for the ten undisturbed samples taken from the M25 site.
A) Samples taken from the grass covered plot (UG) and B) samples taken from the copse (UC)

From this preliminary investigation it is evident that the sample size is problematic from a sample disturbance aspect, which may be addressed by a more careful sampling procedure. Sample disturbance can be more noticeable at lower cell pressures such as the 20 kPa chosen for this suite of tests, and it may be preferable to select higher cell pressures, however, this necessitates a trade off of representative confinement of shallow samples. Sample disturbance may be reduced with the use of a sharper cutting shoe or by excavating around the sample prior to driving it into the ground, as done with the *in situ* shear box preparation. Driving the sample tube was selected in preference to the excavation methodology because it was considered to best represent samples obtained from percussion drilling, as window sampling and cable percussion are common techniques for geotechnical ground investigation. Therefore, it was important to assess the validity of this methodology. However, it is apparent that samples retrieved from percussion drilling techniques, such as boreholes and window samples, are useful for vertical root distribution data, but not for root reinforcement determination unless the sample only contains fine roots which are readily cut by the cutting shoe, minimising internal disturbance associated with root movement. If root reinforcement is to be determined by triaxial testing, high quality manually excavated samples should be obtained, whereby the roots are trimmed around the sample prior to the sample shoe progressing into the soil to minimise sample disturbance related to root movement within the sample.

8.3.2 Shear Box Testing

A large undisturbed soil block sample was taken from the M25 site to facilitate laboratory shear box tests. The sample was carefully excavated, wrapped in cling film and transported to the laboratory. The roots contained within the block rendered sub sampling difficult, however, a set of three samples were retrieved and trimmed to 60 x 60 x 20 mm. The *in situ* falling head tests conducted on the M25 site indicated that the root permeated soil had a permeability of between 2.4^{-3} and 4.8^{-2} mm/min, therefore, the strain rate of 1.2 mm/min was chosen for the direct shear box test procedure to determine the undrained shear strength (S_u) of the root permeated soil. Following the shear box tests the roots along the shear plane were counted to determine the root area ratio. The roots within the three undisturbed samples did not exceed 2 mm diameter and the mean root area ratio across the shear plane was 0.29%.

The roots were removed and the soil was then remoulded and tested for comparative analysis of root permeated and fallow soil to determine the relative increase in shear strength. The shear strength envelopes for the root permeated and fallow soil are illustrated in Figure 8.7. The undrained shear strength of the root permeated soil was 31 kPa compared to a S_u of 13 kPa for the fallow soil, which indicates a 2.38 fold increase in shear strength from the root reinforcement, while the internal friction angle was similar for the two soils (43° and 42°, respectively).

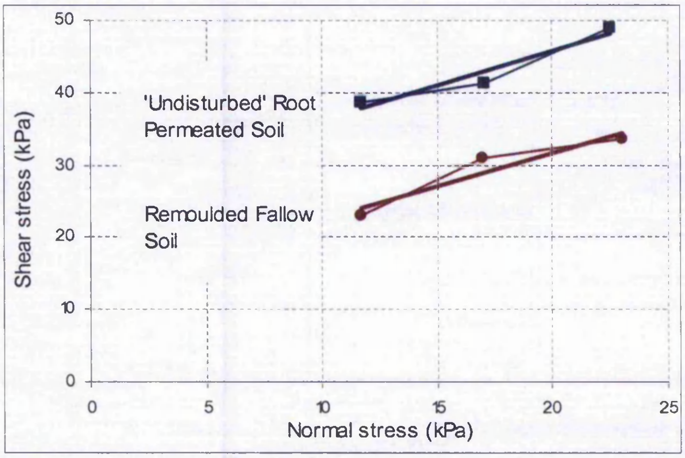


Figure 8.7 Failure envelope of root permeated and fallow soil indicating an increase in the cohesion intercept with root reinforcement, while the internal angle of friction remains unaffected

The results compare well with those reported in the literature, whereby the cohesion intercept is observed to increase with reinforcement while the internal friction angle is relatively unaffected (Coppin and Richards 1990; Endo 1980). However, the results are not directly comparable due to the requirement to remould the soil to fabricate a fallow sample. Attom *et al* (2001) reported that the unconfined compressive strength of undisturbed samples were 1.35, 1.6 and 2.53 times higher than that of soil specimens compacted according to the dynamic, static and kneading procedures, respectively. Therefore, the increase in shear strength observed between the two soils may be associated with a loss in strength of the re-compacted sample compared to the undisturbed sample.

It is feasible to conclude that the increase in shear strength recorded may be a function of both the compaction methodology employed to fabricate the fallow samples and some reinforcement contribution from the roots. However, the displacement curves of the root permeated and fallow soil samples (Figure 8.8) indicate a similar failure mechanism for both soils. The mean horizontal displacements at peak shear resistance are similar, with 6.92 and 5.92 mm for rooted and fallow samples, respectively. The mean vertical displacements are slightly larger for the root permeated soil with dilation measurements of 0.03, 0.09 and 0.12 mm for the undisturbed sample and 0.002, 0.01 and 0.09 mm for the remoulded sample.

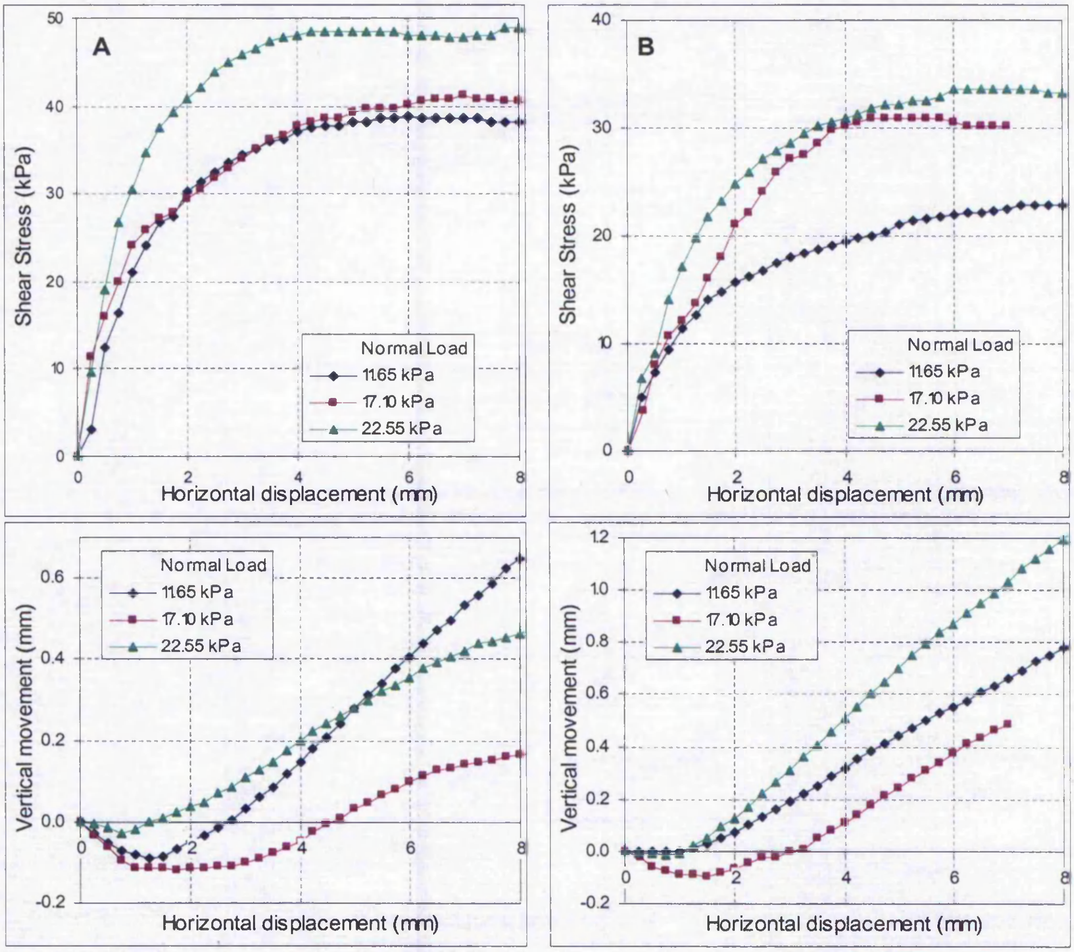


Figure 8.8 Stress strain and vertical displacement plots for A) root permeated soil and B) fallow soil

The results from the five *in situ* shear box tests conducted on the M25 site indicate that the potential root reinforcement is realised at displacements in the order of 17 mm, with the results ranging from 9.57 to 25.10 mm. Unfortunately, the maximum displacement available in the laboratory shear box is only 10 mm and may not be sufficient to mobilise the reinforcement potential of the roots, to give the true reinforced shear strength of the soil root composite.

8.4 SHEAR BOX TRIAL

Variability of the shear zone height was observed while conducting the *in situ* shear box tests during the fieldwork. Shewbridge and Sitar (1989) reported that the reinforcement and associated increase in strength are affected by the thickness of the shear zone. A thin shear zone is associated with a large increase in soil strength by reinforcement, while a thick shear zone will produce a low increase in shear strength through reinforcement (Shewbridge and Sitar 1989). A large dataset would be required to investigate the effect of the shear zone depth *in situ* due to the variability associated with root and soil heterogeneity and field conditions. Therefore, the 135 mm *in situ* shear box apparatus was set up in the laboratory to explore the variability associated with the height of the shear zone. The trial employed a fine and a coarse grained soil and root analogues to minimise variability associated with natural root systems.

8.4.1 Apparatus

The 135 mm *in situ* apparatus was erected in the laboratory and secured to a bench via a wooden frame (Plate 8.7). A second box of similar dimensions to the *in situ* shear box (135 mm) was fabricated to facilitate testing in the laboratory and was secured to the wooden frame (Plate 8.8). The shear plane was varied by raising the steel frame, to which the top box is secured. To prevent the sample riding up during the test (as observed during the preliminary field work, discussed in Chapter 6) the front bar was secured with a clamp to blocks of wood, this set-up also served to take the load of the horizontal frame and runners and kept them level during the test.

Plate 8.7 Laboratory set up of in situ shear box

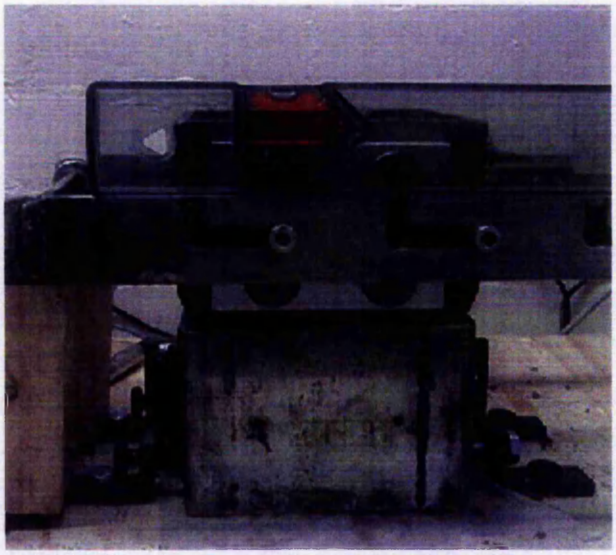


Plate 8.8 Second box secured to base and shear box fixed to runners on frictionless bearings

The system used rolling element bearings along the runners, to minimise frictional resistance. However, there was potential for friction within the system, therefore, the apparatus was trialled by conducting tests without soil samples to ascertain the amount of friction within the system prior to shear box testing of the soil samples. The results ranged from 11.82 to 13.97 N, which yielded an average of 13 N, this equates to a shear stress of 0.58 kN/m^2.

8.4.2 Sample Selection and Preparation

London Clay soil samples collected from the M25 were used in order to relate the laboratory results with field data. Leighton Buzzard Sand was also tested in the 135 mm shear box test apparatus for comparison. Classification tests including water content, Atterberg limits and particle size distribution were undertaken on both soils according to the British Standard (BS 1377-2: 1990). Both the clay and sand samples were oven dried and reconstituted to representative field water contents of around 29% and 5% respectively.

The sand samples were compacted in layers directly in the shear box around the perpendicular root members. However, to enable placement of the reinforcement members within the clay, the sample was compacted in layers into a suitably sized mould. Mitchell (1956) studied North American clays and silty clays and found that the orientation of the clay particles in relation to the orientation to the applied stress distribution has a marked influence on the strength of the soils. Therefore, the tests were conducted with the layers vertical and parallel to the shear plane to control anisotropic behaviour during the test.

In the absence of a suitable proprietary mould the 'Springbox' mould and compaction jacket (Plate 8.9) was used to compact the sample as it produced a sizeable clay block that could be extruded and then trimmed to the relevant size for each shear box test. The sample was left for 24 hours in accordance with the British Standard (BS 1377-4: 1990), to allow any excess pore water pressure to dissipate. The sample was then cut to size using either the 60 or 100 mm cutting shoe or the top box of the 135 mm apparatus, which was designed to perform as a cutting shoe and sample box for the *in situ* test (Plate 8.10).

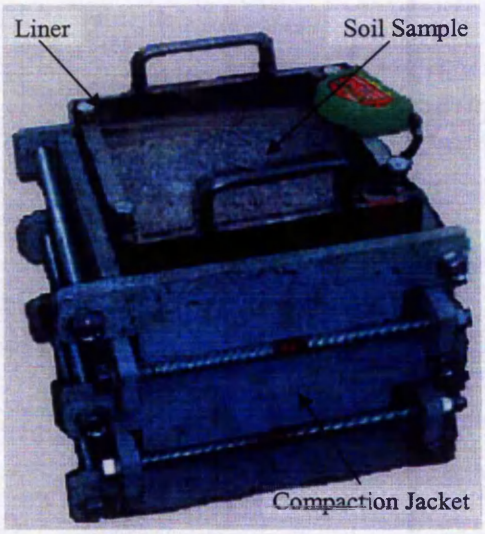


Plate 8.9 Springbox liner and compaction jacket (Edwards *et al.* 2004)

Plate 8.10 135 mm shear box used to trim clay block to size

The laboratory trial employed root analogues of balsa to minimise the variability associated with real root systems. Bailey (2000) reported that reinforcement crossing the mechanically induced shear plane, perpendicular to the shear force, gave similar reinforcement to randomly orientated reinforcement, which is anticipated to be more representative of a natural root system that encounters a slip plane in an overall random orientation. Therefore, the wood was equally spaced across the sample perpendicular to the shear zone. The number of reinforcement members included within the samples was varied to represent root area ratios, of 0.17 and 0.5%

8.4.3 Results

Sample duplicates (of the same water content and dry density) were tested to investigate the sensitivity of the peak shear resistance to the gap between the base and top box. Each sample of the duplicate pair was tested with a shear zone of either 1 mm or 15 mm, the results are illustrated in Figure 8.9. The London Clay samples that contain no reinforcement plot close to, but below the line of equality, while the samples with reinforcement border on the 10% margin, below the line of equality, indicating that the height of the shear plane influences the peak shear strength. Similarly, the Leighton Buzzard sand sample with no roots and a root area ratio of 0.17% plotted within the 10% margin of equality. While a root area ratio of 0.5% in the sand was significantly affected by the wider shear plane as the peak shear stress for the wide shear plane was approximately half the value of that recorded with the narrow shear plane. Therefore, the

London Clay samples are less sensitive to the height of the shear plane than the Leighton Buzzard sand samples.

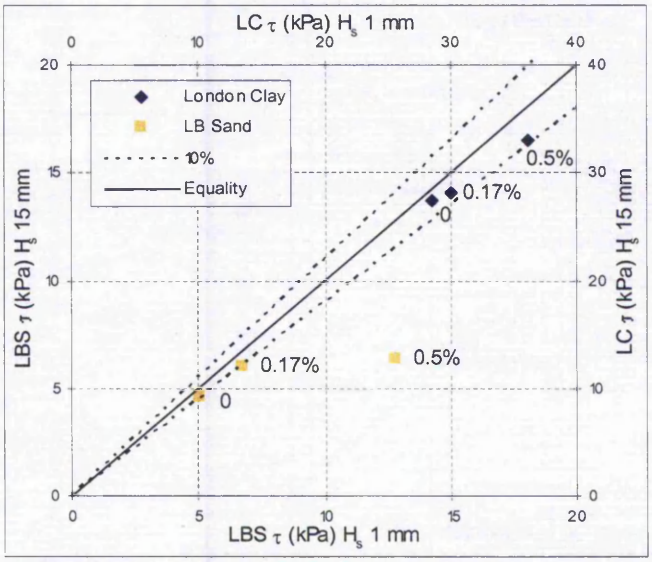


Figure 8.9 Peak shear strength results for the London Clay and Leighton Buzzard Sand for a shear zone height (H_s) of 1 and 15 mm. Samples contain no reinforcement and root area ratios of 0.17 and 0.5%

From this study it may be assumed that the results of the *in situ* tests conducted in the London Clay were not adversely affected by the variability of the shear plane. However, if *in situ* shear box tests are conducted on a granular material the height of the shear zone will influence the results and may even negate the reinforcement contribution of the roots. Therefore, it is necessary to control the height of the shear plane to minimise variability within the results. This can be achieved by the use of a base box fabricated to the same dimensions as the top box, which could be progressed into the soil before the top box producing a uniformly confined column. The use of the two boxes could also protect the sample during the set up of the apparatus if there was the facility to secure them as one unit prior to testing as illustrated in Figure 8.10.

