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ROOT MECHANICS
APPLIED TO SLOPE STABILITY

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Frontispiece. Root stabilisation at Woodbury Castle, an Iron Age hill fort, Woodbury Common, Devon (O.S. Grid Reference SY 032 873). Photograph A. Swift.

ABSTRACT

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Many embankments and cut slopes in the United Kingdom are prone to shallow slope failures as they are often constructed of or within stiff overconsolidated clays, which soften with time. Reinforcement by natural vegetation is potentially a cost-effective method of stabilising these types of slopes over the medium to long term. However, there is a lack of information on the strength and root reinforcement values of natural vegetation, that can be effectively used to stabilise a clay slope.

To investigate the potential of reinforcement by vegetation the biological characteristics and mechanical properties of roots were reviewed and the key properties identified for slope stability. The interactions between the plants' root system and the soil were investigated by designing and developing field apparatus to measure the *in situ* root-soil strength and the pull out resistance of roots. Root strength, root-soil interactions and root architecture were investigated on a highway embankment, highway cut slope and a preserved railway embankment. New relationships between root morphology and pull out resistance were discovered and a revised classification scheme proposed.

The properties of roots that are required for slope stability analysis calculations were identified and assessed. The methods of slope stability analysis were reviewed and suitable methods identified that include the effects of vegetation in the analysis. Methods of determining suitable input parameters for the various root properties were devised from the experimental data. A spreadsheet program known as SLIP4EX was used to model the stability of the vegetated embankments and cut slopes. Further modelling was carried out to determine changes in stability when vegetation is removed from a slope.

Keywords: root architecture, root pull out resistance, root-soil interaction, root strength, slope stability.

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List of Notation and Abbreviations

Notation/ Abbreviation	*Explanation*
α	Angle of slip surface
β	Angle of slope
b	Width of slice
bgl	Below ground level
CSA	Cross sectional area of the root (mm)
c'	Effective cohesion
c'_s	Changes in undrained soil strength due to moisture removal by vegetation
c'_v	Root cohesion
d	Root diameter (mean of two or more axes)
dbh	Diameter at breast height of trees (taken at 1.3 m above ground level)
D_W	Wind force
E	Modulus of Elasticity
Ext.	Extension of tensometer during root tensile tests
F	Factor of Safety
F_r	Partial Factor of Safety due to roots
gl	Ground level
G.S.	Ground surface
H1-5	Hawthorn trees from M11 site used for root pull out and root tensile tests
HRA	Hawthorn tree used for root architecture investigations from M11 site
ℓ	Length along base of slice
m.c.	Moisture content (gravimetric)
NR	Data not recorded

ϕ'	Effective soil friction angle
RAR	Root Area Ratio
Rud…	Shrubs from Site 3 (Ruddington)
σ'_n	Effective normal stress
Δs	Increase in shear resistance by roots
SB1-4	Shear box tests from M25
T	Root tensile force
T_{rd}	Design root force per square metre of soil
T_{ru}	Ultimate pull out resistance
θ	Angle of roots to slip surface
TP	Trial Pits
U_1, U_2	Interslice water forces
ΔU_{1v}, ΔU_{2v}	Change in interslice water forces due to vegetation
u	Water pressure on base of slice
u_v	Change in pore water pressure due to vegetation
W	Total weight of slice
W_v	Weight of vegetation acting on slice
z	Shear zone

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Chapter 1: Introduction

1.1 History of the use of vegetation in civil engineering (bioengineering)

Civil engineering and vegetation or biology may seem a somewhat surprising or unusual combination of subject areas to research and study. In 1948, Sir Roger G. Hetherington CB, OBE, MA, President of the first Conference on Biology and Civil Engineering had initially wondered what the connection was between biology and civil engineering and had become rather startled when the conference was first proposed. However, he soon realised that there was a very close connection between the two subjects when he thought of the recently bombed sites in London which were slowly being engulfed by colonising plants (I.C.E., 1949). This conference brought internationally recognised civil engineers and biologists together to discuss the potential benefits of vegetation and also the disastrous consequences inappropriate vegetation can have on civil engineering structures. The papers presented at this conference ranged from soil erosion, soil conservation, the effect of vegetation on slope stabilisation for artificial slopes, sand dunes and on the settlement of structures to the influence of algae in civil engineering design (I.C.E., 1949). Even in 1948, bioengineering was being practised but not recognised as a discipline in its own right.

In fact, the first recorded use of vegetation for slope protection was written in the late sixteenth century by Pan (1591), the Minister of River Flooding Control in the Ming Dynasty of China, who described the method and results of using vegetation to protect an earth dam embankment. The relevant extract is reproduced in Figure 1.1. According to Lee (1985), Pan fails to discuss the relationships between vegetation and slope stability, although he obviously recognised that vegetation provides surface protection.

For five centuries now human instinct has taught us to use vegetation for river bank protection, soil conservation, sand dune stability and slope stability but without fully understanding the role played by the vegetation. This understanding has also been hampered by the fact that many disciplines use vegetation for multiple applications e.g. whether it's agriculturalists growing cereal crops, foresters managing pine forests, landscape architects or designers managing vegetation for its aesthetics and low maintenance qualities.

> "... It is observed that both side of the earth dam embankment surfaces are covered with Creeping Sage grasses (*Salvia substolonifera*), which provide sufficient surface protection. If it is intended to raise and thicken the embankment, the grasses have to be removed and the surface protection condition could become worse .... It is revealed that the best method for protecting the embankment is planting willows (*Salix* L.). Among the six planting methods of willow, the lateral planting method is the best. Since this method permits the willow's branches to grow much closer from the root system, thus it allows the willow to have much blooming branches to resist the impact of the impounding water. Every 1 zhang (= 3200 mm) long of embankment should plant 12 numbers of willow .... The willow shoot should have a minimum girth of 2 cun (= 32 mm) and stick out from the embankment of 3 chi (= 960 mm). The planting should be started from the inner portion of the embankment, then to the outer portion. Any dead willows found should be replaced immediately ..."

Figure 1.1. Extract from the earliest literature by Pan (1591) concerning the use of vegetation for earth dam embankment protection (Lee, 1985).

Each individual discipline has concentrated their efforts on a particular vegetation species to maximise the potential of this species for their own use, e.g. foresters have conducted wind throw experiments on pine forests to maximise forest stand stability (Cucchi *et al.*, 2004; Stokes, 1999) or agriculturalists experimenting with cereal crops for the most disease resistant variety or plants that resist lodging (Bailey *et al.*, 2002; Ennos, 2000).

Civil engineers in the UK, however, have in the last twenty years started realising the potential of vegetation and are gradually incorporating the bioengineering techniques established in Europe and America into our civil engineering design. In Europe, bioengineering techniques were established in 1973 by Hugo Schiechtl (Sicherungsarbeiten im Landschaftsbau, Schiechtl, 1973), Schiechtl's work was translated and published in English in 1980 (Schiechtl, 1980). Schiechtl was the foremost practitioner and proponent of soil bioengineering in Europe (Gray and Sotir, 1996). In 1982 in North America, Gray and Leiser produced a similar book on bioengineering techniques called "Biotechnical slope protection and erosion control". There then followed two further books from America and Europe, (i) by Gray and Sotir in 1996 titled "Biotechnical and soil bioengineering slope stabilisation. A practical guide for erosion control" and (ii) by Schiechtl and Stern also in 1996 titled "Ground bioengineering techniques for slope protection and erosion control" (Schiechtl and

Stern, 1996). Schiechtl and Stern (1997) also produced a separate companion book for the application of bioengineering in riverbank stabilisation.

In Hong Kong, Japan, Nepal, America and New Zealand, bioengineering is a well established and practised discipline mainly due to the physical and institutional conditions of these countries. The Geotechnical Engineering Office in Hong Kong has produced technical manuals (G.E.O, 2000a, b) and public information leaflets (G.E.O. 2002) on bioengineering and slope stabilisation.

In the UK, Skempton (1964), during the annual British Geotechnical Association's Rankine Lecture, recommended the use of vegetation on unstable natural slopes as it promoted stability. Although, the first comprehensive work wasn't published until 1984 when Bache and MacAskill produced a book on "Vegetation in civil and landscape engineering". This text instigated engineers to incorporate vegetation in civil engineering structures and in the last twenty years a number of trials and guidelines have been implemented.

The first of these guidelines is Coppin and Richards' book published in 1990 on the "Use of Vegetation in Civil Engineering". The result of a CIRIA (Construction Research and Information Association) research project aimed at providing technical guidance to practising engineers on the use of vegetation as an engineering material with reference to the UK construction industry. This led to a live demonstration trial on the M20 motorway cutting at Longham Wood, from 1993-1998. The trial was set up to investigate and monitor the effects of different types of vegetation (willows & alders; gorse & broom; and grasses) on undrained and drained parts of the cutting slope. The live trial demonstrated to the engineering community and its clients the benefits of vegetation in improving slope stability (Greenwood *et al.*, 2001).

In 1995, Morgan and Rickson (1995) published a textbook on "Slope stabilization and erosion control: a bioengineering approach". The book reviewed the basic understanding of the principles and practices of vegetation growth and establishment, and describes how vegetation can be treated as an engineering material and used to solve practical erosion and slope stability problems.

In 1994, a second conference was held in Oxford, UK on "Vegetation and Slopes, Stabilisation, Protection and Ecology" (Barker, 1995). This conference focused on the positive roles of vegetation and halted the waning interest in biology and engineering after the 1948 conference. Yet again, the conference united plant specialists and engineers, and aimed to clarify the concepts and benefits of the use of vegetation on slopes.

In 2001, three reports were produced by TRL (Transport Research Laboratory) investigating the use of "Vegetation for slope stability" (MacNeil *et al.*, 2001), the "Establishment of vegetation for slope stability" (Marriott *et al.*, 2001) and "A review of the use of live willow poles for stabilising highway slopes" (Hiller and MacNeil, 2001). The live willow pole review led to the setting up of four willow pole trial sites on highway embankments and cuttings across southern England (M23, A5, A10 and M1). The trials led to recommendations and guidance on willow pole selection, design, installation and maintenance issues (Steele *et al.*, 2004).

A one day conference on "Soil bioengineering, integrating ecology with engineering practice" held in Birmingham (March 2001) readdressed the current research in to vegetation and also the awareness of practising civil/geotechnical engineers, sending the message that "successful integration of soil bio-engineering relies on a balanced understanding of both civil engineering and ecology" (Soudain, 2001).

In 2001, a three year European project on "Eco-engineering and Conservation of Slopes for Long-term Protection from Erosion, Landslides and Storms (ECOSLOPES)" began. This multidisciplinary project united engineers, geomorphologists and foresters in unifying techniques and tools for using vegetation to improve slope stability and erosion. Initially, seven 'problematic' field sites across Europe were described using measures of slope history and stability, soil mechanical, physical and hydrological properties, vegetation types and plant root architecture. The interaction between roots and soil is extremely important for soil stability either from erosion or land slip therefore *in situ* root strength and pull out tests were carried out on these 'problematic' sites. Root morphology and architecture were described for each plant species. The data was used to model slope and tree stability. A Slopes Decision Support System (SDSS)

(Stokes *et al.*, 2004; Mickovski and van Beek, 2006) and manual (Norris *et al.*, in prep.) was developed to provide guidance for a newly emerging generation of eco-engineers (the SDSS is available on the projects website, www.ecoslopes.com). The final report from the ECOSLOPES project is available on the website (Anon, 2004).

The author of this thesis was the lead researcher and coordinator for the Nottingham Trent University contribution on the ECOSLOPES project.

The ECOSLOPES project terminated in September 2004 with the first conference on Eco-engineering in Thessaloniki, Greece (Spanos and Stokes, 2004; Cammeraat *et al.*, 2006; Stokes *et al.*, 2005, 2006).

1.2 Rationale

Within the civil and geotechnical engineering community in the United Kingdom, the level of knowledge and the number of reliable datasets regarding the contribution of vegetation to soil slopes is fairly limited. Although a number of design manuals and trial site results have been published (e.g. Coppin and Richards, 1990; Greenwood *et al.*, 2001; Hiller and MacNeil, 2001), engineers do not commonly design soil slopes with vegetation or soil bioengineering in mind.

However, for over a hundred years, engineers have been allowing vegetation, either planted or by natural generation, to grow on our road/rail embankments and cuttings without any real notion of the consequences except for their aesthetic nature. The vegetation is commonly left for many years without proper maintenance and is only maintained when it becomes a hazard to traffic or health and safety. In these cases, it is cut back and cleared to such an extent that the vegetation no longer provides any protection from the weather, root growth may be inhibited and die back and the soil slope may become unstable. This may lead to the hazard of shallow landslides (e.g. Perry *et al.*, 2003a, b).

McGinnity *et al.* (1998) reports the state of vegetation development across the London Underground railway system. Up until 1960, vegetation on the slopes of earthworks was closely controlled. Since that time, the vegetation has been allowed to grow unchecked and by the beginning of the 1990's, much of the surface railway was overgrown with mature trees close to the lines (Gellatley *et al.*, 1995).

Aerial photographs were used to establish the development of vegetation on the earth structure slopes. In the mid-1940's most earth structure slopes were covered by grass with occasional trees and shrubs with systematic vegetation control of regular coppicing and maintenance. By the early 1960's, shrub and small tree cover had extended along the earth structure slopes although at only a low to moderate density with many clear areas. In the early 1970's, this cover had matured significantly and the spacing between the canopy cover was much reduced. By the early 1990's, the majority of slopes were completely obscured by the mature canopy resulting in significant shrink-swell cycles in the earth structure slopes (McGinnity *et al.*, 1998). More recently, many of these mature canopies across the whole rail network have been clear cut resulting in, in some cases, shallow landslips, e.g. the Brighton to London Victoria derailment:

> " … A spokesman said: "The cause of this derailment appears to be a landslide caused by the recent heavy rain." …
> Sam Livermore, whose house is beside the track, said: "Since they uprooted trees about 10 months ago the banks have become increasingly unstable as there are no longer any roots to keep the ground in place."…
> A spokesman for Network Rail said …
> …"The trees were taken out because of the risk of them falling on to tracks," he added. "They presented more of a risk than landslides and, contrary to popular belief, they do not make the embankments more stable." …"

2nd January 2003, The Daily Telegraph (Payne, 2003).

Two recent publications by CIRIA on the infrastructure of embankments and cuttings (Perry *et al.*, 2003a, b) give brief recommendations about the use of vegetation for stabilisation and discuss planting schemes, plant types and grassing methods. However, both publications tend to reiterate the beneficial environmental effects and the negative aspects of vegetation without necessarily encouraging its use.

It is because of the lack of information about how vegetation (roots) interacts with the soil and the effects of the vegetation on soil slope stability, that this PhD research is centred around investigating how natural vegetation on selected road and rail embankments and cuttings contributes to their stability with particular focus on the mechanics of roots and the effects of root-soil interaction.

This research programme identified typically occurring vegetation on a motorway embankment, motorway cutting and railway embankment. The vegetation on these sites was characterised and recorded. A variety of explorative work was carried out to investigate the role of roots, the mechanics of roots and slope stabilisation using naturally occurring vegetation.

The research was supported by the European Union Fifth Framework 'ECOSLOPES' project (QLK5-CT-2001-00289).

1.3 Sources of literature

Within the traditional civil and geotechnical engineering journals, published literature on bioengineering or slope stabilisation with vegetation and/or plant mechanics is scarce. The lack of information within the civil and geotechnical engineering journals is due to the established traditional practices of using materials such as concrete and steel for slope stabilisation. Vegetation is unpredictable in its nature, and due to the cellular composition of the plants' roots has in the past formed a barrier to performing geotechnical tests. Published works on root-soil interaction, *etc.* in most cases can be found in agricultural, biological, botanical and forestry journals such as *Plant and Soil*, *Forestry*, and the *Journal of Experimental Biology* where researchers have tested plants for economical reasons e.g. crop losses from destruction by storms. Although even in these journals, no one source had an abundance of papers dealing with soil stabilisation by vegetation.

A series published by Kluwer Academic Publishers based on annual conferences called Roots: the dynamic interface between plants and the Earth (e.g. Abe, 2003) revealed some interesting root mechanics papers in amongst the highly biological orientated papers on the cell structure of roots.

There have been a number of bioengineering text books dedicated to the restoration of river banks or for combating soil erosion and conservation problems, e.g. Schiechtl (1980), Morgan and Rickson (1995), Gray and Sotir (1996), Morgan (2005). These text books describe the installation procedures of many bioengineering techniques while briefly reviewing the mechanics of stabilisation. The one and only dedicated textbook to using natural vegetation for slope stabilisation (i.e. real live plants and not cut parts of plants as in many of the bioengineering techniques) is Coppin and Richards (1990) book on "Use of vegetation in civil engineering".

A number of technical reports published by CIRIA and TRL have proved useful sources of information on the effect of vegetation on the UK's infrastructure (Perry *et al.*, 2003a, b), and the effect of live vegetation trials on slope stability (Greenwood *et al.*, 2001; MacNeil *et al.*, 2001; Steele *et al.*, 2004).

The world wide web has provided valuable assistance in enhancing learning about the biological components of roots and also obtaining numerous manuals e.g. the Geoenvironmental Office in Hong Kong (2000a, b; 2002), Washington State Department of Transportation roadside manual (2003) and case studies on using vegetation to stabilise slopes (e.g. Polster, 2003). The online library databases such as the British Library, Nottingham Trent University's library databases and www.scirus.com made the problem of sourcing the obscure published literature much easier.

1.4 Aims and objectives

The aim of the research was to investigate the role of vegetation in stabilising shallow slope failures by considering the mechanics of the roots and their corresponding parameters for use in slope stability analyses. The main objectives of the research were:

1. To design and develop portable field apparatus for measuring the *in situ* strength of roots and soil.

2. To investigate the *in situ* mechanics of roots in soils and to explore the effects of root-soil interactions during root reinforcement and root pull out resistance experiments.

3. To identify and assess the key properties of roots that are required for slope stability analysis calculations with vegetation effects included and to model the effects of the vegetation on the Factor of Safety of a slope.

1.5 Structure of thesis

This chapter introduces the philosophy of the research presented in this thesis, with a short history of the use of vegetation in civil engineering (bioengineering). Chapter 2 introduces the biological characteristics of roots and relates the plant terminology of roots to more simple engineering definitions. The adverse and beneficial properties of roots for slope stabilisation are introduced. Chapter 3 outlines the test procedures and methods of investigation used for assessing the role of roots in slope stabilisation as applied in this thesis. The investigation of the different root properties took place on three study areas, these study areas are described in Chapter 4. The results of the investigations are also presented. Chapter 5 discusses the mechanics of uprooting and the factors that influence root strength. Chapter 6 investigates the effects of removing vegetation from a slope and the resulting loss in slope stability. Chapter 7 introduces the well known root reinforcement models. These models are thus applied to the three field study areas. Chapter 8 considers the variation in root architecture of a limited number of plant species; the distribution, pattern and extent of roots on slopes. Chapter 9 considers the role of the vegetation in slope stability analysis and shows the effects of the vegetation parameters on the Factor of Safety of the slopes from the three study areas. The thesis closes with a summary of the main research findings and recommendations for further research. A bibliography of all relevant reference material is included along with the cited material.