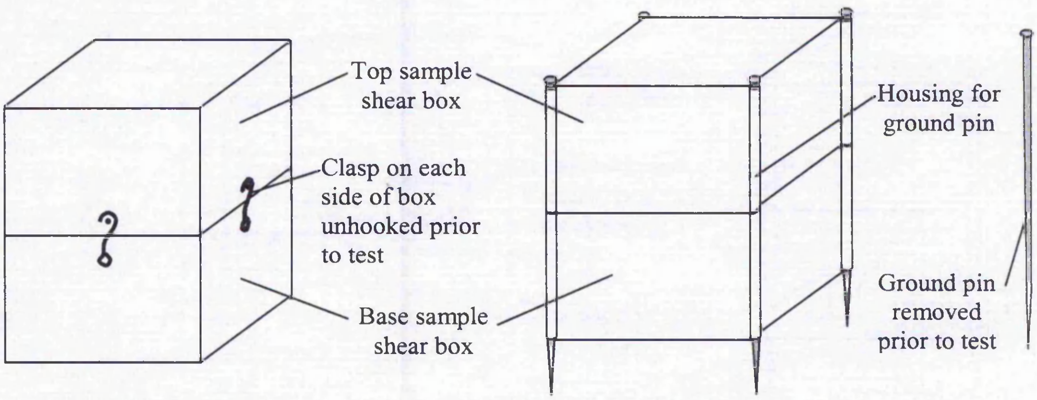


Figure 8.10 Two designs to secure the base and top boxes to facilitate control of the mechanically induced shear zone height and protect the sample during apparatus set up

8.5 DISCUSSION

Soil classification testing was conducted on samples collected from the M11 and M25 sites to characterise the soil. Root characterisation was also conducted on hawthorn roots collected from the M11 site. Ten undrained triaxial tests were conducted on U100 samples collected from the M25 site, and the split U100 samples were used to ascertain the root content and water content within the copse and grassed area. A set of laboratory shear box tests was also conducted to assess the root reinforcement using an undisturbed block sample collected from the M25 site. In addition a trial was instigated to investigate the influence of shear zone height on peak shear strength, following the observation of shear zone height variability during the *in situ* shear box testing.

Although direct tensile apparatus may be used to determine both the root tensile strength and stiffness, the problems encountered with clamping the roots can affect the results obtained. Stress concentration at the clamp can promote premature failure near the clamp rather than at the centre of the sample affecting the tensile strength determination, and therefore, should be ignored. While insufficient grip can allow the root to slip, affecting the displacement recording, this in turn will affect the determination of Young's modulus as it not possible to ascertain whether the change in length was due to root elongation or slippage.

To minimise stress concentration at the clamp it is necessary to modify the specimen either by creating a narrow section near the centre of the sample or widening the ends of the sample, to promote failure near the middle of the sample. However, modification of the root to promote failure at the centre is also problematic. Reshaping the root to produce a narrow midpoint is not an option because factors such as the number of annual rings, bending points and junctions influence the true root strength value (Abe and Iwamoto 1986a). Similarly, a modification of the root ends, by setting in resin can affect the cell structure and alter the root properties (Hamza *et al.* 2005b). In addition any process of root modification creates an additional stage in which time the root can dehydrate. The dehydration of roots has been shown by Papa (2003) to adversely affect the root tensile strength which is not regained by rehydration. Therefore, to obtain realistic root tensile strength data it is important to test the roots at their natural water content prior to dehydration. The investigation of roots at natural water content, air dried and soaked conducted as part of this research, yielded similar results for the natural and soaked roots, indicating that hydration does not adversely affect the root properties.

Therefore, roots should be stored in a moist environment prior to testing, to prevent dehydration of the sample.

Commandeur and Pyles (1991) reported a sigmoid failure of roots in direct tension and related the phenomenon to the sinuosity of the root, producing a form and material elastic modulus. However, direct tension tests on root analogues revealed a similar failure mechanism indicating that the form modulus is not only due to the sinuosity of the root but is also a function of the test apparatus, namely the clamp seating into the sample. This may be overcome by setting the ends in resin to reinforce the sample, which has its limitations, or keen observation to distinguish the seating displacement from the root straightening and elongation. Alternatively, the use of a remote displacement transducer to measure the root displacement directly rather than recording clamp movement could improve the quality of data obtained.

The static bending test was investigated as an alternative methodology to direct tension for assessing both tensile strength and stiffness. Although, the four point method is considered to give the most accurate results, as the bending moment is constant and there is no shear stress along the length of the test, the method requires a modification to the ends of the specimen to secure the load hangers. However, the three point loading method does not require modification of the ends, and is considered to give sufficiently accurate results (BS 373: 1957). Therefore, the three point loading method was considered a more viable option than the four point method for testing roots.

The comparative analysis of results of the undrained triaxial tests conducted on reconstituted re-compacted fallow and 'undisturbed' root permeated samples did not exhibit an increase in shear resistance to correlate with the root content. Conversely, the root free samples yielded higher undrained shear strength results than the 'undisturbed' samples. There was a positive correlation between root content and undrained shear strength between samples containing fine roots, but samples containing roots larger than 5 mm diameter did not exhibit an increase in undrained shear strength. One explanation for the discrepancy in the results is augmented sample disturbance encountered during percussive sampling, due to the movement of roots within the sample that have not been severed by the cutting shoe. Therefore, sample disturbance encountered when collecting the samples is an important consideration, and if root reinforcement is to be determined by triaxial testing high quality manually excavated samples should be obtained.

One high quality manually excavated large block sample was taken from the M25 site and sub sampled to conduct a set of laboratory shear box tests. Following the shear box tests roots were removed from the sample and the soil was remoulded to facilitate comparative analysis of root permeated and fallow soil. The root permeated soil sample yielded more than twice the undrained shear strength of the fallow sample. However, research by Attom *et al* (2001) showed that the strength of undisturbed samples could be 2.5 times higher than samples compacted in the laboratory. Therefore, the increased shear strength observed in the root permeated soil sample may be a function of the undisturbed soil structure rather than the root reinforcement. The displacement characteristics of the two soils were similar indicating that the potential root reinforcement had not been mobilised within the 8 mm displacement of the samples, as root reinforcement was realised at displacements in the order of 17 mm in the *in situ* shear box tests conducted on the M25 site. Therefore, the *in situ* shear box apparatus is considered preferable to the laboratory apparatus for shear strength determination. However, the lack of control of variables evident during the fieldwork such as the height of the shear zone raised concern over the quality of the data obtained. Therefore a laboratory trial to investigate the sensitivity of the test to shear zone height was conducted.

The shear strength results are influenced by the height of the mechanically induced shear zone, or the lack of confinement within the gap between the top and base sample boxes. The London Clay samples tested plotted close to the line of equality therefore it may be assumed that the *in situ* tests conducted on the M25 were not adversely affected by the variation of shear zone height. However, granular soils are particularly sensitive to this phenomenon, and the height of the shear zone may even negate the reinforcement contribution of roots. Therefore, when conducting *in situ* shear box tests on granular soils it is important to minimise the gap between the shear box and the ground. This is not always possible as it is dependent on the quality of the excavation in front of and around the sample pedestal, which needs to be over excavated to a degree to minimise excess resistance during the test. To facilitate comparative analysis, the height of the gap may be controlled by the use of a split shear box, the top of the base box and the base of the sample box will create a mechanically induced plane of weakness similar to that evident in the laboratory apparatus.

9 Framework Development

It is a capital mistake to theorize before one has data
Sir Arthur Conan Doyle (1859-1930). The memoirs of Sherlock Holmes

The literature review was undertaken to discover the effects of vegetation on slope stability, the parameters required to characterise a vegetated slope and the investigation techniques available to determine these parameters. Following the literature review, fieldwork was conducted to evaluate botanical and *in situ* biomechanical testing techniques. In addition, samples were collected from site to facilitate laboratory testing. The laboratory investigation was conducted to assess the appropriateness of soil testing techniques for characterising root permeated soil, and material testing techniques for characterising roots. A supplemental laboratory trial was instigated to determine the influence of shear plane height using the small (135 mm) *in situ* shear box test apparatus. Subsequently, a modification for the *in situ* shear box apparatus was designed to improve control over the shear zone height. Finally, a critical assessment of the candidate techniques was undertaken to develop a framework for the geotechnical assessment of vegetated slopes.

The aim of a geotechnical site investigation for a slope stability assessment is to obtain sufficient data to characterise the site, to facilitate slope stability analysis, which may take the form of theoretical or finite element modelling. The quality of the data entered into a slope stability model ultimately affects the quality of the output of the model. Therefore, if too many incorrect assumptions are input into a model the confidence in the output of the model will be reduced. However, to record all the parameters obtainable to ascertain the contribution of vegetation to slope stability would involve a very detailed investigation, taking a number of years to monitor the seasonal and annual variability, which may not be economically viable or ultimately necessary. Therefore, the framework for investigating a vegetated slope must address a balance between testing, modelling and characterisation (Burland 1989).

The method for determining the parameters, whether directly measured, derived or assumed must also be balanced. Although it may be tempting to measure everything to characterise a slope for input into a chosen model, it may prove to be a wasted effort if some parameters may be more effectively derived or assumed. Similarly, an inappropriate testing methodology or technique may render key results unreliable, which will impact on the determination of the overall contribution to slope stability gained from the vegetation.

The level of confidence required from the slope stability analysis will impact on the level of detail required from the investigation of a vegetated slope. To achieve confidence in the contribution of vegetation determined from an investigation of a vegetated slope it is important not only to select the most relevant parameters for the site and problem in question, but also to select the most appropriate method to determine those parameters and the number of tests to best represent the site conditions. Therefore, a framework for the geotechnical characterisation of a vegetated slope should not be a prescriptive process, but should provide a structure from which the most appropriate approach for the desired outcome may be selected; ranging in detail from the qualitative analysis based on the visual assessment and desk study data through to a quantitative analysis based on a detailed site investigation, incorporating many of the measured quantifiable parameters.

9.1 PARAMETER SELECTION

The literature review revealed a wide array of parameters required to characterise a vegetated slope, including geotechnical, botanical, biomechanical, hydrogeological and meteorological. However, to ascertain the contribution of vegetation to slope stability approximately only half of these parameters may be utilized as direct inputs into the relevant slope stability models. The remaining parameters highlighted in the literature review are important, in so far as they contribute to the overall characterisation of the slope and vegetation cover, or they may be employed to derive certain direct input parameters through empirical correlation. Therefore, both direct and indirect input parameters are necessary to characterise a vegetated slope and for slope stability analysis.

9.1.1 Direct Input Parameters

An initial investigation is required to assess the problem and facilitate the design of the main investigation. The design of the main investigation hinges on what parameters are required to characterise the site and assess the stability of a slope. Table 9.1 summarises the parameters that directly input into theoretical slope stability models that consider vegetation, such as CHASM, SLIP4EX and the modified FLAC program, or stand stability models such as ForestGALES.

Table 9.1 Direct input parameters for slope stability analysis

Parameter	Application	Determination	Test
Slope Geometry	All	Survey	Topographic
Morphology	All	Survey	Topographic
Strata	All	Survey	Intrusive
Depth of horizons	All	Survey	Intrusive or geophysical
Displacement (large)	All	Survey or monitoring	Topographic, photogrammetric or inclinometer
Saturated bulk density	All	Laboratory test	Density and water content
Natural Water Content	All	Field monitoring or Laboratory test	Gravimetric or volumetric determination
Dry Density	All	Laboratory test	Bulk density and water content
Void ratio	All	Laboratory test	Water content, dry density and particle density
Shear strength	All	Laboratory, field test or empirical	Triaxial, shear box, hand vane, SPT, CPT. Derived from classification
Permeability	All	Laboratory, field test or empirical	Falling, rising or constant head. Derived from PSD
Pore water pressure	All	Monitoring, field or laboratory test	Piezometer, tensiometer, installations or CPT in field filter paper method for suctions in laboratory
Groundwater level	All	Monitoring	Open standpipe
Tree spacing	All	Survey	Topographic
Wind speed	Biomechanical and Hydrological	Monitoring	Anemometer
Tree Height	Biomechanical	Survey	Topographic
Root pull out resistance	Biomechanical	Field test	Root pull out test
Root tensile strength	Biomechanical	Laboratory or field test	Direct tension test or derived from root pull out
Root Young's Modulus	Biomechanical	Laboratory test	Three point static loading or from direct tension
Soil internal friction angle	Geotechnical	Laboratory test or empirical	Triaxial, shear box. Derived from classification
Soil Cohesion Intercept	Geotechnical	Laboratory test or empirical	Triaxial, shear box. Derived from classification
Soil Poisson's Ratio	Geotechnical (FE)	Advanced laboratory test or assumed	Triaxial
Soil Shear modulus	Geotechnical (FE)	Advanced laboratory test or assumed	Triaxial
Soil Young's Modulus	Geotechnical (FE)	Advanced laboratory test or assumed	Triaxial
Coefficient of earth pressure	Geotechnical (FE)	Advanced field test or empirical	Pressuremeter. Derived from classification
Root reinforcement	Geotechnical (FE)	Field test	In situ shear box/ root pull out
Rainfall	Hydrological	Field test	Rain gauges
Water retention	Hydrological	Laboratory test	Water content monitoring of drying cycle
Interception	Hydrological	Field test or empirical	Rain gauges. Derived from Leaf Area Index (LAI)
Net radiation	Hydrological	Field test or empirical	Solar panel. Derived from climate data
Infiltration	Hydrological	Laboratory, field test or empirical	Infiltration, rainfall simulation. Derived from Permeability
Transpiration	Hydrological	Field test or empirical	Sap flow gauges. Derived from evaporation and LAI
Evaporation	Hydrological	Field test or empirical	Pan test. Derived from wind, humidity and radiation

The direct input parameters such as the slope geometry may be estimated, measured directly during a site inspection or derived from a suitable map. While the soil parameters can be determined directly from field, laboratory or advanced laboratory testing, alternatively some of the soil parameters may be derived through empirical relationships or assumed. Similarly the hydrological parameters may be measured directly using portable weather stations but are commonly assumed or derived from published climatological data or nearby weather stations.

9.1.2 Indirect Input Parameters

Indirect input parameters are not required as direct inputs for slope stability models or do not directly contribute to slope stability. However, these indirect parameters (Table 9.2) are necessary to characterise a vegetated slope, and they may indirectly indicate the contribution of vegetation to slope stability, or be used to ascertain the direct input parameters.

Table 9.2 Indirect parameters required to characterise a vegetated slope

Parameter	Application	Determination	Test
Seasonal variation	All	Monitoring	See ground and pore water
Aspect	Environmental	Survey	Topographic
Root Distribution	Environmental	Survey	Intrusive or geophysical
Weathering	Environmental	Survey	Visual
Vegetation cover	Environmental	Survey	Visual
Vegetation type	Environmental	Survey	Visual
Vegetation height	Environmental	Survey	Visual
Leaf Area Index	Environmental	Survey	Visual
Root density distribution	Environmental	Survey	Intrusive, root biomass or area ratio
Root diameter	Environmental	Survey	Intrusive
Vegetation distribution	Environmental	Survey	Visual
Vegetation vitality	Environmental	Survey	Visual
Vegetation maturity	Environmental	Survey	Visual
Biomass (extant)	Environmental	Field test	Fresh or dry weight
Root Biomass	Environmental	Field test	Fresh or dry weight
Organic content	Environmental	Laboratory test	Ash content
Vegetation Surcharge	Environmental	Empirical	Derived from biomass, distribution and cover
Soil texture	Environmental	Survey	Visual or intrusive
Soil Chemistry	Environmental	Laboratory or field test	P, N, K, Na, Ca, Mg, Fe, Mn, Al, pH and Electronic Conductivity
Soil Aggregation	Environmental	Laboratory test	Dispersion, Turbidity or ultrasound
Consolidation Ratio	Geotechnical	Laboratory test or empirical	Oedometer. Derived from shear strength and Atterberg Limits
Particle density	Geotechnical	Laboratory test	Specific gravity
Discontinuities	Geotechnical	Survey	Visual or intrusive
Penetration resistance	Geotechnical	Field test	SPT, CPT, Dynamic probe
Plasticity Index	Geotechnical	Laboratory test	Atterberg limits
Particle Size Distribution	Geotechnical	Laboratory test	Sieve analysis
Air Temperature	Hydrological	Monitoring	Thermocouple
Soil Temperature	Hydrological	Monitoring	Thermocouple
Humidity	Hydrological	Monitoring	Hydrometer
Root water uptake	Hydrological	Empirical	Root distribution and evapotranspiration rates

Indirect parameters such as the soil texture and chemistry may not directly input into a slope stability model. However, they can influence other factors, for example a compacted soil can limit the root penetration depth, and nutrient availability does influence root growth. Therefore, either parameter may indicate the propensity for vegetation to populate and thrive on the slope and ultimately contribute to slope stability in the long term.

Indirect parameters such as soil classification test results may be used to derive direct input parameters such as the cohesion intercept and the internal friction angle. Similarly the leaf area index (LAI) may be used to determine evapotranspiration and interception, which are required as direct input parameters in some hydrological models such as CHASM, while permeability may be derived from the particle size distribution. To improve user confidence and allow for the typical heterogeneity/variability of the ground, and hence the retrieved investigation data, established empirical relationships within geotechnical engineering are based upon a large volume of data for a particular soil formation and history of use. However, as yet such a comprehensive volume of data does not exist for root reinforcement analysis, although datasets for certain species are becoming available as research in this area continues. This is a major factor influencing the approach (based on current knowledge) within the proposed framework for the geotechnical investigation of vegetated slopes.

9.2 INVESTIGATION TECHNIQUES

The literature review has revealed a number of techniques suitable to ascertain various geotechnical, biomechanical, botanical and hydrological parameters. The field and laboratory investigation has facilitated familiarisation with some of the techniques used to assess the contribution of vegetation, which has raised several issues about the quality or appropriateness of the results achieved. Investigation techniques employed for geotechnical ground investigation have been the subject of many trials and as such are generally widely accepted for obtaining the necessary data for slope stability analysis. However, the incorporation of vegetation into a slope stability analysis is relatively new, and the techniques employed to obtain root reinforcement data are index rather than fundamental tests. The non-fundamental nature of these tests must be recognised, and the proposed framework will ultimately require engineering judgement to be used, as is the case with other geotechnical test methods. Therefore, the current lack of case study data and experience in this area means that the initial approach to the subject should be conservative in nature.

9.2.1 Visual Assessment

Visual assessment is an integral part of any site investigation and, therefore, is incorporated into the initial desk study stage. The walkover stage facilitates the visual assessment of the site, whereby the geometry and condition of the slope, location of drainage, evidence of instability and vegetation is recorded, in addition, to characterising the slope visual assessment of the covering vegetation, underlying soil and roots permeating the soil are also fundamental to a geotechnical investigation of a vegetated slope.

The vegetation on a slope is traditionally regarded as an obstruction to site works that must be cleared prior to the ground investigation, or may be noted for its potential to damage structures or drains. Alternatively, the presence of hedges and trees might be noted due to the recognised influence of vegetation on shrinkable soils. However, when characterising a vegetated slope the vegetation is a crucial rather than a cursory parameter. Therefore, the type, location and distribution density of vegetation are important parameters. Consultation with an ecologist or similar professional would be prudent if any protected species inhabit the site or if a site is to be regenerated and the environmental impact of the planned construction or the introduction of new species has to be ascertained.

For a slope stability analysis the vegetation is grouped according to certain characteristics such as grasses, herbs and woody vegetation. Therefore, it may not be necessary to employ the talents of a botanist or ecologist for a geotechnical investigation of a vegetated slope, as it is not obligatory to identify each species present on site because it is only necessary to identify the functional types (deciduous versus evergreen, shrub or tree etc.) and group the vegetation accordingly. If classifying the species present into relevant functional types is beyond the scope of the field engineer specialist advice is recommended. Different types of vegetation will have different rooting structures and different water demands, and subsequently different effects on the stability of the slope.

The location and distribution density of the vegetation are important parameters, for example, if a stand of trees is present on the slope their influence as a disturbing or restoring force will depend on whether they are located toward the crest or toe of the slope, respectively. Similarly, the size and number of trees per m^2 will influence the amount of surcharge and rooting density. The seasonal variation of distribution density may also be monitored by visual assessment. A fixed plot is required for comparative analysis, and the size and shape of the fixed plot will depend on the subject vegetation, the size of the site, and whether the vegetation is managed as part of a plantation or naturally distributed.

Visual assessment is also an important technique for characterising the soil and rooting density. Trial pits are the best way to assess the soil profile *in situ* as it is possible to ascertain whether the soil type is persistent and forms a horizon or whether it is a lens or pocket within a horizon. It is also possible to identify evidence of instability, such as slickensides, within the soil profile more efficiently with a trial pit than via other methods such a continuous borehole sampling. The trial pit face also facilitates root area ratio determination and potentially the maximum root penetration depth, which are important parameters for modelling the root reinforced soil.

The engineering soil description (BS 5930: 1999) is used for the visual assessment of soils, however, the descriptions do not encompass soil quality classification and generally disregard the properties of the topsoil horizon as this is not considered a suitable engineering material, due to its variability, shallow placement and respective quantity. The soil classification system employed by pedologists is very detailed and incorporates soil processes such as eluviation, illuviation and podzolisation, and incorporates soil formation mechanisms such as climate, geology and geomorphology. The detail incorporated into a pedological description, observed during the preliminary fieldwork, does not necessarily add value to the engineering description, for strata that may be classed as engineering soils. The sub division of a topsoil horizon into the litter, organic and humus horizons may also be considered excessive for a geotechnical site investigation. However, the presence and condition of the topsoil horizon are important when considering the contribution of vegetation. In summary, the engineering description of soils is adequate for the geotechnical investigation of vegetated slopes, however, the field engineer should pay due attention to the topsoil horizon, and the amount of roots in each soil horizon, and therefore, would benefit from an awareness of pedological soil classification.

The amount of roots in each soil horizon is a parameter that does not feature in an engineering soil description. However, this is an important parameter when considering the stability of a vegetated slope as it will facilitate the modelling of root contribution for each soil horizon, or zones of influence, defined by root content, may be modelled in a homogeneous soil. The root area ratio is the total cross sectional area of roots to the surface area of soil, and is determined by counting the number of roots for a variety of size classes within a given area of soil. Two methods for determining the root area ratio were trialled on site:

- The quadrat method disregards the soil horizons and employed the arbitrary boundaries of the quadrat.
- The horizon method employs the soil horizons as boundaries but does not pick up the gradual reduction in root area ratio down the profile of a homogeneous soil.

Therefore, it would be prudent to employ a combination of the two methods, whereby the roots are counted within the quadrat to determine the decline in root density with depth, but the quadrat must be reset at the top of each soil horizon, to align the data with a naturally occurring rather than an arbitrary boundary. The root area ratio may be expressed within the engineering description for each soil horizon, or for each arbitrary increment in a homogeneous soil, to facilitate incorporation into the slope stability model. Therefore, the subsequent engineering soil description must detail the topsoil horizon and include an assessment of roots present in the soil profile. The size and amount of roots for each horizon may be given qualitative descriptors such as very fine to coarse (Böhm 1979; Meidinger 1998) or few to many, although at present these boundaries are arbitrary. Therefore, a key or statement of which system has been employed must be included with the logs. It is recommended that the root density distribution be recorded per unit area or unit volume, as it provides a definitive description for that horizon. In addition, the maximum depth of root penetration should also be recorded, where it has been encountered in the soil profile, as it may be used to ascertain the limit of mechanical reinforcement.

In summary, visual assessments allow the collection of data for subjective judgements to be made about the contribution of vegetation to slope stability. Identification of key functional types that have extensive woody root systems, or have high water demands, will give an indication of the potential contribution to slope stability. The spatial distribution of these functional types across the slope needs to be put into the context of grouped or dispersed elements, and their location on the slope. The potential reinforcement may then be modelled as a veneer or disperse elements, and the surcharge can be included as a restoring or disturbing force. Excavations are required to estimate root distribution density and penetration depth. The potential exists for this information to be incorporated into numerical models, which could be more readily achieved if site specific correlations were established. Such correlations would require monitoring and testing over a period of time, and it is recognised that this would require significant commitment, which may only be practicable on large scale site investigations. Generic correlations may be employed for small scale projects as more data becomes available.

9.2.2 Non Destructive Testing

There are a variety of geophysical techniques that may be employed as part of a geotechnical site investigation to determine the stratigraphy of the underlying soil. The data from the geophysical investigation is commonly used to infill data between exploratory holes to provide a 3D characterisation of the subsurface. However, the literature review revealed that Ground Penetrating Radar (GPR) has also been used experimentally to locate tree roots and determine the water content of the soil. The research groups investigating the use of GPR for root distribution determination reported varying degrees of success.

The success of root location by GPR is dependent on the contrast between the soil and the roots, the size and depth of the roots and the type of soil. In addition, there is a trade off between resolution and signal penetration, which in turn is influenced by the electronic conductivity of the soil. The signal is attenuated in high conductivity soils such as clays, which reduces the penetration, this may not necessarily be a consideration for shallowly rooted soils, but will limit the applicability of GPR for root mapping. In addition, data analysis and interpretation is reported to be time consuming and artefacts within the echogram where roots cross over or branch may be misinterpreted. The use of GPR for the assessment of root distribution is still in its infancy and as such may be employed as a technique to investigate a vegetated slope, but should be used with caution as it has many limitations.

GPR has also been investigated as a tool to determine the soil water content. Similarly, this research is still at the experimental stage, and although it is reported to have the potential for rapid soil water assessment a site specific calibration is required (Charlton 2001). The GPR signal amplitude is correlated to a volumetric water content, which has been successfully related to TDR determined volumetric water content. However, at present the technique is limited to shallow surface determination of approximately 1 m. Soil water content determination to a depth of 1 m may be sufficient to determine the influence of some vegetation, but its application is limited as vegetation can influence the hydrogeology to a depth of several metres or more. Therefore, although GPR for water content determination is a potentially powerful tool for the investigation of vegetated slopes, a greater penetration is required to adequately assess the influence of vegetation on the hydrogeological properties of the slope.

In summary, geophysical investigation techniques, especially GPR, may be employed to as part of a geotechnical investigation of a vegetated slope, namely to infill data between exploratory holes to facilitate 3D characterisation of the geology. In the future, with the continuing development of the GPR equipment, such as antenna frequency, the use of GPR to identify root systems and soil water content may become more prevalent within geotechnical site investigation. The use of GPR shows significant potential for allowing non destructive assessment of volumes and depths of roots. This could provide a significant advance on the current need to excavate trial pits. However, the application of this technique is ultimately subjective unless the data can be tied into input parameters for slope stability analysis. Identification of water content is currently of more fundamental value, however, it compares poorly to the suites of data that can be determined from more direct *in situ* monitoring instrumentation. Therefore, its use is likely to be limited to providing a snapshot of the soil water profile to a limited depth.

9.2.3 *In situ* Testing

In situ testing and monitoring are currently the most useful methods for determining the contribution of vegetation to slope stability. Both standard geotechnical testing and non-standard testing has been trialled and evaluated in order to assess its suitability for inclusion within the framework.

The standard penetration (SPT), dynamic penetration (DP) and static cone penetration tests (SCPT) are all used within geotechnical site investigation to determine the penetration resistance of the soil. The wide use of penetration testing has led to the development of empirical relationships to determine other soil properties. However, the use of penetration testing on a vegetated slope may prove problematic as lightweight plant will have minimal impact on the vegetation but has a limited depth penetration.

While large plant can penetrate to greater depths its use may necessitate vegetation to be felled to create a working platform. Therefore, the selection of penetration testing equipment will depend on the site conditions; size and angle of slope, depth to potential slip plane or embankment foundation and the type and amount of vegetation present on the slope. Although penetration testing is a useful geotechnical testing technique, the dimension of the cone is generally too small for the test to detect the mechanical contribution of roots to the shear resistance of the soil. However, the penetration test may indirectly detect the hydrogeological influence of vegetation on soil, since a reduction in soil water content can result in greater penetration resistance. Therefore, penetration is still an integral part of the geotechnical investigation of a vegetated slope, but other testing techniques are required to directly evaluate the contribution of roots to the shear resistance of a soil.

The *in situ* shear box test is not a standardised test for use on soil slope stability analysis However, it has been employed by a number of researchers to determine the enhanced shear resistance of a root reinforced soil, which is achieved by comparative analysis of root permeated and fallow samples. The literature review revealed the size and design of the apparatus varied with each research group, as did the procedure. The choice of *in situ* shear box sample size will largely depend on the size of the site and the subject vegetation. The field trial employed both a small (135 mm) and large (600 mm) *in situ* shear box to undertake comparative analysis of root permeated and fallow soil. The small *in situ* shear box was only capable of testing fine root systems associated with grasses, small shrubs and saplings or tree roots distal to the tree. However, this may be considered the most appropriate sample size, producing the most conservative shear strength data, as roots will fail at their weakest part, usually at small diameters. Unfortunately, the maximum root size or even whether any roots crossed the shear plane is not known until after the test. Therefore, some test results will have to be disregarded depending on the post test assessment of the soil root composite, because the inclusion of large roots or cobbles will disproportionately influence the test results.

The large *in situ* shear box was of a suitable size to test entire root systems of some trees, and is, therefore, less sensitive to the inclusion of large roots or cobbles within the sample. However, the large shear box test incurs a substantial amount of disturbance to the slope. To test large trees an unfeasibly large shear box would be required or the possibility of employing a bulldozer to shear the test area while recording the load and displacement may be considered, although this would cause a great amount of damage to the slope, while only providing one index test result, so is not the most sensible proposal, as anticipated heterogeneity would require several tests to be conducted.

The quality of the test results gained from the *in situ* shear box is also an issue, as there is a lack of control over the drainage conditions. A fine grained soil requires a very slow rate of strain due to the low permeability, although, the presence of roots may improve the permeability enabling a quicker strain rate. However, a slow rate of strain is not logistically viable for an *in situ* test because the weather and temperature may change during the test affecting the results. Similarly, introducing a preconsolidation stage to determine the optimum strain rate will prolong the overall length of the test. It also introduces another level of complexity, as it requires the vertical displacement to be recorded, which may not give a true value because of the reaction or lack of it from the underlying soil. Protecting the sample from environmental change during a long test may again be considered a wasted effort because it is still little more than an index test, which may only be used for comparative analysis with a sample tested without roots, to give a relative increase in shear resistance due to root reinforcement.

The application of a normal load onto the sample surface may be straight forward for grassed samples, which are relatively level, but the presence of a tree stump is problematic to the even loading of the soil sample. Abe and Iwamoto (1986b) cut the tree stump flush with the ground surface and with the aid of a cover plate applied weights to achieve a normal load, across the sample. However, a normal load applied to the sample surface will be transferred through the soil matrix to the root system. Alternatively, the normal load could be applied to the tree stump, where the stress will be transmitted through the roots to the soil. The two different load applications generate different stress conditions; a normal load applied to the sample surface may be used in conjunction with similar tests at different normal loads to determine the Mohr Coulomb failure criterion, whereas, a load applied to the stump would be used to replicate the extant biomass, which has been removed. Potentially the most effective procedure would be to combine the two methods and load the stump to replicate the removed biomass and apply a set of normal loads to the surrounding sample surface to determine the Mohr Coulomb failure envelope.

Finally, while conducting the *in situ* shear box tests a variation in shear zone height was observed. The variation of shear zone height was a function of the sample preparation, whereby soil was excavated to create a soil pedestal around which the shear box apparatus was set up. For some tests the shear box base coincided with the surrounding ground surface while for other samples the surrounding soil was over dug to ensure the shear box sample could move freely without obstruction. Shewbridge and Sitar (1989) reported the influence of shear zone height on the reinforcement potential, therefore a laboratory trial was undertaken to verify the field results undertaken in the London Clay. The laboratory trial showed that the influence of shear zone height is dependent on the soil type, and a shear zone height of 15 mm can negate the reinforcement potential in a sand sized granular soil. Therefore, it is important to control the height of the shear zone during the *in situ* test to provide comparable results necessary for comparative analysis. The use of a base box secured to the top box during sample preparation, would not only produce a controlled shear zone height but would also protect the sample while the apparatus was set-up around the soil pedestal and may introduce symmetry to the test specimen.

In summary, the *in situ* shear box test should not be considered as a fundamental test, and its use should be restricted to comparative analysis. To facilitate comparative analysis the controllable variables must be kept to a minimum and any deviations from a set methodology reported. As a consequence of these considerations, and lack of a fundamental alternative for measuring the *in situ* shear soil root composite, it is recommended that the potential root reinforced shear resistance be determined using a theoretical model rather than conducting *in situ* shear box tests. This has been incorporated into the framework by allowing flexibility to facilitate theoretical analysis from related parameters, in order to provide an initial assessment of potential reinforcement, which may be supported by subsequent testing.

The root pull out test provides pull out resistance and soil root interface parameters that may be employed in theoretical models to determine the reinforcement potential. Previous researchers that have used the root pull out test have derived a tensile strength for the root from the pull out force, but the derivation of the tensile strength depends on the failure mechanism of the root during the pull out test. Therefore, it is important to determine the failure mechanism to facilitate suitable assessment of the data. It may be possible to determine the tensile strength from a tensile failure of the root in close proximity to the excavated soil surface. However, where roots fail within the soil, an element of skin friction is introduced and so the peak pull out resistance comprises both the tensile strength of the root and tangential friction from the soil root interface. Alternatively, the soil may fail around the root and the maximum pull out force is a result of the soil root composite. The skin friction element of the test result is also influenced by the sinuosity and branching of the root. In addition, the displacement recorded during the test can not be separated into the discrete elements of elongation, straightening or actual displacement, which are necessary to distinguish the root strength and interface friction from the bulk parameter of pull out stress.

The fieldwork conducted during this research highlighted the variables inherent to the root pull out test and the variability of the roots. The test is affected externally by the soil strength, water content and particle size distribution, while the root length, sinuosity, branching, tapering angle, surface roughness, tensile strength, stiffness and cell differentiation between the stele and core of the root or presence of root knots can also affect the test results. Each root is unique, because it has responded to the immediate environment, by gravitropism, hydrotropism phototropism, and chemotropism. The root also responds to the movement of the plant (thigmorphotropism) and creates reaction wood to enhance root strength and provide stability. In addition, the root, being a living entity, will alter throughout the year (Moore and Clarke 1995); many roots die back or shrink when the plant is dormant in winter or during prolonged dry periods, which will minimise the surface contact and subsequent skin friction. Similarly, root dimensions may vary as a diurnal response (Huck *et al.* 1970), therefore, comparative analysis may be influenced by the time of day and year the test is conducted. Finally, roots may also fall victim to pests and disease, which can affect the performance of a root during the root pull out test. Therefore, it is important to conduct a sufficient number of tests to reflect the variability and heterogeneity of the key vegetation, and to record the condition and age of the vegetation as well as the environmental conditions at the time of the test.

Like the *in situ* shear box test, the root pull out test may also be considered as an index test. However, putting aside the variability associated with natural root systems and the heterogeneity of soil the test results are of greater fundamental use than those from the *in situ* shear box. Overall it is considered to be more efficient to reserve *in situ* biomechanical testing techniques for a detailed investigation of a vegetated slope, to endorse calculations of potential reinforcement contribution derived from root tensile strength and soil strength parameters, which may be tested in the laboratory under controlled conditions. Waldron (1977) and Wu (1984) developed 2D models to demonstrate that the reinforcement from root inclusions could be calculated from the embedment length, stiffness and tensile strength of the root inclusions. Similarly, the pull out resistance can be derived theoretically from the effective diameter, embedment length and ultimate stress of the interface friction. This study has shown that there is a lack of data, compared to the range of variables associated with vegetation and soil. Therefore, a detailed investigation of the vegetation and its interaction with the slope is recommended, if the optimal root reinforcement is to be incorporated into a slope stability analysis.