1.6 Contribution to knowledge

The research has led to a greater awareness of bioengineering within the civil engineering community (Greenwood *et al.*, 2003, 2004; Norris and Greenwood, 2006) while at the same time fostering links with other scientific disciplines i.e., foresters, plant biologists and soil scientists (Norris *et al.*, *in prep.*). The development and application of *in situ* field apparatus (Norris and Greenwood, 2003b) and laboratory techniques to measure the contribution of the root-soil composite bond and the tensile root strength has enabled other scientists to undertake such research activities (e.g. the practical advice on how to clamp roots led to a study by Genet *et al.* (2005) on the tensile strength of roots; and the procedure of *in situ* shear box and root pull out testing enabled van Beek *et al.* (2005) to carry out root reinforcement tests on abandoned terrace slopes in the Alcoy mountains of Spain. New relationships between root morphology and pull out resistance were discovered and a revised classification scheme proposed (Norris, 2005). New datasets on the tensile strength of roots and root cohesion values have been formulated and can be applied to slope stability calculations. A method for calculating the value of the tensile force of the roots, T, from either the tensile strength or root pull out resistance value has enabled the contribution of the vegetation within limit equilibrium stability analysis methods to be determined (Greenwood *et al.*, 2004). The author's published works are included in Appendix 4.

Chapter 2: Root Characteristics

2.1 Introduction

Roots are not 'simple' engineering materials such as steel and concrete. There are no British or International Standard tests to determine their strength properties. Roots are living materials and consequentially have different properties when they are alive to when they are dead. It is important to review the biological and morphological characteristics of roots and root systems in order to understand their mechanics and their relationship with the soil and slope stability. Definitions of the biological features are given in simple engineering terms to enable geotechnical engineers to appreciate and interpret the engineering attributes of root systems. The properties of roots that make them useful for slope stabilisation are introduced.

2.2 The biology of roots

When examining root characteristics it is important to understand the prime elements of the root system. These elements include the root structure, the formation of woody roots and the interface between the root and the soil. The biological characteristics of roots can be found in any good textbook on plant biology e.g. Raven *et al.* (2005). A description of the main features are given here.

2.2.1 Root structure

The biological terminology of a root is shown in Figure 2.1. The root consists of three distinct parts: the root tip; the cortex and the stele (Foster *et al.*, 1983; Raven *et al.*, 2005). The root tip consists of a root cap and an apical meristem. The root cap is a protective sheath of cells that protects the growing root tip from abrasion and damage. The apical meristem produces new cells for root growth and also produces the cells which form the root cap. The cells produced in the apical meristem undergo elongation in the direction of the axis of the root (elongation region) and differentiate to form the stele and cortex. The apical root is surrounded by a gelatinous non-cellular material, known as mucigel.

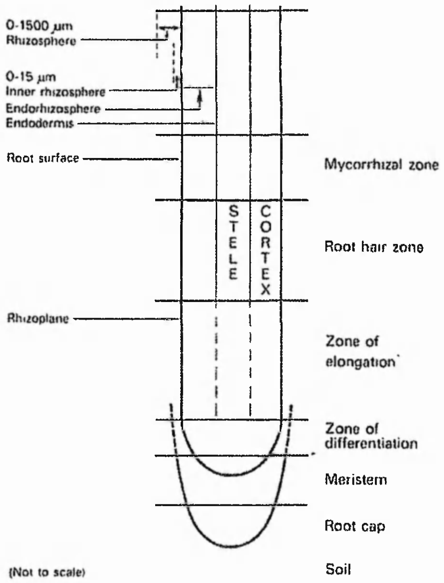


Figure 2.1. Longitudinal root cross section showing rhizosphere zone (modified from Foster *et al.*, 1983).

The cortex consists of an epidermis, a single layer of flattened cells at the surface, which when first formed have extensions called root hairs. These hairs greatly increase the surface area available for the uptake of water from the soil. The cortex is a band of parenchyma cells that develop beneath the epidermis. The inner surface of the cortex is bounded by the endodermis and encases the stele.

The stele contains the xylem and phloem in which nutrients and water are conveyed to and from the shoots. The pericycle, the outer surface, surrounds the xylem and phloem and is where secondary roots branch from.

In older parts of the root, another meristem forms between the xylem and phloem called the cambium. Cell division in the cambium produces new secondary xylem and phloem.

The root cap remains relatively constant in size as growth proceeds since new cells develop at the same rate as external cells are sloughed off. If the root cap is removed, elongation of the root continues. The root cap is responsible for regulating the geotropic curvature of the roots and plays a role in the secretion of mucigel (Russell, 1977).

Root hairs originate as protuberances from epidermal cells. They have considerable variation in their size, ranging up to lengths of 1000 μm with diameters of 10-15 μm, and only exist for a maximum of a few days (Russell, 1977). They are prevalent to microbiological attack. Root hairs normally develop within 5–10 mm of the root apex in an acropetal manner (progressively towards the root apex). Root hair development is very much dependent on soil conditions, for instance, a root growing round an obstruction causes cell extension to be retarded on one side of the root resulting in a concentration of root hairs in the elongation region (Russell, 1977). Root hairs play a very important role in anchoring young roots as they penetrate the soil (Russell, 1977).

Lateral roots originate from tissues lying inside the parent root, therefore they grow through the parents root tissues in order to emerge. Lateral roots develop away from the apex of the root. According to Lloret and Casero (2002), the random distribution of lateral roots along the parent root is related to the environmental conditions in which the root grows, for instance, the availability of soil moisture and nutrients. The lateral roots thus utilise the soils' resources to their full potential.

2.2.2 Woody root formation

In roots of woody plants, the outer cortical region and the inner central core or stele are regions of bark or wood formation.

2.2.2.1 Bark formation

The cortical region in woody plants is known as the bark. The bark of the root includes the cambium, the secondary phloem, the remainder of the cortex and other cork layers (Figure 2.2). The layer of cortex cells directly under the epidermis becomes meristematic i.e. able to divide and is called the cork cambium. These cells form a single layer of parenchymatous cells towards the inside called the phelloderm and numerous layers of cork cells towards the outside. The cork cells deposit suberin in their cell walls which makes them, and therefore the bark as a whole, water resistant. The epidermis breaks under the pressure of the new cells which are forming below it and eventually falls off. The layers of cork cells are constantly being formed by the cork cambium and flake off on the outside of the bark. Cork cells are non-living when they are mature. This process of bark formation is obviously a factor in why the bark strips off from the root during pull out (see Chapter 5). The endodermis is the innermost layer of the cortex and surrounds the inner core.

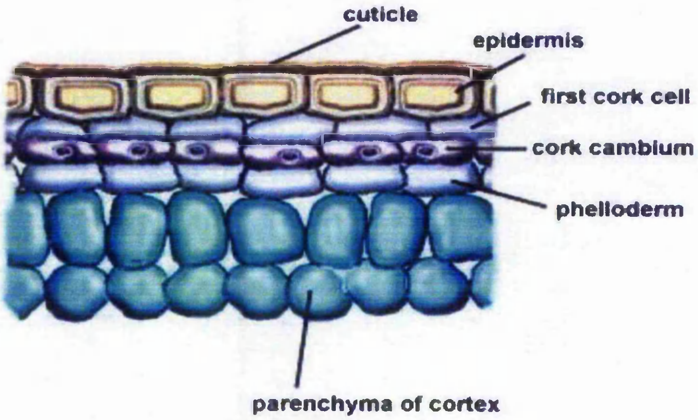


Figure 2.2. Cell structure in the cortical region of the root (Source: Cocks, undated: http://www.botany.uwc.ac.za/ecotree/trunk/Formationwood2.htm).

2.2.2.2 Wood formation

The inner core or stele contains alternating groups of phloem and xylem cells. Phloem cells contain abundant cytoplasm, they have thin walls and form sieve-tubes. Phloem cells transport the manufactured food throughout the plant in a process known as translocation. Xylem cells have no living cytoplasm but have lignin strengthened walls. Some xylem cells form long tubes or vessels, which continue up through the root and stem to end in the veins of the leaf. Others are spindle-shaped with thick walls forming fibres, which assist in the rigidity of the stem (Brocklehurst and Ward, 1970).

The process of wood formation in stems, starts when the cells in the cambium divide to form new cells. Cells which form on the inside of the cambium are transformed into secondary xylem (wood) and those that form on the outside to secondary phloem. The secondary xylem cells are 4 to 10 times more abundant than secondary phloem cells (http://www.botany.uwc.ac.za/ecotree/trunk/ Formationwood2.htm). The accumulation of these xylem and phloem cells produces compact rings, or growth rings. The thickness of these rings increases as growth proceeds which causes the stem to slowly increase in girth and become woody. The lignified walls of the xylem form the main supporting tissue of the woody stem (Brocklehurst and Ward, 1970).

The growth in girth and woodiness of the root are factors in the strength of the roots.

2.2.3 Engineering terminology

In engineering terms, the biological features of roots can be simplified to two terms, one representing the inner (woody) core i.e. the stele and the other representing the bark of the root i.e. the outer cortical region.

2.2.4 The interface between the root and the soil

The root-soil interface is an extremely complex region. The soil becomes more and more influenced by a root the closer one gets to the root surface. The interface can be broken down into four components: the biological relationships, soil fungal associations, physical characteristics and soil porosity.

2.2.4.1 Biological interface

At the root-soil interface, the principal biological components of the roots which interact with the soil are the epidermis, root hairs, the mucigels (gelatinous non-cellular materials), soluble exudates (carbohydrates, amino acids, organic acids and enzymes) and the microbiological flora of the rhizosphere and rhizoplane.