In summary, a combination of root characteristics and their interaction with the soil can be used to incorporate root reinforcement into slope stability analysis, as discrete elements. As previously discussed, the lack of comparative data means that these initial assessments should be conservative, or supplemented by *in situ* and/or laboratory studies using root pull out resistance and tensile strength tests.

9.2.4 Sampling and Laboratory Testing

Appropriate sampling techniques must be employed in order to obtain suitable samples for laboratory testing. Percussive sampling techniques such as cable percussion boreholes and window sampling are used to provide 'undisturbed' samples for geotechnical laboratory testing. However, the sample will suffer a degree of disturbance, due to stress relief, although, the area ratio and cutting edge taper are the most important causes of disturbance (Clayton 1986). The amount of disturbance encountered by the 'undisturbed' sample is generally sufficiently negligible to qualify the samples as undisturbed, unless sensitive soils are being sampled, in which case piston sampling is often used.

During the fieldwork U100 samples of root permeated soils were obtained from percussive sampling techniques for comparative analysis with reconstituted re-compacted fallow samples. However, the industry standard cutting shoe was not sharp enough to severe woody roots greater than 5 mm diameter, without causing undue sample disturbance, related to root movement in the sample. The subsequent laboratory testing confirmed that the integrity of the sample had been compromised. The U100 samples were split and successfully used for root density and water content distribution. In short, percussive sampling is not considered to be appropriate for obtaining samples for shear strength determination of root permeated soil but is useful for determining the vertical root distribution.

To conduct laboratory shear strength tests a high quality manually excavated undisturbed sample is required. Such samples may be readily obtained from trial pits in cohesive soils although granular soils may prove problematic, in which case the *in situ* shear box test is preferable, as the permeability associated with granular material will facilitate the faster strain rates necessary for the field test. Cohesive soil samples have a lower permeability and require slow strain rates, which can be achieved in the laboratory without the influence of environmental variability, which may occur in the field.

The root tensile strength and elastic modulus are important parameters for many theoretical models. The elastic modulus can not be derived from the root pull out test as it is not possible to accurately define the true strain encountered in the root, because the recorded displacement also includes straightening and elongation. The tensile strength of roots may be derived from some root pull out tests; however, it is preferable to retrieve samples from the field for laboratory analysis, to control as many variables as possible.

Several researchers that have used the direct tension apparatus reported various techniques to overcome the problem of clamping roots in the apparatus. However, the removal of bark or setting the ends of the root in resin may improve the grip but can also alter the root properties. Therefore, testing unmodified roots will yield the most representative results, but only the successful tests, where the roots fail near the centre of the sample should be used. Data from tests on roots that fail at the clamp should be disregarded as stress concentrations related to the self tightening jaws may influence the results. The laboratory tests conducted on root analogues and real roots revealed that the direct tension test can yield a sigmoid failure curve, which is not only a function of sinuous straightening but is also induced by the self tightening jaws squeezing the sample. Therefore, if the modulus of elasticity of the root is to be determined the material modulus rather than the form modulus, put forward by Commandeur and Pyles (1991), should be use to characterise the root properties. Alternatively, the static bending test may be used to determine the bending strength and elastic modulus of the root. The three point loading method is particularly suited to root testing as the root ends do not have to be modified, unlike the four point loading method, which requires a modification of the root ends to secure the load hangers.

This study revealed the sensitivity of root strength and stiffness to the water content of the root. The laboratory trial conducted on roots that were air dried, soaked and roots at natural water content revealed deterioration in tensile strength for the air dried roots compared to those at natural water content, whereas, the soaked roots exhibited little difference, in tensile strength and elastic modulus, compared to those at natural water content. In addition, Papa (2003) reported that the tensile strength of roots increased after roots lost 5% of their original water content but decreased thereafter, and this was not regained following rehydration, compared to those tested at the natural water content. Therefore, if roots that have been collected from site for laboratory analysis are to be stored prior to testing, they should be kept in a moist environment to prevent dehydration of the samples, as dehydration of the roots will affect the results obtained.

In summary, undisturbed specimens of the soil root composite are difficult to obtain. This is a common problem, even when trying to obtain undisturbed soil samples, which do not contain roots. Standard percussive techniques may not be suitable for obtaining composite samples for laboratory strength testing. However, they do provide a window to view root density distribution with depth. Therefore, laboratory testing of roots sampled from site is favoured over testing the soil root composite. The root tensile strength and modulus of elasticity can be determined using the direct tension apparatus or the three point static loading. However, gripping the root ends for the direct tension test is still problematic and roots that fail near the clamp due to stress concentrations should be disregarded. Furthermore, care is required during sampling and subsequent storage of the roots to minimise dehydration as this has been shown to have a significant effect on both the tensile strength and modulus of elasticity.

9.2.5 Monitoring

Monitoring is an integral part of a slope stability assessment, which generally comprises ground movement and/or ground water/soil water monitoring installations. However, the monitoring of meteorological parameters is also important especially when investigating a vegetated slope. The literature review revealed a variety of instruments that may be installed to monitor ground movement, ground water, soil water content or pore water pressures, which range in precision and price but the reliability of any instrument relies on the quality of the installation.

Take and Bolton (2004) reported the occurrence of small strains induced by seasonal wetting and drying. Therefore, meteorological monitoring is recognised as an important asset to slope stability analysis. Portable weather stations and rainfall gauges can be installed on site but may be subject to vandalism, or require manual monitoring/resetting after each rainfall event. Alternatively, regional meteorological data can be obtained from the met office. However, this may not pick up local variations in weather encountered on the site as the data is collected at the permanent weather stations owned by the met office.

The seasonal variability of soil water content can be augmented by the presence of vegetation, and plant water demand may create negative pore water pressures, which can persist through the wet seasons, or even reduce the groundwater level. The lowered water table or increased suctions can improve the soil shear strength and in turn the stability of a slope. However, it is important to monitor the influence of vegetation on the soil water conditions (ground water and/or pore water pressures) to ensure that any beneficial contribution evident during the dry periods does prevail into the wet periods. There are a number of proprietary systems available for measuring and monitoring ground water and pore water pressures, although using different techniques may produce variation within the results, so it is prudent to install one system to facilitate comparative analysis of installations situated near to and remote from trees located on the slope.

The leaf area index of the canopy and sap flow gauges attached to a representative amount of trees in the stand may be used to ascertain the evapotranspiration rates and subsequent water demand of the stand. Alternatively these data may be derived from published datasets that are available for some species. Evapotranspiration rates of the covering vegetation along with regularly recorded meteorological data either from a nearby fixed station or using a portable station will provide sufficient input and output information to model the influence vegetation has on hydrological parameters.

In summary, slope instrumentation can be used to measure pore water pressures and ground movements. In order for these parameters to be fed into complex long term slope stability models incorporating vegetation, the measurements need to be supplemented by meteorological and specific vegetation factors (such as evapotranspiration). Monitoring does not allow the measurement of root reinforcement. However, the benefits of water uptake on soils within a slope can be monitored and modelled. The most important role of monitoring is, therefore, the potential to observe sites over a long period of time and to develop an understanding of seasonal variation.

9.3 HIERARCHY OF INVESTIGATION

Following the evaluation of the parameters and the most suitable techniques available, the framework for the geotechnical investigation of a vegetated slope has been developed into a tiered approach. The three tiers include simple, moderate and detailed levels of investigation, which include techniques adopted from the related disciplines. The procedures for the relevant investigation techniques have been discussed in the previous chapters, and are published as various standards and research techniques. Therefore, the framework developed is not prescriptive but outlines the necessary stages within a phased approach. The phases within each tier takes into account the following considerations:

- Angle and height of slope, potential slip plane morphology, which may be derived from slope morphology such as tension cracks or bulging near toe, or measured with slip plane indicators.
- Shear strength, friction angle, density and depth of soil horizons, which may be measured, derived or assumed depending on level of confidence required from model.
- Ground water level, seepage and drainage, may be assumed, measured or derived from desk study data, depending on level of confidence required in output.

Permeability, pore water pressures, meteorological data and soil properties determined from advanced laboratory testing techniques are also important parameters that may be considered as greater user confidence is required and the complexity of the model increases. While the incorporation of vegetation into a slope stability analysis requires the addition of:

- Botanical characterisation to identify the functional types present on the slope, along with their location and distribution across the slope, to delimit the spatial distribution of potential reinforcement.
- Root distribution data, namely vertical and lateral extent of roots and density distribution with depth, to ascertain whether the root reinforcement may be modelled as a veneer or as disperse elements and the vertical limits of the reinforced zones.
- Comparative analysis to ascertain the influence of the vegetation on the geotechnical and hydrogeological properties of the slope. To quantify the

contribution of vegetation to shear resistance either from root reinforcement or reduced pore water pressure.

The most efficient approach for obtaining the parameters necessary for slope stability analysis is to introduce a hierarchy of investigation. Figure 9.1 illustrates the proposed hierarchy for the geotechnical investigation of a vegetated slope, which includes the visual assessment of vegetation included in the Tier One site walkover and the modified ground investigation phase of Tier Two, along with dedicated biomechanical testing and seasonal botanical and hydrogeological monitoring, required for the comparative analysis necessary to quantify the effect of vegetation on the geotechnical and hydrogeological parameters, and ultimately slope stability (Tier Three).

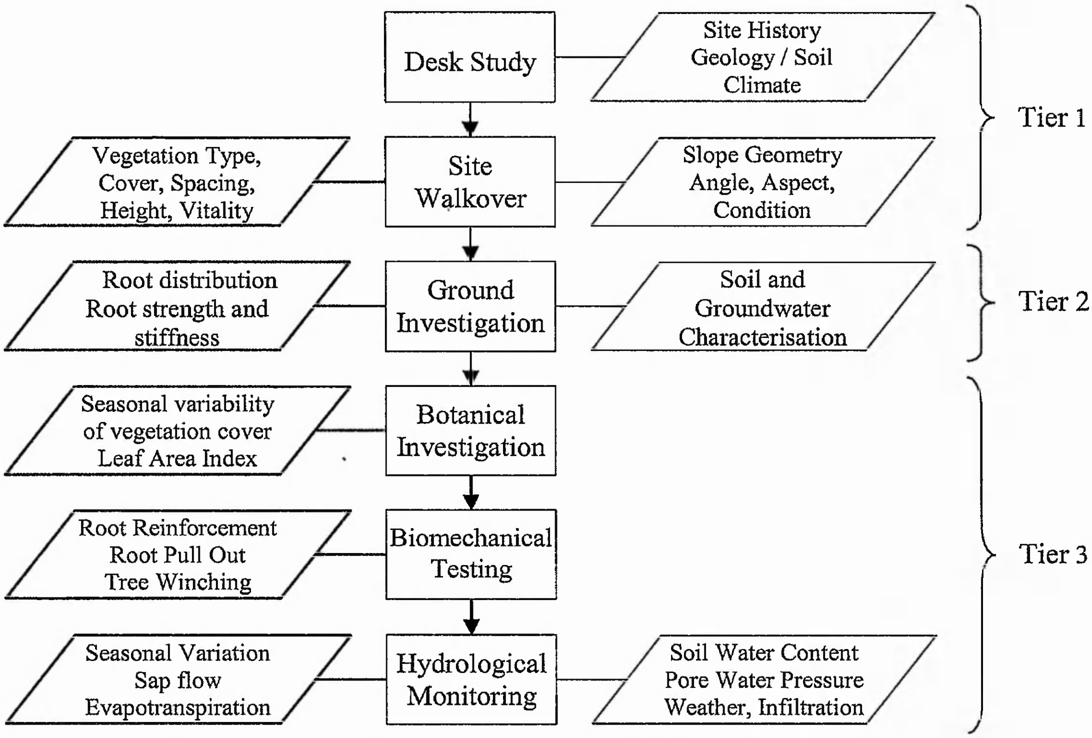


Figure 9.1 Hierarchy for the geotechnical site investigation of a vegetated slope

Tier One is a simple investigation that may be factored into an existing asset management risk assessment, whereby a desk study is conducted followed by a site walkover to facilitate the visual assessment. In addition to the desk study data retrieved for a geotechnical investigation it is also important to obtain any climatological or weather data to anticipate seasonality and the subsequent variability within the vegetation cover. Similarly, the site walkover will include a visual assessment of the vegetation, including amount of cover, location, spacing of trees and identification of the functional types. It is also important to identify desiccation cracks that may have been induced by the water demand of the vegetation cover.

The information gained from such an investigation is mainly qualitative, therefore, only a qualitative judgement of the contribution to the slope stability from the vegetation may be made. Although it may be tempting to assume parameters to input into slope stability models, this would not be prudent as there is virtually no confirmatory information. However, to include the visual assessment of the vegetation while assessing the site facilitates a judgement on whether or not the vegetation may contribute to slope stability or assess the extent of any detrimental effects the vegetation may have, such as desiccation cracks.

To facilitate the use of standard slope stability models geotechnical parameters obtained from a ground investigation are required. Therefore, Tier Two will comprise Tier One along with geotechnical testing for soil and groundwater characterisation, with the addition of root quantity estimation and maximum rooting depth. In addition, representative samples of roots should be collected for laboratory tensile strength and stiffness determination. Care should be taken when locating exploratory holes and taking root samples as damage to the root system can be detrimental to the tree, as it limits the water and nutrient supply. The percentage of the total root system affected, the overall health of the tree, time of year, and the type and age of the tree will influence the survival and recovery rate of the tree.

This level of investigation would produce the necessary input parameters for a semi quantitative slope stability model, and facilitate an estimation of potential root reinforcement and onset of desiccation. However, without long term monitoring of vegetation and soil water parameters, which may change seasonally, the conclusions of such an investigation, would represent a snapshot in time. Once put into context the design would have to assume a worst-case scenario, which may be over conservative and ultimately negate the contribution of vegetation. If the contribution of vegetation is to be relied upon to any degree of certainty a detailed investigation is essential.

The Tier Three characterisation of a vegetated slope will include Tiers One and Two, along with detailed characterisation of the vegetation. This stage will include biomechanical testing to determine the influence of vegetation on the geotechnical properties, while regular monitoring will be used to determine the influence of vegetation on the hydrogeology of the slope throughout the year. Advanced laboratory testing may also be conducted to obtain geotechnical parameters necessary for improved confidence in the output of finite element models.

The combination of comprehensive biomechanical, geotechnical and hydrogeological testing and monitoring would provide a quantitative characterisation of a vegetated slope and should produce a reliable output from any theoretical model. The detailed investigation would warrant *in situ* biomechanical testing such as shear box and root pull out testing, or tree winching if tree stability was a consideration. Botanical monitoring would be necessary to ascertain the seasonal variability of vegetation cover, which influences the water demand and the persistence of vegetation induced suctions. Hydrogeological monitoring would also be necessary to ascertain the occurrence and persistence of any seasonal or vegetation induced suctions, and may also be used to determine the depth and lateral extent of the negative pore water pressure zones. In conclusion, the framework based upon the tiered approach for a geotechnical investigation of a vegetated slope is summarised in Table 9.3.

Table 9.3 Framework for the geotechnical investigation of a vegetated slope

	Tier One	Tier Two	Tier Three
Characterisation Techniques	Desk Study Survey Site history Geology Climate Walkover Survey Visual Assessment of Slope Geometry Condition Vegetation Type Location & Distribution Hand Excavated Pits to Verify desk study data Initial root assessment	Ground Investigation Exploratory holes to Retrieve soil and root samples for laboratory testing Install Instrumentation Determine root density distribution and penetration depth *In situ* Geotechnical Testing Geophysical Testing to infill data Laboratory Testing for Soil Classification Root Characterisation	Advanced Ground Investigation Biomechanical Testing to Determine mechanical influence of vegetation Hydrogeological monitoring to Determine influence of vegetation Botanical Monitoring to Determine seasonal variability Ground Movement Monitoring Advanced Laboratory Testing to Determine geotechnical parameters
Outcome	Subjective Data Qualitative Assessment Simple qualitative modelling using some assumed parameters	Subjective and Objective Data Semi Quantitative Assessment Readily obtained inputs for geotechnical models incorporating vegetation	Objective and Subjective Data Quantitative Assessment Combined geotechnical and hydrogeological models incorporating vegetation

9.4 SUMMARY

To develop a framework for the geotechnical characterisation of a vegetated slope the influence of vegetation on its environment has been studied to determine what parameters can be measured to characterise a vegetated slope with regard to slope stability. Following which, candidate procedures and testing techniques have been selected from a number of disciplines including geotechnical engineering, forestry, botany, biology, geomorphology, hydrology, pedology and agronomy, to measure the identified parameters. To measure all the parameters that are available to characterise a vegetated slope would result in an unfeasibly comprehensive detailed investigation that would be unnecessary for most slope stability assessments. Therefore, the parameters associated with a vegetated slope have been divided into two key groups to clarify which can be used as direct input parameters, for some of the more common slope stability models, and the indirect input parameters that can be used to derive certain direct input parameters or for general site characterisation. Similarly, the wide variety of techniques available to ascertain the parameters led to an evaluation of the candidate techniques that may be employed as part of a geotechnical site investigation of a vegetated slope.

The complex nature of vegetated slopes and the choice of techniques available to determine the parameters necessary to characterise the vegetation, geology, hydrology and slope, resulted in the development of a non prescriptive tiered approach, whereby the number of parameters quantified will depend on the level of detail required for the chosen slope stability model. A qualitative assessment, associated with asset management appraisal, will require minimal quantitative data and may be achieved through a Tier One investigation. Whereas, tiers Two and Three provide quantitative data as more detailed testing and monitoring is built into each investigation phase. The phases within the three tiers can be used iteratively depending on the site, time of year and vegetation present, facilitating an accumulation of data that may be used to characterise the vegetated slope and refine input parameters for the selected slope stability model.