The rhizosphere is a zone of soil in which the environment for microbial activity is influenced by the root of any species, distinguishing it from the bulk or non-rhizosphere soil. This soil is not directly influenced by growing roots except by the withdrawal of water and nutrients. The rhizoplane is the external surface of roots and of the soil particles and debris adhering to them. The rhizosphere and the bulk soil merge into one and the boundary between them cannot be rigidly defined (Figure 2.1). The diameter of the rhizosphere at least equals the cylinder of soil, which root hairs explore (between 0-1500 μm thick) and into which exudates are released (Russell, 1977).

In the rhizosphere, the root interacts with the soil in a variety of ways –

(a) soil particles can become trapped in the epidermal cells of the root;

Scanning electron microscopy has shown that the surface of roots are coated with mineral grains that protrude from the mucilage, clay platelets coat the epidermal cells (Foster *et al.*, 1983) and bacteria also becomes enveloped (Rovira, 1979) as the apex of the root is forced through the soil in search of water and nutrients.

(b) roots release organic matter to the soil;

Roots release organic matter as exudates, lysates and mucilages to the soil. The abundance of organic matter stimulates the micro-organisms that are in contact with the root into both active metabolism and reproduction. Other organisms in the soil such as fungi, flagellates, amoebas and nematodes are attracted to the roots by organic compounds, carbon dioxide and volatile compounds near the root surface. These exudates therefore create a rapid build up of micro-organisms near the root surface (Foster *et al.*, 1983).

(c) microbial colonisation of roots.

The bacteria and fungi of the rhizosphere and rhizoplane affect their host plants through their influence on such factors as the availability of nutrients, the growth and morphology of roots, the nutrient uptake processes and the physiology and development of the plants (Rovira and Davey, 1974).

Root exudates and the rhizosphere microflora can affect plant growth indirectly, either for the benefit or detriment of the plant, through their effects on the availability of nutrients (Rovira and Davey, 1974).

2.2.4.2 Soil fungal associations

Roots of all land plants (except brassicas and herbaceous annuals) form mycorrhizoral associations with soil fungi. The roots are colonized by the fungus, which also ramifies through the soil. The combination of root and fungus is called mycorrhiza (St. John, 2000). Mycorrhiza relationships are generally mutually beneficial (or mutualistic) between the plant and the soil fungi. This mycorrhiza relationship facilitates the sharing of some of the plant's storehouse of organic compounds (which are essential to fungi, as they are to all living organisms). In addition, water is exchanged along with the organic compounds, and the fungi assist with the absorption of nutrients such as phosphorus and other minerals. Carbohydrate is passed from the plant to the fungus and in return the fungus facilitates increased nutrient uptake, particularly of phosphorus, from the soil to the plant (Figure 2.3). There are two main types of mycorrhizas found in association with agricultural and forest plant species. They are ectomycorrhizas and endomycorrhizas.

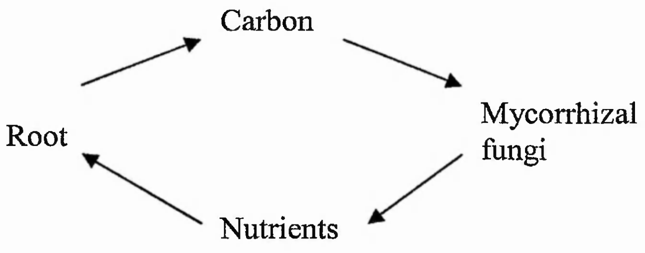


Figure 2.3. Mycorrhizae – root cycle (after Marschner, 1995).

In ectomycorrhizas, the fungus does not penetrate the cells of the root. In endomycorrhizas the root cell walls are penetrated by the fungus. Mycorrhizas increase the surface area for absorption around the root enabling a greater quantity of nutrients such as phosphorus and zinc to be absorbed into the plant. The largest group of endomycorrhizas is the arbuscular mycorrhiza and is the most common type found within the plant kingdom (St. John, 2000). The arbuscules are structures found in the roots of mycorrhizal plants.

Mycorrhizal fungi bind the soil in ways that the plants alone cannot, thus promoting the formation of soil aggregation and at the same time conserving the macro-porous soil structure that allows penetration of water and air (Miller and Jastrow, 1992).

Mycorrhizal fungi promote rapid establishment of plants although soil disturbance decreases the natural mycorrhizal potential (Schmid *et al.*, 2006). Mycorrhizal associations can significantly alter the properties of the bulk soil from the soil from the rhizosphere, as shown in Table 2.1.

Table 2.1. Changes in bulk soil properties due to the effects of the rhizosphere (after Marschner, 1995)

Soil property	Rhizosphere
Bulk density	Increase bulk density
Organic matter	Increase organic matter
Moisture content	Less moisture content due to transpiration.
Nutrient concentration	Increased concentration especially for Ca^{2+} or Mg^{2+}
pH	Variable, e.g. increased acidity increases P solubility and absorption
Redox potential	Depends on soil water content and root response to hypoxia; Fe, Mn and Al have increased availability.
Micro-organism count	Increase micro-organism count

2.2.4.3 Physical contact

An important aspect of the root-soil interface is the degree of physical contact between root and soil. Roots proliferate in soil where they can penetrate freely, therefore large parts of root systems will often develop in pores of diameters larger than themselves. The preferential growth of roots in voids or planes of weakness is readily observed. In such circumstances roots may not be in contact with the soil over their entire surface (Russell, 1977). Physical contact at the soil-root interface cannot be assumed to be necessarily continuous or complete (Russell, 1977).

Soils which contain an appreciable quantity of clay, shrink on drying. The growth of roots is dependent on an adequate water supply, therefore young roots are likely to grow in soil which is at or near its maximum expansion. Loss of water from the soil due to dry weather and to its removal by roots may cause the soil to contract as growth proceeds. Subsequent shrinkage and cracking of the soil may then rupture roots (Russell, 1977). However, the uptake of water and nutrients within the structure of the root is outside the scope of this research.

2.2.4.4 Soil porosity

Roots grow in pores of diameters greater than their own and only ones which are easily enlarged. Root tips can enter pores with a minimum diameter of 10 μm (Greenland, 1979).

Figure 2.4. Exposed roots in an investigation trench observed to be exploiting fissures in Gault Clay, Longham Wood Cutting, CIRIA bioengineering trial (Greenwood *et al.*, 2001).

Soil porosity varies depending on soil type. Total porosity of soil is normally greater than 40% and frequently over 50%, but the majority of the pore space is in pores of less than 1 μm diameter. Sandy soils have larger pore spaces. In clays, pore spaces of 50 μm or larger are very rare (Greenland, 1979). Root growth is thus restricted to fissures, interconnected pores or other discontinuities (Figure 2.4). As the root grows within the pore space it becomes significantly larger than the original pore space diameter and thus forces the soil particles apart. This action is obviously dependent on soil resistance, bulk density, *etc.*

2.3 Root system morphology

2.3.1 Types of root systems

Four different types of root systems have been identified in grasses and flowering plants (Raven *et al.*, 2005). They are:

(1) **Fibrous root systems** - these plants have a mass of hairy roots, e.g. grasses.

(2) **Taproot systems** - these plants send a carrot-like spear into the earth to anchor themselves. The root "taps" into the ground and grows straight down. The taproot has many branches, or lateral roots. Taproots usually penetrate the ground deeper than fibrous roots.

(3) **Bulbs and corms** - some plants have a solid mass of material resembling an onion with roots emerging from the underside. These propagate by splitting off and making more little bulbs and corms that eventually grow to flowering size.

(4) **Tubers and rhizomes** - these include plants such as potatoes. The tuber or rhizome form eyes, from which new plants emerge and grow.

Roots are the first structures to develop in a growing plant, providing anchorage and a means of obtaining water and nutrients. The initial root of a plant, generally present on the embryo within the seed is called the radicle. The radicle forms the primary root of the young seedling. In monocotyledons (e.g. grasses, orchids), the radicle is short lived and before it dies adventitious roots have developed and formed a new fibrous root system. In gymnosperms (e.g. pine, yew, cedar) and dicotyledons (e.g. rose, potato), the primary root commonly grows to become a thick central root, the taproot, which may or may not have thick lateral roots or branches. This structure is known as the tap root system (Figure 2.5). Lateral roots originate from the inner tissues or pericycle of the root (see Figure 2.1). Lateral roots can be derived from the primary root, an adventitious root or another lateral root. Lateral roots constitute almost the whole root system (Lloret and Casero, 2002).

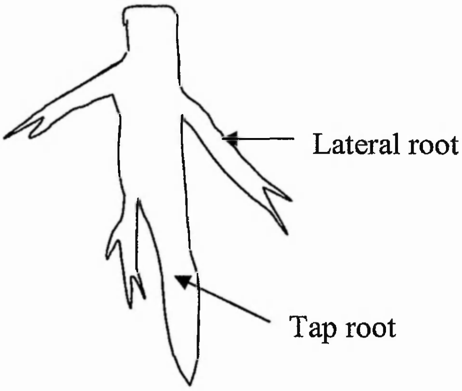


Figure 2.5. Elements of a tap root system.

It is the combined tap and lateral root system which is the most beneficial form of the root system in stabilising soil slopes. The fibrous root system is ideal for preventing soil erosion as the network of fibrous roots binds the soil together (Morgan, 2005).

The length and radius of plant roots varies according to the medium in which it grows. If the medium is difficult for the roots to penetrate then the roots will have a larger radius and may be shorter (Barber, 1979).

Trees have been classified as having three main root system types: plate, heart and tap (Köstler *et al.*, 1968; Stokes and Mattheck, 1996; Figure 2.6). Plate root systems have large lateral roots and vertical sinker roots, heart systems possess many horizontal, oblique and vertical roots and tap root systems have one large central root and many smaller lateral roots. Some species may be classed as having a mixture of two types of root system (Stokes, 2002).