Conclusion

10

To be absolutely certain about something,
one must know everything or nothing about it.
Voltaire (1694 - 1778)

The contribution of vegetation to slope stability has attracted many research groups each applying a different focus depending on their research background. However, the uncoordinated approach, from a high level perspective, to the determination of the contribution of vegetation to slope stability and the lack of optimisation of the testing and monitoring necessary to quantify the parameters required for slope stability assessment is clearly evident within the literature. This disparate research has resulted in the use of inconsistent testing procedures and subsequent analysis. In short, the review of the literature revealed the requirement for standardisation of testing procedures, which will ultimately increase confidence in data acquisition and promote comparative analysis of available datasets. Therefore, the contribution to knowledge of this thesis is the development of a framework for the geotechnical investigation of a vegetated slope, incorporating the relevant techniques available to determine the pertinent parameters that can be employed to ascertain the contribution of vegetation to slope stability. In addition, the procedures within this framework have been refined and guidance given on their appropriate use.

An industry standard geotechnical site investigation does not incorporate the techniques required to characterise the vegetation, or determine the influence of vegetation on its environment. Similarly, the techniques available to determine the influence of vegetation on geotechnical and hydrogeological properties do not provide sufficient data to conduct a slope stability analysis. Therefore, it is necessary to integrate the appropriate techniques into a coherent framework, that adopts a cross disciplinary approach. The data obtained from such an investigation may then be employed to characterise a vegetated slope and determine the contribution of vegetation to slope stability. The framework developed in this thesis integrates the quantification of the contribution of vegetation to slope stability into a geotechnical investigation and, therefore, avoids conflicts that would arise from bolting separate investigations onto the standard geotechnical practice. The development of the framework was achieved by a number of objectives, namely the identification of the effects of vegetation on slope stability and the quantifiable parameters, to facilitate identification and optimisation of the testing techniques and procedures available to determine said parameters. The wealth of knowledge available regarding geotechnical and hydrogeological parameters allowed a theoretical appraisal, whereas *in situ* field and laboratory testing was undertaken to evaluate the suitability of botanical and biomechanical techniques.

Vegetation has been shown to be influenced by, and influence its environment, the key aspects of which, regarding slope stability analysis, are the geotechnical and hydrogeological effects of vegetation on its environment. The direct contribution of vegetation includes soil water depletion through root water uptake and the mechanical reinforcement of binding, anchoring or buttressing. Anthropogenic and native fauna may influence the stability of a slope, however, current methods of slope stability analysis do not incorporate such activity, and as such these parameters currently have little design value. Therefore, the literature review focused on the geotechnical, botanical and hydrogeological parameters that have design value, and the techniques available to quantify these parameters.

Following the identification of the ways vegetation can influence slope stability, the parameters by which the influence of vegetation on slope stability can be measured have been determined and categorised into direct and indirect inputs. These parameters include geotechnical and hydrogeological parameters that would be included in a routine slope stability analysis, along with botanical and biomechanical parameters that are required to quantify the contribution of vegetation to slope stability. The input parameters have been grouped according to their application within slope stability models that can incorporate vegetation.

The most suitable techniques and procedures for the determination of these parameters have been identified. Evaluation of candidate *in situ* and laboratory testing techniques, to determine the influence of vegetation, was undertaken. A range of sites was investigated, and the evaluation and subsequent optimisation of the testing techniques facilitated the development of procedures for ascertaining the identified parameters. Issues identified include the variability associated with root pull out testing, and identification of the limitations associated with the *in situ* shear box test. Visual assessments were identified as the simplest means by which to collect data for subsequent subjective judgements to be made about the contribution of vegetation to slope stability. However, this requires a fundamental understanding of the nature of root reinforcement and species behaviour to be in place, from which assumptions may be made to facilitate engineering judgement.

The practical evaluation of available techniques, which can be employed to quantify the contribution of vegetation to slope stability allowed current knowledge and practice to be put into a non prescriptive tiered framework. The framework is designed to provide a structure from which the most appropriate approach for the desired outcome may be selected; ranging in detail from the qualitative analysis based on the visual assessment and desk study data through to a quantitative analysis based on a detailed site investigation, incorporating many of the measured quantifiable parameters. The framework gives recognition to the scale, complexity and state of current knowledge of the issues associated with the assessment of the influence of vegetation on slope stability.

On the basis of the literature review, experimental research and subsequent analysis discussed in this dissertation, a number of recommendations for further research can be made. The framework has been structured to readily allow the following potential developments to be incorporated.

Index properties and empirical correlations employed in geotechnical slope assessment are based on a wealth of data that is currently lacking with regard to the contribution of vegetation to slope stability. Therefore, the adoption of this standardised framework and outlined testing procedures to develop a database of root reinforcement index properties, will facilitate correlations with data determined from the visual assessment stage and increase confidence in the data determined from *in situ* testing techniques.

Subsequent to this, development of non invasive techniques such as Ground Penetrating Radar (GPR) could allow rapid assessment of root reinforcement potential on slopes. GPR has been employed to map root systems to varying degrees of success, however, the trade off between penetration and resolution, especially in high conductivity soils, and the software and processing power required to analyse the data, currently limits the use of this technique. For a geotechnical investigation, GPR may be more efficiently employed to detect zones of high and low root density, which may be correlated with root density distribution data, rather than the root morphology mapping that has been undertaken to date. However, such an application requires a wealth of data to facilitate comparative analysis and correlation. Therefore, further development regarding these issues is required to facilitate a wider use of GPR on vegetated slopes for root distribution determination.

The use of the *in situ* shear box is problematic; the choice of a suitable scale of test to determine the root reinforcement without incurring influence from the boundary conditions is still an issue. Similarly, the influence of inclusions on the shear zone height and drainage of the sample are considerations that require further research. Furthermore, the stress conditions associated with a normal load placed on the sample surface of the *in situ* shear box are different to those encountered in the soil by the extant biomass. Therefore, to replicate the biomass that has been felled it is necessary to attach the load to the tree stump rather than apply the load to the soil surface. Further research is required to determine whether it is necessary to combine the two systems to achieve a pertinent Mohr coulomb failure envelope, or whether the stresses imparted by the biomass are negligible.

Clamping of the roots for both the root pull out test and the direct tension test has also proved problematic. The separation of cortex from the stele can be both species and water content dependent, and some researchers have removed the cortex or dried the root prior to testing, to improve grip. However, these methods can affect the properties of the root and will impact on the root soil interface interaction data obtained. Therefore, further development of the root clamping device is required.

The conference and journal publications produced during the interim stages of the overall research project are included in the appendix.

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Was ist dem die wissenschaft? Sie ist nur des Lebens kraft
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Appendix

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Observation and simulation of root reinforcement on abandoned Mediterranean slopes

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Abstract

The mechanics of root reinforcement have been described satisfactorily for a single root or several roots passing a potential slip plane and verified by field experiments. Yet, precious little attempts have been made to apply these models to the hillslope scale pertinent to landsliding at which variations in soil and vegetation become important. On natural slopes positive pore pressures occur often at the weathering depth of the soil profile. At this critical depth root reinforcement is crucial to avert slope instability. This is particularly relevant for the abandoned slopes in the European part of the Mediterranean basin where root development has to balance the increasing infiltration capacity during re-vegetation. Detailed investigations related to root reinforcement were made at two abandoned slopes susceptible to landsliding located in the Alcoy basin (SE Spain). On these slopes semi-natural vegetation, consisting of a patchy herbaceous cover and dispersed Aleppo pine trees, has established itself. Soil and vegetation conditions were mapped in detail and large-scale, *in-situ* direct shear tests on the topsoil and pull-out tests performed in order to quantify root reinforcement under different vegetation conditions. These tests showed that root reinforcement was present but limited. Under herbaceous cover, the typical reinforcement was in the order of 0.6 kPa while values up to 18 kPa were observed under dense pine cover. The tests indicate that fine root content and vegetation conditions are important factors that explain the root reinforcement of the topsoil. These findings were confirmed by the simulation of the direct shear tests by means of an advanced root reinforcement model developed in FLAC 2D. Inclusion of the root distribution for the observed vegetation cover mimics root failure realistically but returns over-optimistic estimates of the root reinforcement. When the root reinforcement is applied with this information at the hillslope scale under fully saturated and critical hydrological conditions, root pull-out becomes the dominant root failure mechanism and the slip plane is located at the weathering depth of the soil profile where root reinforcement is negligible. The safety factors increase only slightly when roots are present but the changes in the surface velocity at failure are more substantial. Root reinforcement on these natural slopes therefore appears to be limited to a small range of critical hydrological conditions and its mitigating effect occurs mainly after failure.

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Introduction

Roots can contribute significantly to the stability of shallow soils on slopes (e.g., O'Loughlin, 1974; Schmidt et al., 2001). The mechanics of root reinforcement have been described satisfactorily for a single root or several roots passing a potential slip plane (e.g., Abe and Ziemer, 1991; Waldron, 1977; Wu, 1984, 1995) and these models have been corroborated by field and laboratory measurements (e.g., Riestenberg, 1994; Wu et al., 1988). Yet, precious little attempts have been made to apply these models to the hillslope scale pertinent to landsliding. This omission should be attributed to the limited size at which root reinforcement can be tested in the field and the emergence of the variability in soil and vegetation properties as a major factor at the hillslope scale. Consequently, the strain and strength at failure may be very different for actual landslides when compared to those under the controlled and idealised conditions of *in-situ* tests.

This paper therefore aims to translate local measurements of root reinforcement to the hillslope scale. Field evidence of root–soil interaction is combined with a geomechanical model by which root reinforcement and ultimately root failure can be simulated under different conditions. Such a model is needed because root behaviour under strain is essentially different from that of soils.

The model that considers the root reinforcing mechanisms in detail has been developed as a routine in FLAC 2D, a commercial finite difference code with widespread application in geo-engineering (Itasca, 2002). It simulates the stress-strain behaviour numerically so the strain-dependent effect of reinforcement can be simulated more realistically with fewer simplifying assumptions. Moreover, the root reinforcement model in FLAC offers the user to specify varying root and soil properties along the slope and the influence of the hydrology on the effective stress can be evaluated rigorously. This is highly advantageous since root reinforcement is influenced by the type and nature of the vegetation and local variations in soil conditions.

Descriptions of *in-situ* measurements and the root reinforcement model are given prior to the presentation of the case study that provides the field evidence for the application of the model. The field evidence stems from two slope transects affected by slope instability in the region near Alcoy in SE Spain. Here, landsliding is rife on steep slopes in weathered Miocene marl (see for a detailed description: La Roca and Calvo-Cases, 1988; La Roca, 1991; Van Beek, 2002). This region conforms to the general trend of the abandonment of marginal agricultural fields in the European part of the Mediterranean basin (MacDonald et al., 2000). Subsequent re-vegetation of these fields increases the infiltration and storage capacity of the topsoil. On abandoned slopes this leads to elevated pore pressures during prolonged or intense rainstorms and induce landsliding (Cammeraat et al., in press). However, these negative aspects may be partly counter-acted by increased root reinforcement that would define the ultimate stability of such abandoned slopes.

In-situ measurement of root reinforcement

Root reinforcement was studied by *in-situ* direct shear tests and root–soil interaction by pull-out tests. Additional descriptions and measurements provide background information to these tests and are presented briefly as part of the Case Studies where appropriate.

Pull-out tests were performed *in-situ* using a frame that allowed steady straining of the root until failure occurred. During the tests, the soil remained at the ambient moisture content. The maximum mobilised force was measured by means of a spring balance and recorded against the applied displacement (Cammeraat et al., 2002). In addition, species, diameter, orientation and inclination were noted for every root tested.

The shearing resistance of the rooted topsoil was tested *in-situ* by large-scale direct shear tests, as small samples cannot truthfully represent the effect of root reinforcement. The dimensions of the shear box used were 0.6 × 0.6 m in plan and 0.4 m deep to encompass a sufficiently large volume of rooted soil. The box was sunk vertically into the soil and the base excavated to provide a level surface over which the encased block could travel. Shear was applied by means of a jack and the generated shearing resistance measured with a proving ring as a function of the displacement. A normal load was applied by means of a dead weight of concrete blocks. Two loads were used, resulting in normal stresses of 3.3 and 4.1 kPa.

The soil was wetted thoroughly prior to testing to eliminate any suction-derived resistance and the shear rate kept low (4 mm min^{-1} on average) to avoid the build-up of excess pore pressures. Tests were carried out in two modes. In the first mode, a four-sided shear box was used, in the second mode the soil block was bounded by plates only perpendicular to the direction of shearing so that roots extending through the soil block were not truncated. In the second mode, 10 metal rods were installed on either side of the box to measure strain in the adjacent soil. After testing, root counts were made (see below). Root reinforcement was calculated by subtracting the theoretical shearing resistance of the non-rooted soil, which was determined in the laboratory on undisturbed samples.

From the direct shear tests and the pull-outs roots were collected to be tested in the laboratory in order to determine root elasticity and tensile strength.

Root reinforcement model

The root reinforcement model is based on the theory of reinforced soil (Vidal, 1966) and an extension of existing two-dimensional analytical models (e.g., Waldron, 1977; Wu, 1984). This process description applies to a 2D case in the vertical X–Y plane on which all roots are projected. According to the concept of reinforced earth root reinforcement is the result of the elongation of roots across a potential slip plane which generates a root force F_r that is transferred to the soil by the cohesive and frictional contacts between the root and the soil (Figure 1). Roots have been shown to deform elastically to imposed stresses (Waldron, 1977; Wu et al., 1979) and the root stress can therefore be calculated by means of Hooke's Law:

$$\sigma_r = E_r \frac{\Delta L}{L} \tag{1}$$

where σ_r is the resultant root stress [Pa],
E_r is the modulus of elasticity (Young's modulus) of a root [Pa],
$\Delta L / L$ is the elongation of a root per unit length of a root [m m^{-1}].

The actual reinforcement that can be mobilised is limited by two failure modes. Dependent on the loading, fully anchored roots will snap when the root stress exceeds the tensile or compressive strength. Alternatively, roots may fail prematurely by pull-out if during the loading of the root the resistance along the root–soil interface is overcome (Waldron, 1977). For a root extending across the slip plane the longitudinal stress, σ_a, along the root before failure by is given by (Waldron, 1977):

$$\frac{d\sigma_a(x)}{dx} = 4^B \Big/ d_r, \tag{2}$$

where d_r is the root diameter [m], and,
B is the bond strength, i.e. the shearing resistance at the root–soil interface for a unit length of an embedded root [Pa] and x is the distance along the root.

The bond strength is assumed to be independent of the root stress and the Mohr–Coulomb failure criterion is adopted here to describe it:

$$B = \mathrm{CO} \cdot (c_r + \sigma_n \tan\phi_r) = \mathrm{CO} \cdot R(c + \sigma_n \tan\phi), \tag{3}$$

where CO is the effective contact length along a root [m m^{-1}],

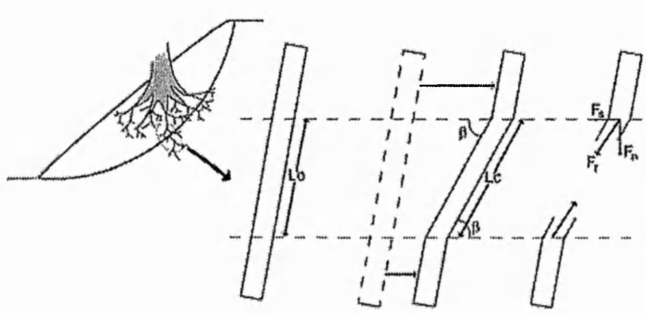

Figure 1. Schematisation of root reinforcement. A root passing a shear zone – indicated by the dashed horizontal lines – is extended from its original length L_0–L_c. This generates the root force $F_r = \sigma_r \cdot A_r$ that can be resolved by the angle of root inclination β into components normal and parallel to the shear plane, respectively F_n and F_s.

σ_n is the normal stress acting on a root [Pa],
c_r and c, are respectively the cohesion along the root–soil interface and of the soil itself [Pa],
ϕ_r and ϕ, are respectively the friction angle along the root–soil interface and of the soil itself [°],
and R is a reduction parameter [–] that relates the strength properties along the interface to those of the soil.

At the slip plane $x = 0$ (x_0) the root stress is at a maximum, $\sigma_a(0) = \sigma_r$ and it decreases towards its end (Waldron, 1977). To avoid failure by pull-out, the equilibrium along the soil-root interface before failure is given by the integration of Eq. 2 over the root segment x_0x_1:

$$\sigma_a(x_1) - \sigma_a(x_0) = 4B(x_1 - x_0)/d_r, \tag{4}$$

assuming that the diameter d_r is constant along this segment.

Since $\sigma_a(x_1)$ would be zero under equilibrium conditions when the bond strength is fully mobilised, the maximum shearing resistance along the soil–root interface is used to determine whether the root would fail by pull-out, i.e. $\sigma_r \geq 4B(x_1 - x_0)/d_r$, or in tension $\sigma_r < 4B(x_1 - x_0)/d_r$.

The mobilised root stress can be resolved for the enclosed angle β into two components of root reinforcement, working respectively, normal and parallel to the slip plane (Figure 1):

$$F_n/A_r = \sigma_r \sin\beta, \tag{5}$$

$$F_s/A_r = \sigma_r \cos\beta, \tag{6}$$

where A_r is the root cross-sectional area.

The component normal to the potential slip plane exerts a confining stress and adds to the frictional component of the shearing resistance along the slip plane. The parallel component is aligned with the shear stress along the slip plane. When a root is in compression, in which case the enclosed angle β is obtuse, the root stress component works in the direction of the shear stress and the component is negative. When a root is in tension the component counteracts the shear stress and the contribution is positive.

The total contribution of root reinforcement to the shear strength, S_r, depends on the relative root area of every root that passes the slip plane. Provided that the root distribution along the slip plane is known or can be estimated, S_r can be calculated from the sum of the root reinforcement of the individual roots:

$$S_r = \sum \sigma_r \frac{A_r}{A}(\cos\beta + \sin\beta \tan\phi), \tag{7}$$

where A_r/A is the relative root area (root cross-sectional area over total area).