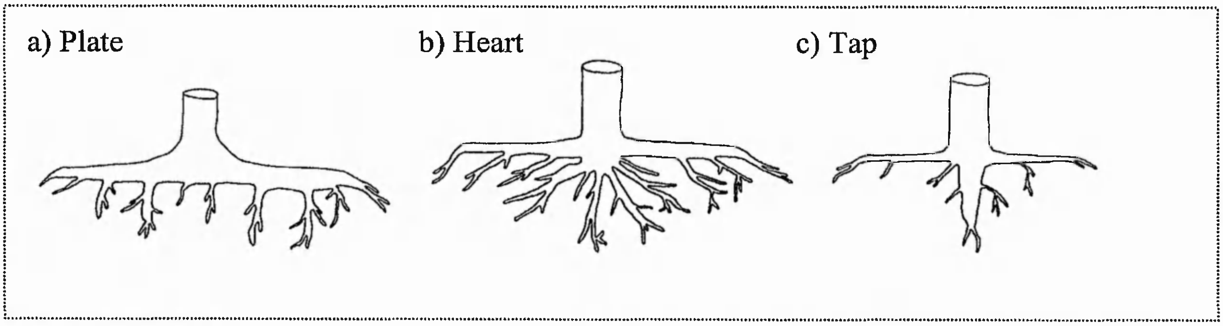


Figure 2.6. Different types of root system architecture a) 'plate' or 'sinker' system with large lateral roots and some smaller vertical roots, b) 'heart' system with many horizontal and vertical roots and c) 'tap' root system with one major central root and smaller horizontal and vertical roots (after Stokes and Mattheck, 1996).

Tree root systems serve three major functions; that of absorbing water and nutrients, storing carbohydrates, and thirdly, of anchoring the tree in the ground. The quality of anchorage depends partly on the morphology and mechanical properties of the root system present (Coutts, 1983a, 1986; Stokes and Mattheck, 1996). When not limited by soil or ground water conditions, herbaceous, shrub and woody species have intrinsic root system morphological characters.

Plants exhibit markedly different capacities for root growth, forming either intensive or extensive root systems. Intensive root systems have localised, short and fine root systems whereas extensive root systems send roots to a considerable depth and spread. Extensive root systems of trees are comprised of lateral roots that radiate outward from the tree and sinker roots that are vertically orientated. A main vertical root or tap root is centrally located in many species.

The form of individual root systems is dependent on soil and site conditions as well as plant species. The relative hardness or compactness of ground stratum, the position and fluctuations of the groundwater table, the capacity of the soil to retain moisture, the availability of nutrients and air and the presence of toxic elements in the soil all have a marked influence on the development of roots. Plants respond to these conditions by producing adventitious roots.

2.3.2 Root lifespan, efficiency and turnover

Roots have a life history in which they pass from birth to death. The size and population of the root system is determined by the birth and death rate of the individual roots. The birth and death rate of roots also influences plant competition. Root competition can be as intensive as shoot (above ground) competition with for example long-lived roots capturing the limited soil resources (Eissenstat and Yanai, 2002).

The first roots of plants developing from seed are indeterminate, typically extending greatly in length as the taproot or other seminal roots develop. The major laterals that first emerge from these primary roots and the adventitious or nodal roots that emerge from the stem base are also typically undefined, often extending tens of centimetres or more in length. These indeterminate roots form the basic framework of the root system and may live as long as the plant lives. Ephemeral roots, on the other hand, are the fine laterals that may be replaced several times during a growing season and may have only a few orders of branching (Eissenstat and Yanai, 2002).

2.3.3 Extent of roots

There are two frequent misconceptions that are believed with regard to tree roots (Hoskins and Rice, 1992). The first is that root spread is equal to the size of the crown and the second is that tree roots are either shallow rooted or tap rooted.

Both misconceptions are incorrect, as roots will develop as required to abstract sufficient water and ensure tree stability. Thus the lateral extent of tree roots can be considerable and can extend well beyond their crown area as hair roots seek to extract water in unfavourable conditions.

The depth of rooting is constrained by a number of factors:

- bedrock at relatively shallow depths in many slopes. The degree to which roots are able to penetrate rock stratum depends on the frequency and nature of discontinuities in the bedrock.
- Oxygen availability
- Seasonal water tables
- Hard pans (Figure 2.7)

Tree roots may spread laterally for considerable distances. The extent of root spread is expressed in relative multiples of the tree height or the radius of the crown.

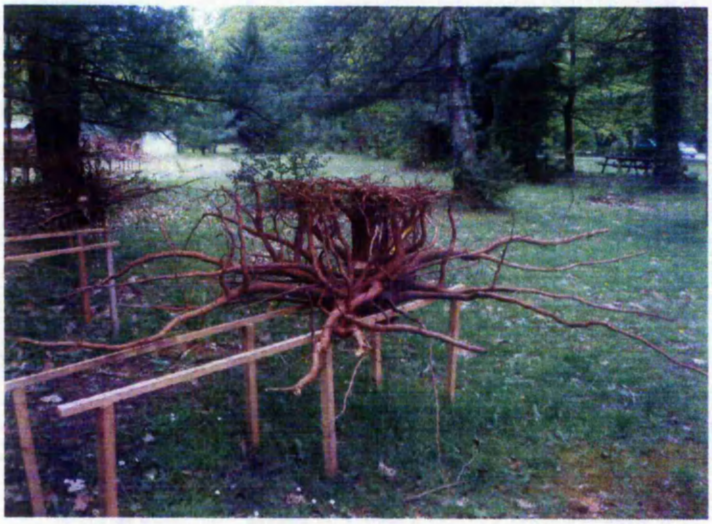


Figure 2.7. Inverted display of pine root system inhibited by hardpan layer at ~ 1 m depth below ground surface (Photograph J. R. Greenwood).

2.3.4 Roots on slopes

According to Hoskins and Rice (1992), roots on a slope tend to grow in an upslope direction to counteract gravity forces and remain perpendicular to the ground slope. The application of forces (e.g. wind) to roots causes them to thicken and thus the thickest roots will be on the upslope side of a tree, particularly those running obliquely to the slope and acting as anchors. Schiechtl (1980) reported that roots growing in an up-slope direction were stronger than those extending down-slope (up to double the tensile strength).

Chiatante *et al.* (2003a, b) studied the influence of steep slopes on root system development. They concluded that root systems developed an asymmetric architecture due to the preferential lateral root emergence and elongation in the up-slope and down-slope direction. These up- and down-slope roots were the main structural roots and showed a considerable shape eccentricity at their base.

Mechanical stresses imposed by wind and slope affect root system organisation. The response of a root system to wind has been studied in nurseries by growing trees in a wind-tunnel (Stokes *et al.*, 1995) or by stimulating mechanical stress by flexing the trunk (Stokes *et al.*, 1997). The root systems of these artificially stressed trees present a particular adaptive growth with an asymmetric allocation of biomass in two preferential directions, i.e. towards and away from the origin of the mechanical stress (Blackwell *et al.*, 1990). Mattheck and Breloer (1998) observed that wind blown trees have thicker and longer roots on the windward side in order to reinforce the less stable soil present on this side of the tree. In the same way, trees on steep slopes have long, rope-like roots on the uphill side of the slope and short, strut-like roots on the downhill side (Figure 2.8).

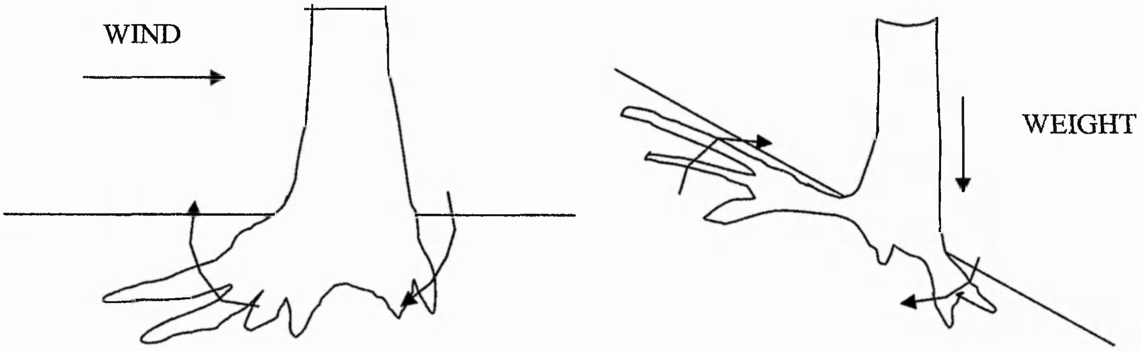


Figure 2.8. Variation in root growth due to wind on horizontal and sloping ground (modified from Mattheck and Breloer, 1998). Arrows show the location of mechanical stability from one-sided loading.

2.3.5 Root shape

Root shapes are typically elliptical in cross section. Mechanical stresses induce changes in root growth, whilst wind induces alterations in secondary root growth, i.e. woody roots change in shape from oval to forms approximating to 'I' beam and 'T' beam shapes. These changes result from the differing amounts of tension, compression and pulling that occur during the growth of the root (Goodman and Ennos, 1996, 1997, 1999; Mattheck and Breloer, 1998; Nicoll *et al.*, 1995; Nicoll and Ray, 1996; Stokes *et al.*, 1997, 1998).

2.4 Properties of roots (vegetation) for slope stabilisation

2.4.1 Hydrological mechanisms

Vegetation alters the natural hydrological cycle, by intercepting precipitation with its foliage, preventing runoff and infiltration by increasing surface roughness and the binding of soil particles together by their root systems. The adverse and beneficial effects of vegetation on slope stabilisation are outlined in Table 2.2.

On vegetated slopes the demands of the biological cycle for water are met by the extraction of soil moisture by roots, this directly lowers the moisture content of the soil within the root zone and may generally alter the distribution of soil moisture (and pore water pressures) well beyond the root zone. Reductions in soil moisture content result in lower pore water pressures within the slope, observable as increased matric suctions in unsaturated soil and lower groundwater levels.

Table 2.2. Adverse and beneficial hydrological mechanisms of vegetation on slope stability (after Greenway, 1987; Coppin and Richards, 1990; Morgan and Rickson, 1995).

Adverse to stability	Beneficial to stability
Foliage – increases size of the raindrop through leaf drip resulting in increased localised rainfall intensity	**Foliage** - Foliage intercepts rainfall causing absorptive and evaporative losses that reduce rainfall available for infiltration, reduce kinetic energy of raindrops and erosion
Roots - deplete soil moisture therefore may accentuate desiccation cracking in the soil resulting in higher infiltration capacity	**Roots** - Roots extract moisture from the soil which is lost to the atmosphere via transpiration leading to lower pore water pressures
Roots and stems - increase the roughness of the ground surface and the permeability of the soil leading to increased infiltration capacity	

2.4.1.1 Interception

Interception of precipitation is controlled by type and species of vegetation present, the proportion of the slope area that is vegetated, rainfall intensity and duration, antecedent moisture content and climatic or seasonal factors. The greater the amount of interception, the lower the amount of precipitated water available to reach the soil, thus reducing the rainfall that can adversely affect the stability of the slope.

The amount of interception varies depending on height, age, amount of cover and species. Grasses have interception rates of 25-40%, low vegetation covers such as bracken vary between 20-50% whereas forests intercept between 10 and 38% of precipitation (Coppin and Richards, 1990; Phillips and Watson, 1994). The amount of interception varies throughout the year and is dependent on the duration of the precipitation within the canopy. Evapotranspiration and interception in the foliage limit buildup of soil moisture stress.

2.4.1.2 Infiltration

Vegetation increases the permeability and infiltration capacity of surface soil layers of vegetated slopes due to the presence of roots, vacant channels from decayed roots and increased macroscopic surface roughness. These factors may increase infiltration rates from rainfall and overland flow into the soil, thus increasing the moisture content above that of unvegetated areas (Coppin and Richards, 1990). However, interception, evapotranspiration and slope angle usually offset infiltration rates.

2.4.1.3 Evapotranspiration

Evapotranspiration is commonly used to describe the removal of moisture from a plant by transpiration and the evaporation of intercepted rainfall from the plant surface. In slope stabilisation, it is the transpiration mechanism that is important. The depletion of soil moisture by plants i.e. the act of transpiration, delays the onset of soil saturation and runoff.

The rate at which a plant consumes soil moisture depends on the type, size and species of vegetation, weather, climatic and seasonal factors, and features of the growing site, e.g. slope aspect, moisture availability and soil type. Transpiration acts to lower groundwater levels. When vegetation is suddenly removed and transpiration ceases, a rise in groundwater level is observed.

Transpiration by trees on clay soils may accelerate the formation of shrinkage cracks during the dry season. A particular combination of soil, vegetation and climatic factors are required to produce such cracking known as desiccation cracking. Desiccation cracking increases infiltration capacity.

2.4.1.4 Soil suction and wilting point

Plants are limited in the extraction of water from the soil by the permanent wilting point, defined as the suction at which plants can no longer extract water from the soil. The suction of the soil water at which plants wilt varies greatly, although the value is set arbitrarily at 1.5 MPa which corresponds to a pore size of 0.2 μm. Some plants, can utilise more strongly bound water (e.g. xerophytes >6 MPa) while some plants, particularly leafy plants, may wilt at lower suctions (0.6–1 MPa) (ETH Zurich, 2004). The cause of wilting is attributable not so much to a low suction, but more to an insufficient supply of water in the soil resulting from low permeability, high water consumption of the plant and inadequate root density in the soil (ETH Zurich, 2004).

2.4.2 Mechanical mechanisms

The adverse and beneficial mechanical effects of vegetation on slopes are widely recognised (Table 2.3; Gray and Leiser, 1982; Greenway, 1987; Coppin and Richards, 1990; Morgan and Rickson, 1995; Gray and Sotir, 1996). The adverse effects of surcharge and wind throw are neglible on slopes such as embankments and cut-slopes on the transport network (Greenwood *et al.*, 2004). The most important mechanism for stabilisation is root reinforcement as roots provide a reinforcing effect to soil through their tensile resistance and frictional or adhesional properties. Whether the reinforcing effect of roots is significant to slope stability depends primarily on the depth of potential slip surfaces within the slope.

Table 2.3. Adverse and beneficial mechanical mechanisms of vegetation on slope stability (after Gray and Leiser, 1982; Greenway, 1987; Coppin and Richards, 1990; Morgan and Rickson, 1995; Gray and Sotir, 1996).

Adverse to stability	Beneficial to stability
Root wedging – tendency of roots to invade cracks, fissures and channels in a soil or rock mass and thereby cause local instability by a wedging or prying action	**Anchorage** - tree roots may anchor into firm strata providing support to the upslope soil mantle through buttressing and arching
Surcharge - weight of vegetation on a slope exerts both a downslope (destabilising) stress and a stress component perpendicular to the slope which tends to increase resistance to sliding. Surcharge at the top of a slope can lead to a reduction in stability.	**Reinforcement** - roots reinforce the soil increasing soil shear strength
	Surcharge - weight of vegetation at the base of a slope aids stability
Wind throw - vegetation exposed to the wind transmits dynamic forces into the slope	**Soil binding** - roots bind soil particles at the ground surface reducing their susceptibility to erosion; increasing shear strength through a matrix of tensile fibres forming a tensile mat effect

The root systems of trees may increase the stability of a potentially unstable soil mass by anchoring through the soil mass into a more competent substrata, provide a cover of a laterally strong root-soil system that acts as a reinforced mat and also provide localised centres of reinforcement across zones of weakness by soil arching (Gray and Sotir, 1996).

2.5 Summary

The biological characteristics of roots have been introduced and where possible simplified in engineering terms. The simplified engineering terms are thus used throughout the remaining text. The different types of root systems and the properties of roots required for slope stabilisation are described. The architecture and reinforcement aspects of roots are further described in Chapters 5 – 8.

Chapter 3: Methods of Investigation

3.1 Introduction

This chapter outlines the test procedures and methods of investigation used in this research for assessing the role of roots in slope stabilisation. Standard geotechnical techniques of collecting soil samples for soil classification were used. However, the geotechnical investigation of roots is a relatively new area of research and as such standard methods of determining root properties and distribution are not available.

The methods of investigation to determine the root and soil properties can be divided into two groups consisting of (1) field investigations generally of an invasive and destructive nature and (2) laboratory investigations. Some general procedures such as photography were applied to all methods of investigation.

The methods used to analyse the relationships between root and soil have been developed through trial and error and also by the application of ecological and forestry techniques. The design and development of the equipment for measuring root-soil strength is therefore reviewed and discussed in detail.

This chapter is not intended to be a review of all investigation techniques applicable to roots and soil. For information on the site investigation of vegetated slopes, the reader is referred to Greenwood *et al.* (2006) and Wint (2005). The investigation techniques used in this chapter have been tried and tested by the author from work carried out between 1997-1999 during the bio-engineering trial at Longham Wood Cutting (Greenwood *et al.*, 2001). The author thus applied the skills learnt during this period to the ECOSLOPES Project (2001-2004) and the doctorate. Table 3.1 provides a summary of the authors research of root-soil investigation.

Table 3.1. Summary of research into root-soil investigation.

Publication	Title	Journal or Conference
Greenwood, J. R. and **Norris, J. E.** (1999)	Moisture in the Bag - a simplified procedure for the determination of soil moisture content by oven drying.	Ground Engineering
Greenwood, J. R. and **Norris, J. E.** (1999)	Measurement of changes in geotechnical parameters due to the effects of vegetation.	Second International Conference on Landslides, Slope Stability and the Safety of Infra-Structures, Singapore.
Norris, J. E. and Greenwood, J. R. (2000a)	Review of *in situ* shear tests on root reinforced soil.	Developments in Plant and Soil, Kluwer Academic Publishers. IUFRO International Conference The Supporting Roots, Structure and Function, Bordeaux.
Norris, J. E. and Greenwood, J. R. (2000b)	*In situ* shear and pull out testing to demonstrate the enhanced shear strength of root reinforced soil.	8th International Symposium on Landslides, Cardiff.
Greenwood, J. R., Morgan, R. P.C., Coppin, N. J., Vickers, A. W. and **Norris, J. E.** (2001)	Bioengineering: a field trial at Longham Wood Cutting.	CIRIA publication RP81.
Norris, J. E. and Greenwood, J. R. (2003a)	Root reinforcement on unstable slopes in Northern Greece and Central Italy.	Proceedings of an International Conference on Problematic Soils, Nottingham.
Norris, J. E. and Greenwood, J. R. (2003b)	*In-situ* shear box and root pull-out apparatus for measuring the reinforcing effects of vegetation.	Field Measurements in Geomechanics. Myrvoll, F. (ed.)
Greenwood, J. R., **Norris, J. E.** and Wint, J. (2006)	Site investigation techniques to assess the effects of vegetation on slope stability.	Journal of Geological and Geotechnical Engineering

3.1.1 Field investigations

Field investigations were carried out on three sites, as explained in Chapter 4. The aim of the field investigations were to determine the nature of the soil, its strength and moisture content and to gather information on the distribution of roots within the ground for further laboratory or data analysis. The field investigations were carried out in the following manner:

3.1.1.1 Soil profiles

Soil profiles were logged in hand excavated trial pits. Trial pits were approximately 0.5 m x 0.5 m x 1.0 m deep. Soil samples for Atterberg Limit tests and moisture content analyses were collected from each trial pit. Each trial pit was photographed before backfilling.