The root reinforcement model based on Eqs. 1–7 has been coded in FLAC 2D (Itasca, 2002). The main differences between the original analytical formulations of the model and its implementation in FLAC concern the deformation of the soil mass and the description of distorting roots therein. In FLAC the soil mass is described by a grid of contiguous zones that connect at nodes. FLAC does not employ predefined shear planes but describes the stress-strain behaviour of the soil numerically leading to elastic or plastic deformation under the imposed loads. Thus, some assumptions on the deformation of the shear plane after failure can be relaxed and root reinforcement can be determined at any location and at any moment during the deformation of the slope.

For the analysis a plane strain configuration is used with the 2D plane coinciding with that in which the major and minor principal stresses are acting. On this plane, roots are projected with an inclination i to the positive x-axis (0–180°). Roots are classified according to this inclination and their diameter to give a root distribution, which specifies the number of roots passing a horizontal plane of one square meter per class.

The roots are treated implicitly in the model and an average root passing through the midpoint of a zone is taken to represent each class. On deformation, the inclination and length of the root segment change as a result of the normal strain, the shear strain and rotation experienced by each zone. For the deforming root, the root stress can be calculated from Eq. 1 if not broken already. The root stress of elongating roots is limited by their tensile strength, that of shortening roots by their compressive strength. If the root stress can be matched by the pull-out resistance and is limited by the tensile or compressive strength of the root, the root will break and no root tensile stress can be mobilised from the next calculation step onwards. For the calculation of the pull-out resistance, first the resistance along the root segment in the zone is calculated by means of Eqs. 3 and 4. If this local resistance is insufficient, additional pull-out resistance may be mobilised from connected root segments in adjacent zones. The connectivity between roots is derived heuristically from the transition probabilities, which are calculated from the root distribution for the zone under consideration. The root connectivity assumes that depending on their inclination roots connect only to the adjacent zone in the x- or y-direction. Also, dependent on their inclination, roots are either coarsening upwards or fining downwards. This results in an equivalent root length of which the corresponding resistance is added to the pull-out resistance. Different layers or root types can be used to capture the distribution of roots with depth or along the slope. For each root class, the parameters CO and R of Eq. 4, root elasticity (Eq. 1) and the root tensile strength must be specified. The latter is related by means of a global parameter to the root compressive strength (Table 1).

The root reinforcement of Eq. 7 is calculated in FLAC as the reinforcement per class and summed. The term A_r/A of Eq. 7 is merely the root cross-sectional area times the root count, N_r, over 1 m^2. The resulting root reinforcement is treated as an additional cohesion for the slope normal component or an additional tension for the slope parallel component. Both material properties cannot be negative in FLAC. Moreover, FLAC constrains the tensile strength to the tension cut-off. In the unlikely event that the root reinforcement violates the physical or theoretical limits of the tensile strength and cohesion, the following procedure is invoked and an error message issued: (1) if the tension cut-off is exceeded, the remainder is added to the cohesion; (2) if the tensile component is smaller than zero, it is subtracted from the cohesion, provided that the overall value, soil cohesion included, does not become negative.

The root reinforcement calculations are invoked at the start of every calculation cycle in FLAC and change the shear resistance of the soil on the basis of the stresses and deformations from the previous time step. The resulting alterations in the strength have consequences for the deformations and stresses that are calculated in main program of FLAC for the current step, and this process is reiterated during the solving process.

Table 1. Parameterisation of the root reinforcement model in FLAC 2D

Root mechanical properties	Generation of root stress and root failure by breakage
Root elasticity, E_r [Pa]	
Root tensile strength, T_r [Pa]	
Ratio between compressive and tensile strength, RCS [–]	
Root–soil interaction	Failure by pull-out
Cohesion*, c' [Pa]	
Friction angle*, ϕ' [°]	
Reduction factor, R [–]	
Effective contact length, CO [–]	
Root distribution	Classified root content linked to vegetation type and depth; used to describe root deformation and cross-sectional area
Root count	
Inclination in X–Y plane	
Diameter	

*Also used by FLAC.

Case studies

General site description

Detailed studies were made regarding morphology, vegetation and soil conditions at the two slope transects. Each transect was set out with three survey lines, 10 m apart, thus delineating a 20 m wide area. Along each survey line points were marked at every 10 m so a regular sampling network was created. From the elevation of these sampling points a profile was generated. This survey provided the basis for the mapping of the morphology and vegetation cover and the positioning of additional sample points.

The transects are located along a ravine (*barranco*) that dissects a pediment developed in Miocene marl (Transects A and B, see Figure 2). The ephemeral stream in the barranco forms the base of both slopes and signs of fluvial erosion are present. The transects receive a similar

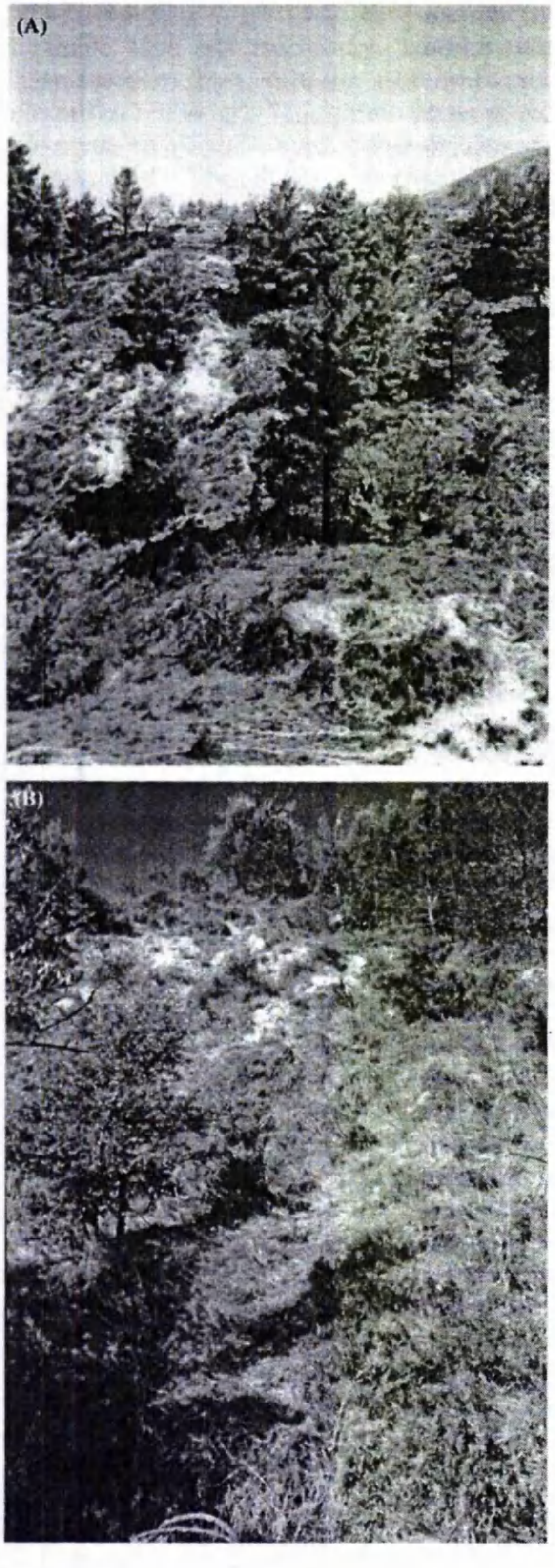

Figure 2. Overview of the slope transects A and B.

amount of insolation although their expositions differ (West and East, respectively). The slope transects have similar dimensions but slope B is steeper than A (Table 2). The relatively flat area of the pediment is presently cultivated but the bench terraces on the slopes have been abandoned and fallen into disrepair. In addition to the old terraces, landslide scars, gullies and deposition areas were identified along the slope. These morphological units were subject to diminishing degrees of erosion and secondary mass movement activity. The activity of these processes on the flatter old terraces was negligible or absent.

Sampling in soil pits and auger holes along the survey lines was used to describe the soil and to determine the porosity, dry bulk density and shear strength. Soil descriptions according to the FAO classification (FAO, 1990) also included determination of the particle size distribution (by dry sieving for the fraction > 63 μm, by hydrometer tests for the fraction < 63 μm), carbon content (cf. Wesemael, 1955) and organic carbon content (cf. Allison, 1935) for the soil pits. For the determination of the porosity and dry bulk density, undisturbed samples of 10^{-4} m^3 were taken in fivefold for every horizon of the soil pits and at 0.25, 0.75 and 1.25 m depth in the auger holes, if not restricted by the presence of bedrock. Undisturbed block samples were also used to determine the shear strength of the non-rooted soil on which anchorage and overall slope stability depend (see below).

In total, five soil pits and 80 auger holes were described and sampled. The observed soil depth was 0.95 m on average for both slopes but tended to be more variable on slope B, where the presence of buried topsoils and Pleistocene soils was attested. Notwithstanding these differences, the soil properties were relatively uniform. The sampled profiles can be classified as calcaric cambisols and the carbonate content is high (> 55%

Table 2. Morphometry of the slope transects A and B

Transect	Length [m]	Slope angle [°]		
		Average	Min.	Max.
A	110	20.7	3.6	32
B	100	23.7	7.8	39.3

by weight). Partly due to the cementation of finer particles by carbonate, the silt fraction dominates the texture. Only in the topsoil a variation in organic carbon content was found and this and the porosity decreased with depth (Cammeraat et al., in press). No obvious differences were attested between the slope transects, hence the average bulk density and porosity, determined from the mass difference between a saturated and oven-dry sample, are respectively, 14 kN m^{-3} and 0.43 m^3 m^{-3} (246 samples).

Characterisation of vegetation and root distribution

Tree location and the extent of the tree canopy as well as that of the herbaceous cover were mapped. Ground cover of the herbaceous cover was estimated visually and classified: < 10, 10–25, 25–50, 50–75 and > 75%. For each polygon a tally of common species was made over a grid of 1 × 1 m at 0.1 m intervals. At selected places this inventory was combined with a determination of the dry above-ground biomass over the grid (cf. Cammeraat et al., 2002).

Of trees taller than 2 m, species and location were noted, as well as its height, diameter at breast height (DBH, 1.3 m) and canopy extent, shape and volume (Cammeraat et al., 2002). Foliage density was measured with a LI-COR LAI-2000 (LI-COR, 1990).

The inventory of common species revealed that areas with near complete cover (> 90% on average) were dominated by *Brachypodium* sp. (over 75%), those with a sparse cover (< 50% on average) were characterised by succulent and aromatic species such as *Sedum* sp., *Sempervivum* sp. and *Thymus* sp. This finding was confirmed by the dry biomass determination of respectively, 1.08 and 0.58 kg m^{-2} (respectively, 3 and 6 samples). Consequently, the vegetation units were lumped into two classes, representing a denser and a sparser vegetation type (respectively, type I and II). Vegetation type II prevails on scars and other less stable surfaces. Overall, slope A had a sparser cover than slope B (48.5 and 80.3% classified as vegetation type I),

An equal number of trees > 2 m was present on slope A and B (respectively, 44 and 41). The majority of these trees were Aleppo pine (*Pinus halepensis* (Mill.)) with insubordinate numbers of olives (*Olea europaea* (L.)), almonds (*Prunus dulcis* (Mill. D.A. Webb)) and hawthorns (*Crataegus monogyna* (Jacq.)). The former crop trees especially abounded on slope B (37% compared to 7% on slope A). Mature pine trees varied in height between 7.5 and 15 m and had a DBH of 0.2–0.5 m and pine trees were generally better developed on slope A than on slope B (Table 3). A good linear relationship exists between height and DBH (R^2 = 0.85).

Root counts were made after the *in-situ* direct shear tests and in the soil pits, predominantly to serve as input for the 2D model. Therefore, the roots were projected on the *X–Y* plane, classified on the basis of their diameter, inclination and depth, and expressed as a number for a given soil volume, in this case 1 m^2 of basal area times the zone height.

For the direct shear tests, all roots were counted over the basal area of the shear box at every 0.1 m depth up to the depth of the imposed slip plane (0.4 m). Roots were counted as totals over four root diameter classes: < 1, 1–3, 3–6 and > 6 mm.

The five soil pits provide information on the overall root content under the two vegetation types (respectively 3, and 2 pits). A 0.1 × 0.1 m grid and 0.5 m wide was placed in the pit and all roots larger than 1 mm in diameter described by its diameter, inclination, orientation and position. Fine root content was determined gravimetrically. At every 0.1 m depth, three undisturbed cores of 10^{-4} m^3 were taken from which the roots were extracted by wet-sieving in the

Table 3. Characteristics of the pine trees at the slope transects

Transect	Number	Tree height		DBH		Drip line		Foliage density	
		Average	SD	Average	SD	Average	SD	Average	SD
A	41	6.53	3.12	0.14	0.12	1.92	1.15	1.47	0.99
B	26	5.13	2.72	0.10	0.08	1.48	0.72	0.97	0.49

All values in [m] except foliage density [m^2 m^{-3}]. Shown are the average and standard deviation (SD).

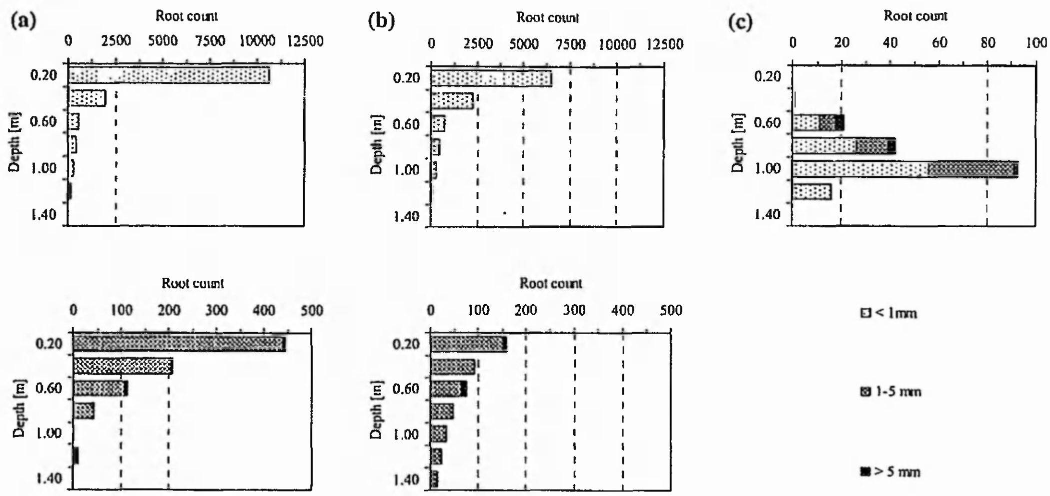

Figure 3. Root distributions for the different vegetation types: (a) Type I (dense), (b) Type II (sparse), (c) pine trees. Note the different scales used to represent the root contents.

laboratory. These roots were dried and weighed. Thus, the volume of roots for the known volume of soil could be calculated by assuming the specific gravity of the roots. By taking the average length of the sampling rings (50 mm) and an average diameter of 0.5 mm the number of fine roots could be estimated.

The root counts from the pits were deemed insufficient in number and size to represent the structural roots of the trees present on the slopes. As an alternative, the three-dimensional information from a digitised root system was used (cf. Danjon et al., 1999). The digitised root was transformed into a two-dimensional representation by means of pole coordinates and broken down into 1m-wide concentric rings in the *X–Y* plane.

Figure 3 summarises the root distribution data for the vegetation types. The overall root content showed that vegetation type I is more rooted than type II. In both cases, however, coarse roots penetrate over 1.2 m into the soil. This applies both for the coarse and fine root content although the conversion factor for the latter had to be tuned significantly in order to bring the root numbers in agreement with the counts from the direct-shear tests. The data on tree roots derive from a digitised root system of maritime pine (*Pinus pinaster* Ait.; Fourcaud et al., 2003). This system had a maximum lateral extent of 3 m and reached a depth of 1.2 m. Since the outer ring only contained 11% of the total root count and 56% of the area of 28.3 m^2 its influence on root reinforcement will be small and its roots have been redistributed over the inner two rings. Compared to the overall root count, the number of structural tree roots is small (Figure 3). All roots are fairly evenly distributed over the different inclination classes (not shown).

Root mechanical properties

Root elasticity and tensile strength were determined by Xylomecá in the laboratory on behalf of the Laboratoire du Rhéologie du Bois de Bordeaux (LRBB). The roots were kept in cold storage and soaked for 24 h prior to testing in tension using a load cell of 1 kN maximum capacity and a constant deformation rate of 2 mm min^{-1} (Genet, 2004). The maximum force at failure and the cross-sectional area were used to calculate the root tensile strength. Root elasticity (Young's modulus) was calculated from the slope of the stress-strain curve during the first, recoverable part of the root deformation.

A total of 52 root samples from the direct shear tests and pull-outs were tested of which 39 were *Pinus halepensis* and the remainder *Olea Europaea* and *Crataegus monogyna*. Of these, 17 had a diameter between 1 and 5 mm with bark, the remaining roots were larger (maximum of 14 mm). No roots smaller than 1 mm were tested.

No apparent differences in root elasticity or tensile strength were found and all roots have been lumped in the analysis. Overall, root elasticity showed a decrease with increasing root diameter. This relationship can be described by a power-function but the variability is large ($R^2 = 0.22$):

$$E_r = 1.25 \cdot 10^7 d_r^{-0.76}, \quad (8)$$

where d_r is the root diameter [m] and E is the root elasticity [Pa].

The observed values range from 0.1 to 2.9 GPa. For the diameter classes of 1–5 and >5 mm the mean and standard deviation are respectively, 1.24 ± 0.81 GPa and 0.66 ± 0.52 GPa.