The soil profile was logged in accordance with the British Standard classification system (BS5930, 1999). Any marked change in lithology, fissures and the presence and abundance of roots were recorded.

3.1.1.2 Soil moisture

A number of techniques for testing the soil moisture were employed depending on time and equipment availability. The standard gravimetric moisture content procedure (BS1377-2, 1990) was conducted in most cases. An adaptation to this standard procedure known as the "moisture in the bag" method (Greenwood and Norris, 1999) was also used as it allows for the rapid determination of moisture contents without the need to transfer soil from the collecting bags to the specimen dishes. All soil samples were collected in clear plastic bags, sealed and labelled.

For instant moisture content readings, a hand held moisture probe, Delta-T ThetaProbe type ML2x soil moisture sensor, was used. The ML2X sensor measures volumetric soil moisture content to within 1%. The sensor has an array of four rods or prongs which are pushed into the soil (Figure 3.1). On entering the soil, a change in impedance is recorded by the active signal rod. The changes in voltage amplitudes will give the relative impedance of the probe, hence the dielectric constant and thus a measure of volumetric water content (Delta-T Devices Ltd., 1999; Miller and Gaskin, undated).

The Delta-T probe could only be used where the soil was free from large stones and tree roots. The probe records volumetric moisture content so a simple calibration between gravimetric and volumetric moisture content is required. To convert from volumetric to gravimetric water content, the following equation can be used:

$$\omega = \omega_v * \frac{\rho_w}{\rho_d} \qquad [3.1]$$

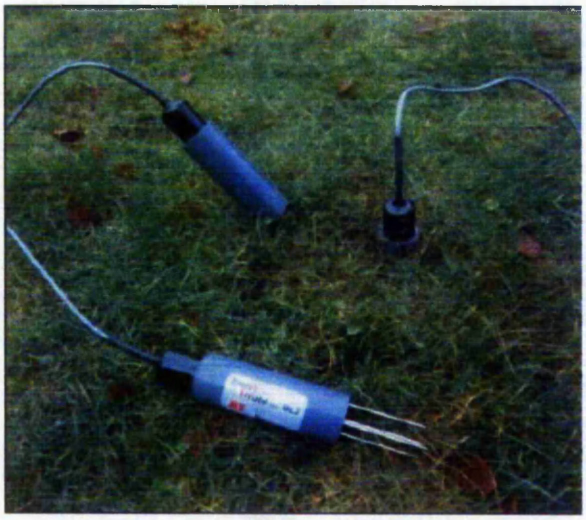


Figure 3.1. The Delta-T ThetaProbe used for measuring the volumetric moisture content of soils. (Photograph: Miller and Gaskin ThetaProbe Manual)

where ω is gravimetric moisture content (%), ω_v is volumetric moisture content (%), ρ_W is the density of water ($\approx$ 1 Mg/m^3) and ρ_d is the dry density of the soil sample (Mg/m^3) (Delta-T Devices Ltd., 1999; Greenwood *et al.*, 2001).

3.1.1.3 Soil strength

In situ 'undrained' soil shear strength was measured using a Pilcon Hand Vane Tester (19 mm vane), in accordance with BS1377-9 (1990).

The combined *in situ* shear strength of roots and soil was measured using a purpose built *in situ* shear box. The test procedure and design of the apparatus for the *in situ* shear tests are described in Section 3.2.

3.1.1.4 Root distribution

Root counts were conducted in the hand excavated trial pits. The distribution of roots was obtained by using two methods, both methods are based on Schuurman and Goedewaagen's (1971) squares on a profile wall method. Method One used a 0.5 m square quadrat subdivided into 0.1 m squares (Figure 3.2). The quadrat was self made using four pieces of scrap timber, nails and string. Each grid square was labelled A-E horizontally and 1-5 vertically, i.e. A1, A2, B1, etc. Method Two: the trial pit faces were subdivided into areas marked by changes in lithology. The number of roots in different root diameter sizes (Table 3.2) were counted in each 0.1 m square or subdivided area. The diameter of the roots were measured using vernier callipers to 0.02 mm. A tally system of recording was used in the field. The results of each root count were plotted as number of roots versus depth plots as shown in Figure 3.3.

Figure 3.2. 0.5 m square quadrat used for counting the distribution of roots.

Table 3.2. Root diameter classifications (after Böhm, 1979).

Root diameter size (mm)	Classification
0-5	Small roots and rootlets
5-10	Medium roots
>10	Large roots

Root area ratios (RAR) for each trial pit were calculated by the sum of the number of roots in each size class multiplied by the nominal average root cross-sectional area (CSA) of that size class, divided by the proportion of area at that depth expressed as a percentage (adapted from Greenwood *et al.*, 2001):

$$\text{RAR} = \frac{\Sigma[\text{No. roots in each class size} \times \text{Average root CSA of that class size}]}{\text{Area}} \times 100 \quad [3.2]$$

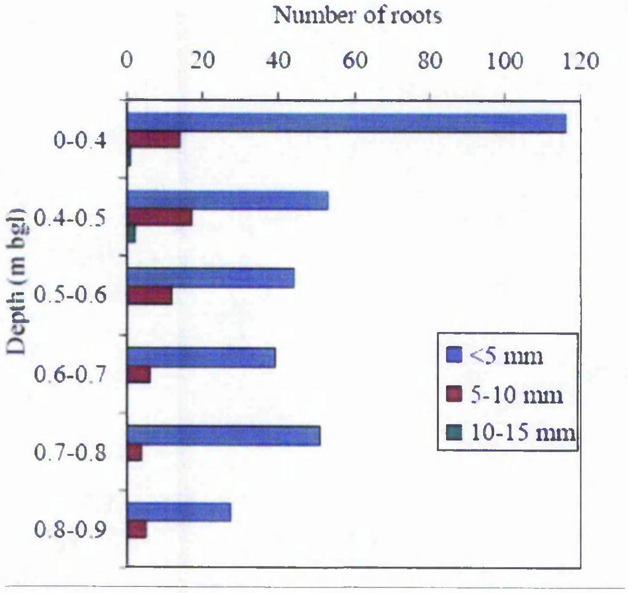
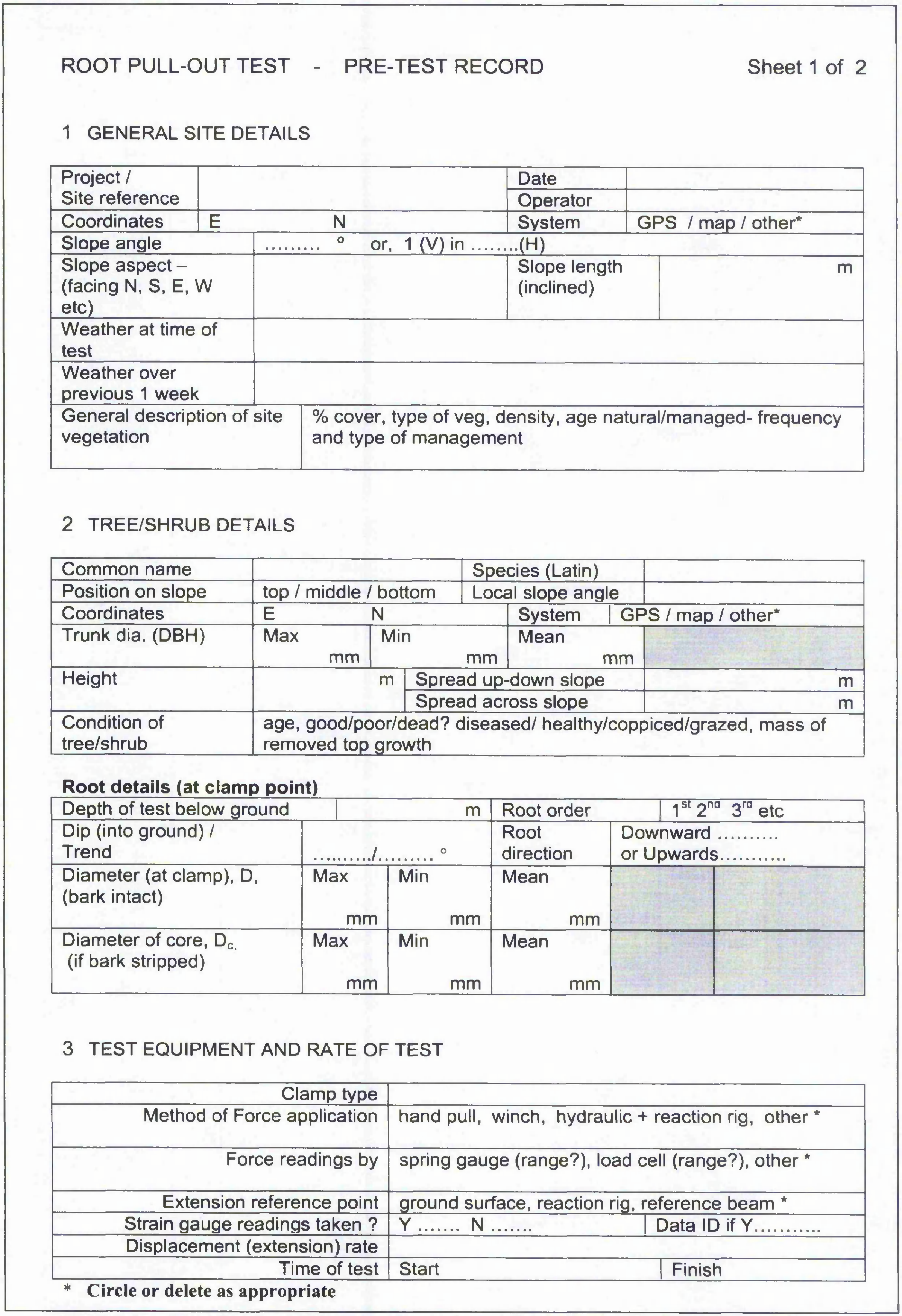


Figure 3.3. Example root count plot with depth below ground surface (see Chapter 4).