A constant but highly variable root tensile strength was found for the diameters tested, ranging from 3 to 43 MPa with an average of 13 MPa and a standard deviation of 6.8 MPa.

After rejection of the *in-situ* pull-out tests in which the root snapped at the attached clamp, 28 successful tests were available with diameters between 1 and 11 mm, the majority on pine. Most roots snapped and only few were pulled clear from the soil. The pull-out resistance measured *in-situ* thus largely coincides with the tensile strength determined in the laboratory with a range between 3 and 24 MPa an average of 9.3 MPa. Again, the tensile strength is independent of the root diameter.

Shear strength of non-rooted and rooted soil

The shear strength of the non-rooted soil was determined on saturated, undisturbed samples from the slope transects. Because of its simple and speedy execution, the tor vane test was used to obtain shear strength measurements from the 232 samples gathered at the 80 sample points (USACE, 1983). These data were spatially interpolated by block-kriging at the respective sample depths of 0.25, 0.75 and 1.25 m. Due to the rapid deformation of the saturated material excess pore pressures are generated and the results should be interpreted in terms of undrained strength (Yarbrough, 2000). Since the onset of failure of the natural slopes in the area generally occurs under drained conditions, the drained shear strength was determined in the laboratory by means of consolidated-drained strain-controlled tests (BS, 1990). The tests were performed on block samples from the soil pits with dimensions of 60 × 60 mm wide and 20 mm high. Of five representative horizons six samples were tested at three imposed normal stresses within the range from 50 to 125 kPa and a strain-rate of 0.2 mm h^{-1}.

The undrained shear strength showed a weak increase with depth. The same tendency was observed for the drained shear strength (Table 4). The close similarity between the undrained shear strength and the drained cohesion points towards the complete absence of the frictional component in the former. The variation in the undrained shear strength and the drained cohesion are large and the latter does not significantly differ from zero. The drained friction angle ϕ' varies between 31° and 36° for the different horizons. A linear regression resulted in an overall friction angle of 33.6° when the cohesion was set to zero. The peak of the drained shear strength was generally achieved at 12% strain or 7 mm strain.

At slope B eight large-scale *in-situ* direct shear tests were carried out on the rooted topsoil under

Table 4. Shear strength properties (6 tests per horizon at three imposed normal loads between 59 and 117 kPa)

Horizon		Depth [m]*	c' [kPa]**	c_u [kPa]†	ϕ' [°]**
Ah	Top soil	0.00–0.17	4.8	4.5	34.4
Bw	Weathered soil	0.17–0.26	1.9	4.8	35.3
C1g*	Gleyic horizon	0.26–0.59	10.2	8.1	31.2
C12*	Colluvium	0.59–0.69	9.8	8.2	31.7
C2	Regolith	0.69–0.92	4.1	6.5	36.4

*The horizons C1g and C12 are not necessarily present and the given depths are indicative only. The depth is the average of the observed layers and indicative only.
**c' and ϕ' are the drained shear strength parameters.
†c_u is the average undrained shear strength (cohesion) based on field measurements ($N = 232$ in total).

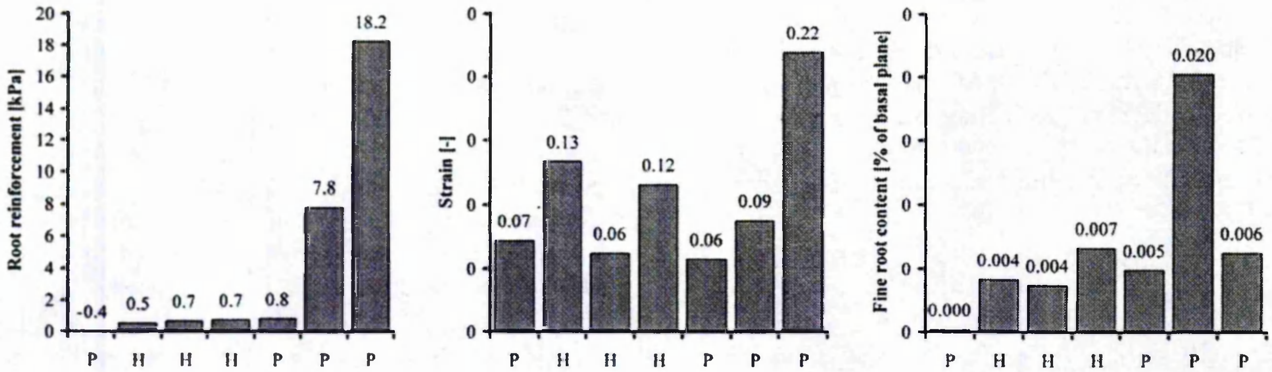

Figure 4. Reinforcement, strain and fine root content (< 1 mm) for seven out of the eight *in-situ* direct shear tests. H and P refer respectively, to herbaceous cover and the presence of pine trees.

varying vegetation conditions (see test description above). Of these, two were of the four-sided design (Tests 1 and 8), 6 of the two-sided design. The strain at failure is more variable than in the laboratory, ranging between 6 and 25% (34 and 150 mm, respectively) and is weakly correlated to the root reinforcement of the soil (Figure 4). During the tests roots could be heard snapping and corresponding drops in the stress–strain curve were observed (Figure 5.C). Some arching into the soil was observed in the two-sided design but the movement was small compared to the displacement of the enclosed block and few roots crossed through the lateral sides with the exception of Test 2 under dense forest cover of *Pinus halepensis*. This test returned the highest root reinforcement of 18.2 kPa while only in one test no reinforcement was observed (−0.4 kPa; Figure 4). The four-sided tests near pine trees yielded reinforcements of respectively 3.3 kPa and 7.8 kPa, the latter made on an 11-year-old sapling. Over all tests, the average root reinforcement is 3.9 kPa. When the largest reinforcement of Test 2 is excluded, a good correlation between the fine root content (< 1 mm) of the slip plane and the root reinforcement is found ($R^2 = 0.96$).

Model applications

General

The root reinforcement model in FLAC has been applied to model the *in-situ* direct shear tests as a test of its validity and to assess the slope stability of the two slope transects.

For the modelling, the average soil properties for the friction angle, bulk density and porosity have been adopted (Tables 5 and 6). For unsaturated conditions an average degree of saturation of 65% at field capacity has been used to calculate the bulk density of the material (Van Beek, 2002). The applied cohesion varied per application (see below). The bulk modulus, K, and shear modulus, G, are needed to calculate the deformations in FLAC and initially literature values were assigned (K = 5.0 MPa, G = 2.3 MPa).

For each root diameter root elasticity was calculated from the power function of Eq. 8. The mean tensile strength was used for all roots. Without any reliable data to suggest otherwise, the ratio between the root compressive strength and the tensile strength, the root contact length and reduction parameter were kept at unity (Eq. 4).

The surcharge due to the self-weight of the vegetation has been ignored due to the want of data and the patchy nature of the vegetation cover.

In-situ *direct shear tests*

Model settings

In the simulation of the direct shear tests, the X–Y plane of the problem was aligned parallel to the imposed shear displacement of the soil block (Table 5). The shear box was located in the centre of the block, on which the corresponding normal load was imposed, and the adjacent areas excavated (Figure 5). The shear plane was modelled as a detachable interface to allow for the observed horizontal displacement. The simulation was carried out in two stages (Table 5). After the

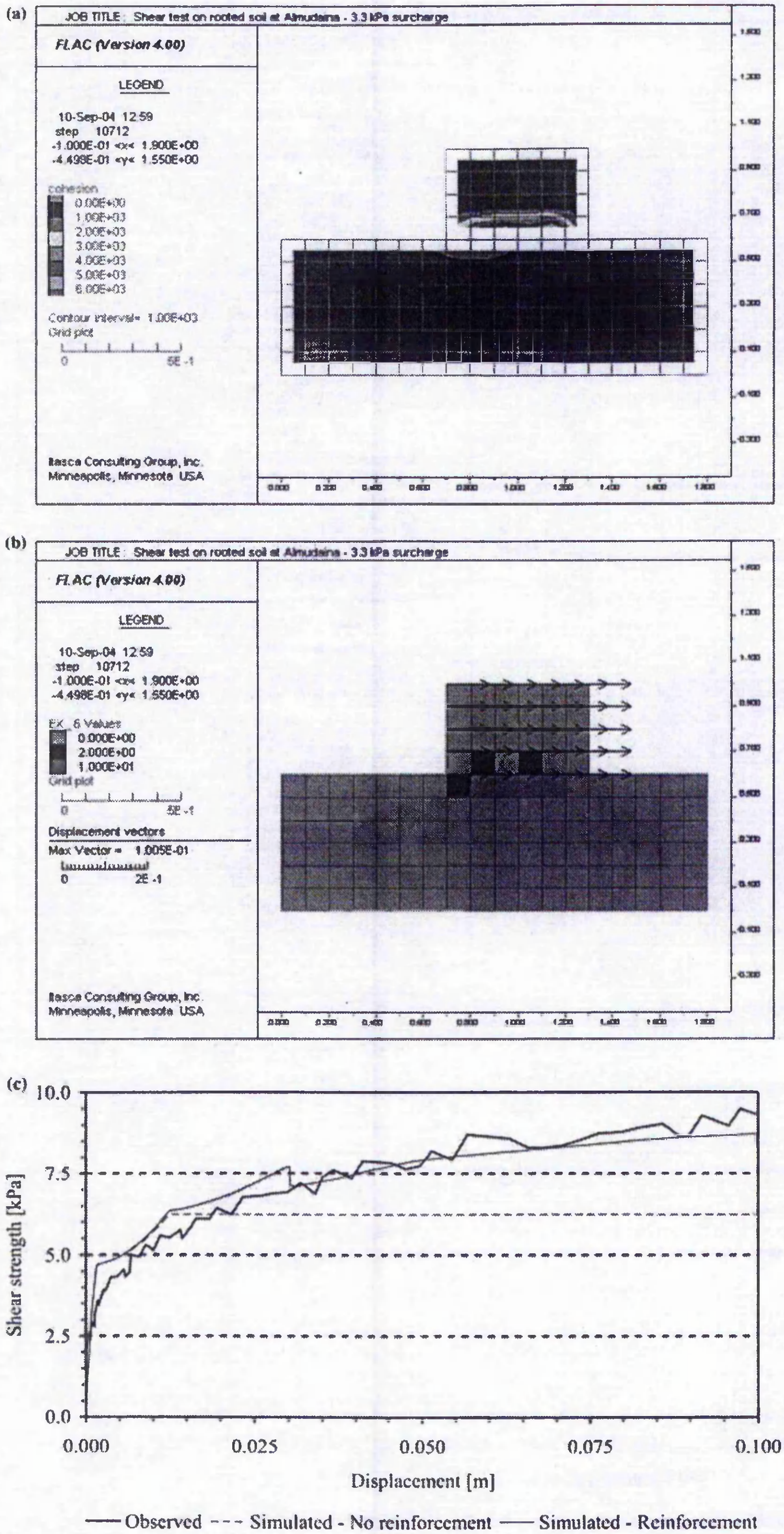

Figure 5. Simulated direct shear tests. (a) mobilised root reinforcement [Pa], (b) zones containing broken roots (zones with values larger than 0), (c) observed and simulated stress-strain curve.

Table 5. Model settings for the simulation of the *in-situ* direct shear tests

Model settings			
Analysis	Plane strain, X–Y plane aligned to direction of shear displacement		
	Mechanical only, total stress analysis		
Grid dimensions	Number of zones	Distance [m]	Resolution in area of interest [m]
Horizontal (X)	18	1.80	0.10
Vertical (Y)	11[*]	1.00	0.10
Model	Mohr–Coulomb		
Mechanical boundary conditions	Left-hand side	Bottom	Right-hand side
	Fixed in X	Fixed in X and Y	Fixed in X
Loads	Gravity, 9.81 m s^{-2}		
	Surcharge (3.3 or 4.1 kPa) at top shear box		
Imposed groundwater conditions	NA		
Imposed root conditions	No roots		
	Actual root distributions		
	Root distribution for vegetation type I		
Parameterisation			
Soil properties[**]	Bulk modulus, K	5.0	MPa
	Shear modulus, G	2.3	MPa
	Dry bulk density	1425	Kg m^{-3}
	Porosity	NA	m^3 m^{-3}
	Degree of saturation	NA	–
	Cohesion, c'	0	kPa
	Tensile strength	0	kPa
	Friction angle, ϕ'	33.6	°
Root distribution	Inclination	Diameter[***]	Depth
	0–60°,60–120°, 120–180°	< 1, 1–3, 3–6, and > 6 mm	0.10–1.0 m depth
Root properties	Elasticity[†]	$1.25 \times 10^7\ d_r^{-0.76}$	Pa
	Tensile strength	13×10^9	Pa
	All remaining parameters (CO, R, RCS) set to unity		
Modelling stages			
Initial	*Obtaining initial geostatic stresses* (with fixed grid for shear box)		
	Force equilibrium[‡]	1 N	
Strain mode	Small strain mode, nodal coordinates not updated		
Root reinforcement	Not invoked		
Main	*Simulating displacement during direct shear test*		
Convergence	None, driven by imposed X-velocity (4 mm min^{-1}) for shear box, displacement halted when total displacement exceeds 0.10 m		
Strain mode	Large strain mode, nodal coordinates updated		
Root reinforcement	Invoked at start of every calculation step		
Additionally reported variables	Average normal and shear stress and displacements along the interface for comparison with the observed stress–strain curves, root reinforcement and root status		

[*]One zone (7th in Y-direction) has been set to zero to create the detachable interface that serves as imposed shear plane.
[**]Properties for the main modelling stage.
[***]The root distribution of vegetation type I is subdivided in three root diameter classes (< 1,1–5, and > 5 mm).
[†]Root elasticity is given as function of root diameter, d_r, in m.
[‡]Maximum unbalanced force.

Table 6. Model settings for the slope stability assessments

Model settings			
Analysis	Plane strain, X–Y plane aligned in the direction of the survey line		
	Mechanical only, effective stress analysis		
Grid dimensions	Number of zones	Distance [m]	Resolution in area of interest [m]
Horizontal (X)	220	110	0.50
Vertical (Y)	30	Var.	0.20
Model	Mohr–Coulomb		
Mechanical boundary conditions	Left-hand side	Bottom	Right-hand side
	Fixed in X	Fixed in X and Y	Fixed in X
Loads	Gravity, 9.81 m s^{-2}		
Imposed groundwater conditions	Fully saturated		
	Critical groundwater level*		
Imposed root conditions	No roots		
	Actual root distribution in connection with vegetation density		
	Fully rooted (complete tree and vegetation cover)		
Parameterisation			
Soil properties**	Bulk modulus, K	5.0	MPa
	Shear modulus, G	2.3	MPa
	Dry bulk density	1425	Kg m^{-3}
	Porosity	0.43	m^3 m^{-3}
	Degree of saturation	0.65	–
	Cohesion, c'	0–29***	KPa
	Tensile strength	0–43***	KPa
	Friction angle, ϕ'	33.6	°
Root distribution	Inclination	Diameter***	Depth
	0–60°,60–120°, 120–180°	< 1, 1–5, > 5 mm	0.20–1.6 m depth
Root properties	Elasticity†	$1.25 \times 10^7\ d^{-0.76}$	Pa
	Tensile strength	13×10^9	Pa
	All remaining parameters (CO, R, RCS) set to unity		
Modelling stages			
Initial	Obtaining initial geostatic stresses (under increased strength)		
Convergence	Force equilibrium‡		100 N
Strain mode	Small strain mode, nodal coordinates not updated		
Root reinforcement	Not invoked		
Main	Calculating stability without and with root reinforcement		
Convergence	Factor of safety ($\Delta F < 0.005$) and critical groundwater levels ($\Delta W < 0.01$ m)		
Strain mode	small strain mode, nodal coordinates not updated		
Root reinforcement	Invoked at start of every calculation step		
Additionally reported variables	Safety factor, critical groundwater depth, surface velocities, root reinforcement and root status		

*Obtained from back-analysis for the non-rooted case.
**Properties for the main modelling stage.
***Cohesion for the first 1.5 m derived from interpolated undrained shear strength measurements, below this depth an exponential increase to a maximum of 29 kPa at 2.5 m. No tensile strength was assigned to the first 1.5 m, thereafter it was taken equal to the tension cut-off of the Mohr–Coulomb failure envelope.
†Root elasticity is given as function of root diameter, d_r, in m.
‡Maximum unbalanced force.

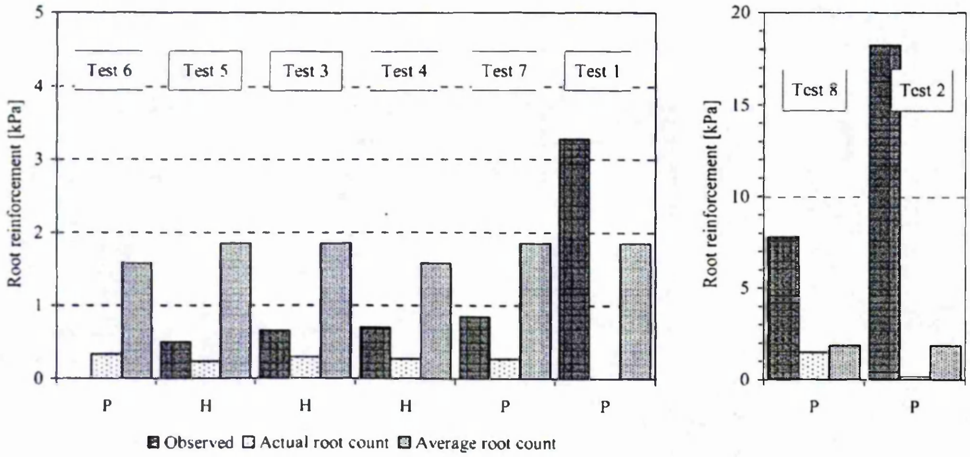

Figure 6. Comparison of the observed and modelled root reinforcement for the *in-situ* direct shear tests. Note the difference in scale between the graphs.

initial stress distribution was obtained, the actual test was simulated. A horizontal strain rate was applied to the soil block contained by the shear box. The imposed strain rate was slow enough to ensure consolidated-drained conditions and pore pressure effects were not considered.

Along the shear plane, both the average normal and shear displacements and stresses were monitored in order to compare them with the observed stress-strain curve. The shearing of the soil block was simulated until the calculated shear displacement equalled the observed displacement in the field.

Parameterisation

All *in-situ* direct shear tests were modelled with the corresponding normal load and the actual root distribution of each test, the root distribution of vegetation type I and without any roots. The actual root distributions were available for the first 0.4 m at a vertical resolution of 0.1 m. Below this depth, root counts were extrapolated to 1 m depth. The actual root distributions were summarised into four diameter classes, as used for the counts in the field (< 1, 1–3, 3–6 and > 6 mm). Except for some structural roots, the inclination and orientation of the roots was not recorded, so the root numbers were divided equally over three inclination classes (0–60°, 60–120°, 120–180°). The same inclination classes were used for the root distribution of vegetation type I for which a distinction in three diameter classes was made (< 1, 1–5 and > 5 mm).

As the imposed shear plane was most times located in the Bw horizon of low cohesion, no cohesion or tensile strength were attributed to the soil.

Results

The result shows that the model simulates the strain-dependent nature of root reinforcement and the failure of roots by breakage or pull-out (Figure 5c). However, the assumed plane strain conditions implied that only the four-sided direct shear tests can be simulated directly and therefore the relative root reinforcement is presented (Figure 6). The simulated root reinforcement for the actual root distributions is approximately 0.3 kPa with the exception of Test 8 for which the reinforcement is 1.5 kPa. Inclusion of the root distribution of vegetation type I gives a simulated root reinforcement of 1.6–1.9 kPa.

Slope stability assessments

Model settings

The slope stability has been assessed for each of the three survey lines of the two hillslope transects that were aligned to the maximum slope (6 in total, i.e. 3 profiles × 2 transects).

The grid of each analysis contained 220 by 30 zones (Table 6). The vertical resolution was constant for the upper 10 zones (2 m) whilst the underlying 20 zones were distorted to generate the slope profile. The total grid length allowed for the inclusion of two flat areas in the order of 5–10 m wide at the toe and crest of the slope. All analyses were made in terms of effective stress assuming fully drained conditions.

After an initial stress distribution was obtained, the safety factor was calculated for each survey line by means of the parameter reduction method (Dawson et al., 1999). In addition the surface velocity field after 1000 calculation steps was evaluated. These velocities are the hypothetical deformation rates by which the model attempts to accommodate the unbalanced body forces that act on each zone of the grid. Since the model was run in small-strain mode for the safety factor calculations (i.e. coordinates of the nodes are not updated), these velocities may be large when they represent plastic strain at the onset of failure. Still, the velocity offers valuable information on local slope stability and the values along the profiles have been interpolated by means of inverse distance interpolation so that the surface velocity field can be compared to the morphology and vegetation along the slope transects.

Root conditions that were evaluated included a completely non-rooted case, the actual rooted case, and fully rooted case for the central survey line. For each root condition, the safety factor was calculated for a worst-case scenario in which the slope was completely saturated and for a more realistic case in which a constant piezometric line was imposed for which the slope was critical (factor of safety of unity) for the non-rooted case.

Parameterisation

The slope stability assessments differ from the simulation of the *in-situ* direct shear tests by the fact that the root distributions are less accurately known, yet have to be specified along the entire slope. In this case root distributions were assigned according to the presence of the two vegetation types along the slope. Where trees were present, the distribution of the digitised tree roots was added. The extent of the tree roots was determined from the ratio between the drip line and the extent of the digitised root system (3 m). This approach seems justified by the good relationship between the drip line and the DBH, which is a good estimator of the dry root mass for conifers (Drexhage and Gruber, 1999). In order to take the opposed inclination of roots on either side of the stem into account the number of root classes was doubled and the inclination of the roots mirrored along the *Y*-axis. This results in four root types that in combination with the two vegetation types and the presence or absence of trees result in 10 root types. For the modelling, all trees intersecting the profiles were included and all trees, including the deciduous ones, were treated as pines. Since no inclination was known for the fine roots (< 1 mm) the root numbers were equally divided over the three inclination classes used (Table 6).

For the analysis under fully rooted conditions trees with a canopy extent of 3 m on either side of the stem were positioned continuously along the slope and the dense vegetation type I was used for the undergrowth.

For the upper 1.5 m of the soil, the interpolated tor vane readings were substituted for the local cohesion. Below this depth, the cohesion increased exponentially until it reached the average cohesion for sound bedrock (Van Beek, 2002). No tensile strength was attributed for the upper 1.5 m of the soil and the theoretical maximum of $c' \times \cot \phi'$ was used below this depth.

Table 7. Safety factors for the survey lines under different conditions for root density and hydrology

Transect	Hydrological conditions	Root conditions	Survey line		
			1	2	3
A	Saturated	None	0.98	0.68	0.92
		Actual	1.06	0.70	0.93
		Full		0.70	
	Critical	None	1.00	1.00	1.00
		Actual	1.09	1.05	0.99
		Full		1.05	
B	Saturated	None	0.74	0.59	0.67
		Actual	0.76	0.63	0.70
		Full		0.64	
	Critical	None	1.00	1.00	1.00
		Actual	0.98	1.05	0.99
		Full		1.05	

Results

Both slopes are potentially unstable as the safety factors under full saturation indicate (Table 7). On both slopes the areas of simulated failure coincide with the actual scars and deposition

Table 8. Average and standard deviation of surface velocities (see also Figure 7) for the two slope transects under different conditions for root density and hydrology

Transect	Hydrological conditions	Root conditions	Surface velocity at failure [mm h^{-1}]	
			Average	Standard deviation
A	Saturated	None	−117.4	171.4
		Actual	−63.0	103.6
	Critical	None	−2.7	8.6
		Actual	−29.3	43.4
B	Saturated	None	−567.5	442.5
		Actual	−492.0	395.3
	Critical	None	−18.2	23.3
		Actual	−28.7	41.6

areas. For slope A, the stability of the central survey line becomes critical when the groundwater is at 0.2 m below the surface. The adjacent survey lines are marginally stable when the groundwater is close to the surface. Slope B is generally less stable and critical groundwater levels vary between 0.25 and 0.45 m below the surface. In the case of full saturation, the presence of roots generally increases slope stability but this increase is small and irrespective of the number of roots since the factor of safety does not increase appreciably whether the actual root content or the fully rooted soil is considered. For the critical groundwater depth, the increase in stability is less marked and sometimes marginally negative. In all cases the soil fails in the C-horizon at approximately 1 m depth. In the unstable soil mass, the simulated root reinforcement is found at the scarp, toe and base. The mobilised reinforcement at the base is less than 1 kPa due to the low root content.

The surface velocities associated with the plastic deformation field are high (Table 8). The velocities generally show a significant decrease in displacement when the hydrological conditions change from fully saturated to the critical water level regardless the root content. Under saturation, root content has a positive influence on the velocities. Again, the velocities do not change along the central profile when fully rooted conditions are imposed (not shown). Under critical conditions, the marginal destabilising influence due to compressing roots is found here again but the associated deformations are generally small (in the order of a few centimetres when FLAC is run in 'large-strain' mode, i.e. when the nodal coordinates are updated).

When the velocity patterns along the slope are compared, it becomes apparent that for both slopes the scars, gullies and deposition areas are the least stable. Slope A clearly shows the largest velocities in the category with less than 10% vegetation cover. Due to the dense cover on slope B, the picture is less clear with the largest velocities occurring in the categories between 25 and 75%. The influence of vegetation on slope stability remains, however, confused. Only in a few locations a clear decrease in the surface velocity is simulated, such as in the middle section of Slope A (Figure 7).

Discussion

In the study area abandonment has led to the emergence of a semi-natural vegetation cover that is characterised by a patchy ground cover, remnants of crops and isolated pine trees of different age and size. Since abandonment slope instability has occurred at both transects. At slope B the buried horizons indicate a higher activity of mass wasting in the past, which is consistent with the difference in slope angle but contradicts the sparser vegetation cover on slope A. Possibly the instability is of a younger date or re-vegetation is slower at this site.

Notwithstanding the differences in process activity, local variability obscures any larger trends in soil properties along the slopes. The uniform composition of the Miocene marl and

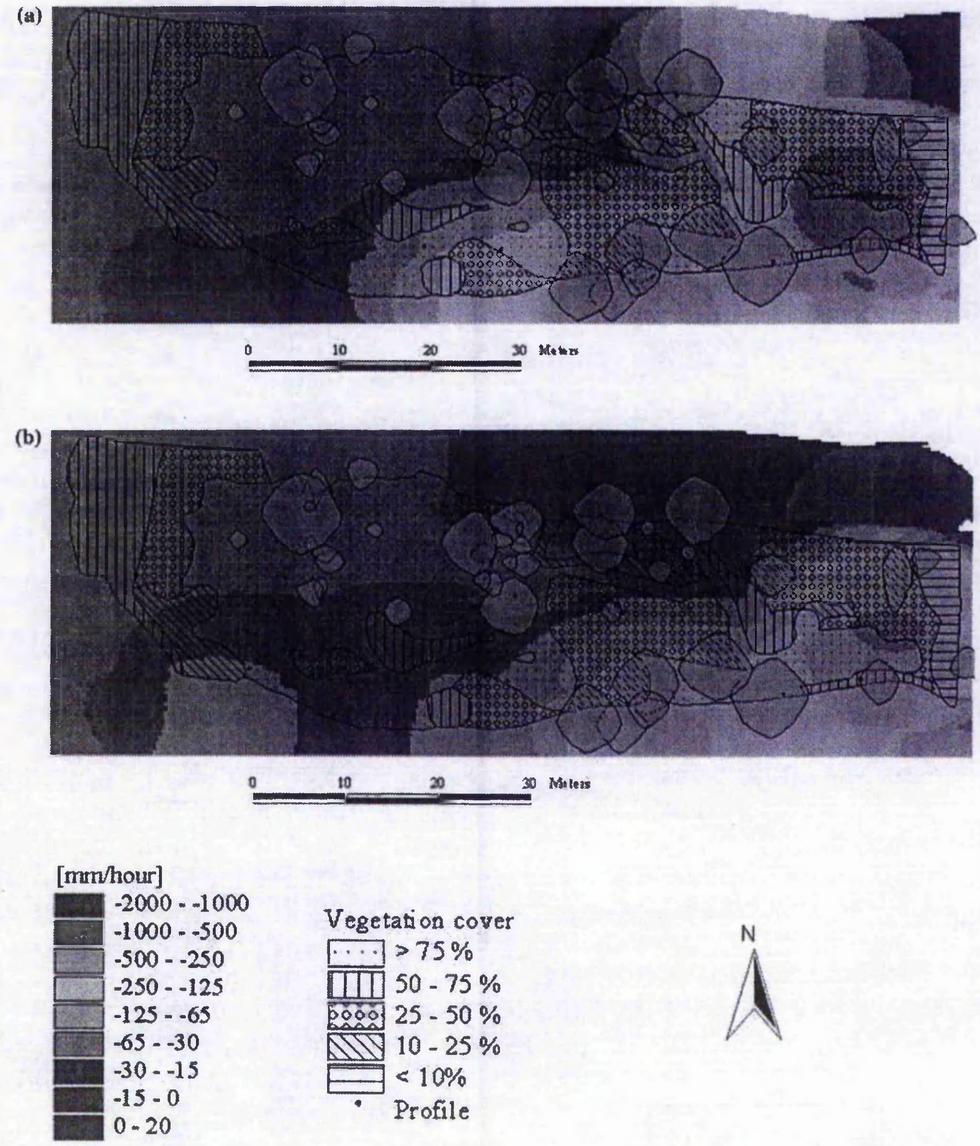

Figure 7. Surface velocities along slope A. Shown are the non-rooted (a) and rooted case (b) under fully saturated conditions. The crest of the slope is to the right. Negative velocities point downhill. Superimposed on the surface velocities, the location of the sampling profiles and the vegetation cover and extent of the tree canopy are shown.

the associated high carbonate content are overriding factors that limit soil development. Cementation by carbonates decreases the activity of clays, thus reducing cohesion, and increases the particle size, thus increasing friction (Lamas et al., 2002; Skempton, 1985).

Since the slopes are prone to instability, root reinforcement may be important to maintain stability under critical hydrological conditions. In the present case root reinforcement was attested in eight *in-situ* direct shear tests. The observed values fall well within the range of values listed in literature for a wide range of vegetation types (op. cit. Sidle et al., 1985). Reinforcement derives mainly from the loading of fine roots as the correlation between root reinforcement and fine root content suggests. Vegetation type appears to be of secondary importance to the actual reinforcement, which should be attributed to the fact that few coarse roots permeated the imposed shear planes in those cases and that there is little variation in root mechanical properties between species and root sizes. Where abundant, coarse roots contribute significantly to the soil shear strength as shown by the high values obtained for two tests made under pine.

The significance of fine roots is confirmed by the simulated direct shear tests. The root reinforcement model approximates the observed stress-strain behaviour with inclusion of the observed mechanisms of root failure during the tests. Yet, the actual root counts returned simulated root reinforcements that underestimate the observed values while the average root count overestimate them. This difference should be attributed to the amount of fine roots included. For the two tests under pine (Tests 2 and 8), neither the actual nor the average root distribution yielded satisfactory results. For Test 2, this shortcoming is partly explained by the absence of lateral roots crossing the soil block. For both tests, also the vertical extension of coarse roots may be underestimated by the vertical extrapolation of the actual root count.

The overestimation of the simulated root reinforcement for the average root distribution implies that the results of the slope stability assessments will be optimistic for the areas under herbaceous cover. The poor representation of the effect of coarse roots, however, called for the explicit inclusion of the root distribution under pine trees. Although these roots add considerably to the coarse root content, the total is small compared to the root counts established under the two vegetation types and the root number dwindles rapidly with depth (Figure 3).

Despite its optimistic nature, the influence of the simulated root reinforcement on the slope stability is small. Under saturated conditions, a small increase in the safety factor and a substantial decrease in the surface velocity at failure are observed. Under critical conditions, these results are more ambiguous due to the strain-dependent nature of root reinforcement. Under small deformations, the model simulates that roots remain in compression and this affects the shearing resistance negatively. Hence the stabilising influence of root reinforcement on the near-critical slopes studied here is confined to a small range of critical hydrological conditions. It can be argued whether roots, and especially the finer ones, are not too flexible to be loaded in compression and this is an obvious limitation of the root reinforcement model. Certainly, compression of roots will affect the bond strength along the root–soil interface and cap the pull-out resistance that can be mobilised in later stages of slope deformation when these roots will be loaded in tension and the soil fabric may fail before the root reinforcement can be mobilised (Mulder, 1991). It is possible to describe such modifications in bond strength conceptually but at the moment the required data from field and laboratory tests to parameterise such routines are lacking.

Since the rooting depth is limited due to the presence of hard regolith or bedrock at the slope transects, root anchorage is deficient (Tsakomoto and Kusakabe, 1984). Failure will occur by root pull-out at low loads due to a loss of effective strength along the root–soil interface. Root properties and density are not significant under such conditions as evidenced by the insensitivity of the safety factor to the imposed root conditions (GEO, 2000). This transient nature of root reinforcement under these conditions is clearly contradictory with the constant values of root reinforcements that are generally used in slope stability assessments.

Some reinforcement may be derived from the confining root mat or from buttressing and arching but their overall effect will be limited given the patchy nature of the semi-natural vegetation cover (Gray, 1995). Consequently, the preferred shearing plane would be expected at the contact of the regolith with the bedrock as is generally observed in the field where percolating water stagnates and root reinforcement absent. Higher in the profile failure is averted by both soil cohesion and root reinforcement.

Conclusions

Detailed studies on root reinforcement were made at two slope transects susceptible to slope stability in SE Spain. These slopes were formerly cultivated but a semi-natural vegetation cover has established itself after abandonment. The studies revealed that:

(1) The semi-natural vegetation consists of a patchy herbaceous vegetation cover with dispersed Aleppo pine trees of different age and size and remnants of crops. Two vegetation types were identified, differing in cover and vegetation composition, which reflect the

activity of mass wasting processes on the slopes.

(2) Along the slopes, the soil properties show a large local variability but no apparent lateral trends.

(3) *In-situ* direct shear tests indicate that a contribution of root systems to the soil shear strength within the topsoil is present but limited. This contribution is in the order of 0.6 kPa under herbaceous cover but may be as high as 18 kPa for densely rooted soil under pines.

(4) Fine root content is a determining factor in the observed root reinforcement and a sensitive parameter in the model. The influence of coarse roots cannot be fully captured, not even by the large-scale direct shear tests employed here. For a more truthful representation of this influence at least a more accurate count of coarse roots is needed.

(5) Root counts and consequently root reinforcement decrease rapidly with depth. Roots cannot penetrate in the underlying bedrock and the anchorage is limited. Shear planes coincide generally with the weathering depth of the soil profile where percolating water stagnates and root reinforcement is absent.

(6) Simulation of root reinforcement at the hillslope scale on the basis of the vegetation patterns returns failure areas and potential shear planes that coincide with the observed instability in the field. Translation of the *in-situ* direct shear tests to the hillslope scale by means of the model therefore seems appropriate although the simulated root reinforcement for the direct shear tests is optimistic. The results reveal that the failure mechanisms at the hillslope scale are intrinsically different and limited by the pull-out resistance of the roots under saturated conditions. The effect of root reinforcement at the hillslope scale is limited to a small range of hydrological conditions and predominantly occurring after failure.

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