3.1.1.5 Above ground vegetation characteristics

The selection of suitable plant specimens for the investigation of root properties were chosen bearing in mind their proximity to other plants, size and limitations of equipment.

Plant characteristics such as height, stem diameter at breast height (dbh) or ground level (gl), spread, position on slope and slope angle were recorded on a datasheet (Figure 3.4). The mass of the above ground vegetation was also recorded.



ROOT PULL-OUT TEST - PRE-TEST RECORD

Sheet 1 of 2

1 GENERAL SITE DETAILS

Project / Site reference		Date	
		Operator	
Coordinates	E N	System	GPS / map / other*
Slope angle	.... ° or, 1 (V) in ....(H)		
Slope aspect – (facing N, S, E, W etc)		Slope length (inclined)	m
Weather at time of test			
Weather over previous 1 week			
General description of site vegetation	% cover, type of veg, density, age natural/managed- frequency and type of management		

2 TREE/SHRUB DETAILS

Common name		Species (Latin)		
Position on slope	top / middle / bottom	Local slope angle		
Coordinates	E N		System	GPS / map / other*
Trunk dia. (DBH)	Max mm	Min mm	Mean mm	
Height	m	Spread up-down slope		m
		Spread across slope		m
Condition of tree/shrub	age, good/poor/dead? diseased/ healthy/coppiced/grazed, mass of removed top growth			

Root details (at clamp point)

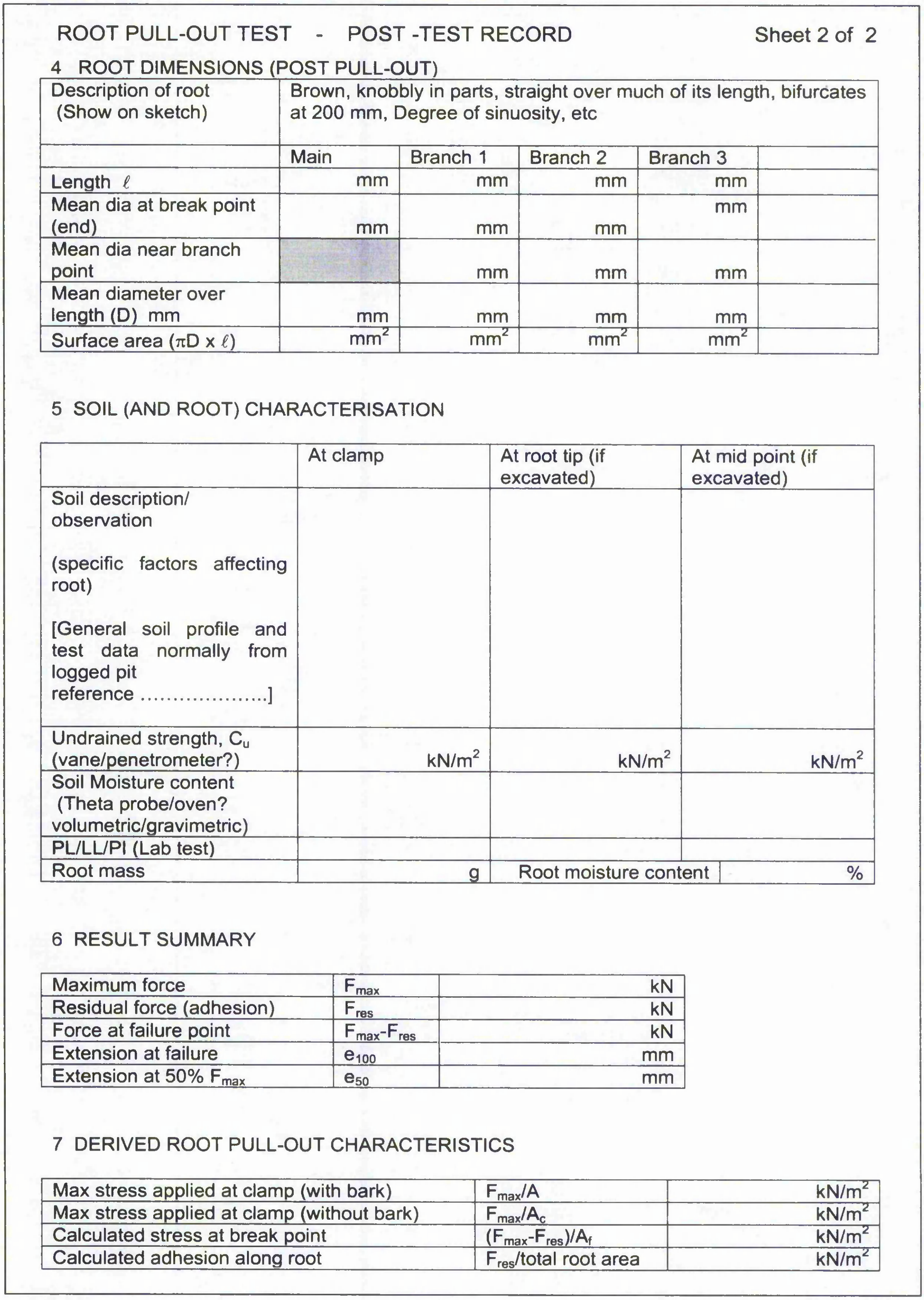
Depth of test below ground	m	Root order	1st 2nd 3rd etc		
Dip (into ground) / Trend	........./......... °	Root direction	Downward .... or Upwards...........		
Diameter (at clamp), D, (bark intact)	Max mm	Min mm	Mean mm		
Diameter of core, D_{c}, (if bark stripped)	Max mm	Min mm	Mean mm		

3 TEST EQUIPMENT AND RATE OF TEST

Clamp type		
Method of Force application	hand pull, winch, hydraulic + reaction rig, other *	
Force readings by	spring gauge (range?), load cell (range?), other *	
Extension reference point	ground surface, reaction rig, reference beam *	
Strain gauge readings taken ?	Y .... N	Data ID if Y...........
Displacement (extension) rate		
Time of test	Start	Finish

* **Circle or delete as appropriate**

Figure 3.4. Datasheet used for recording of vegetation, root and soil characteristics.



ROOT PULL-OUT TEST - POST -TEST RECORD Sheet 2 of 2

4 ROOT DIMENSIONS (POST PULL-OUT)

Description of root (Show on sketch)	Brown, knobbly in parts, straight over much of its length, bifurcates at 200 mm, Degree of sinuosity, etc				
	Main	Branch 1	Branch 2	Branch 3	
Length ℓ	mm	mm	mm	mm	
Mean dia at break point (end)	mm	mm	mm	mm	
Mean dia near branch point		mm	mm	mm	
Mean diameter over length (D) mm	mm	mm	mm	mm	
Surface area ($\pi D \times \ell$)	mm^2	mm^2	mm^2	mm^2	

5 SOIL (AND ROOT) CHARACTERISATION

	At clamp	At root tip (if excavated)	At mid point (if excavated)
Soil description/ observation (specific factors affecting root) [General soil profile and test data normally from logged pit reference ....]			
Undrained strength, C_u (vane/penetrometer?)	kN/m^2	kN/m^2	kN/m^2
Soil Moisture content (Theta probe/oven? volumetric/gravimetric)			
PL/LL/PI (Lab test)			
Root mass	g	Root moisture content	%

6 RESULT SUMMARY

Maximum force	F_{max}	kN
Residual force (adhesion)	F_{res}	kN
Force at failure point	F_{max}-F_{res}	kN
Extension at failure	e_{100}	mm
Extension at 50% F_{max}	e_{50}	mm

7 DERIVED ROOT PULL-OUT CHARACTERISTICS

Max stress applied at clamp (with bark)	F_{max}/A	kN/m^2
Max stress applied at clamp (without bark)	F_{max}/A_c	kN/m^2
Calculated stress at break point	$(F_{max}-F_{res})/A_f$	kN/m^2
Calculated adhesion along root	F_{res}/total root area	kN/m^2

Figure 3.4. continued.

3.1.1.6 Root system architecture

To investigate the variability of root systems, root systems were hand excavated to an approximate radius of 200 mm from the stem and the number of roots, root diameters, exposed root length and orientations recorded (Figure 3.5). Root orientations i.e. the dip of each root and growth direction from the stem were measured using a Silva compass clinometer. On a slope, roots that dipped downwards were marked as (–) whereas roots that ascended up into the soil were marked as (+). Root orientations were recorded in the following manner: 185°/-14°.

Root growth direction were plotted on rose diagrams using GeoOrient v9.2 (Stereographic Projections and Rose Diagram Plots) software available on the web at http://www.earth.uq.edu.au/~rodh/software. The mean root growth direction was calculated by the software using circular statistics (Fisher, 1993; Mardia and Jupp, 1999). An example of a rose diagram is given in Figure 3.6.

Figure 3.5. Root architecture measurements using a compass clinometer to measure angle of root and direction of growth of an Elder shrub, Rushcliffe Halt, Great Central railway embankment, near East Leake, Nottinghamshire.

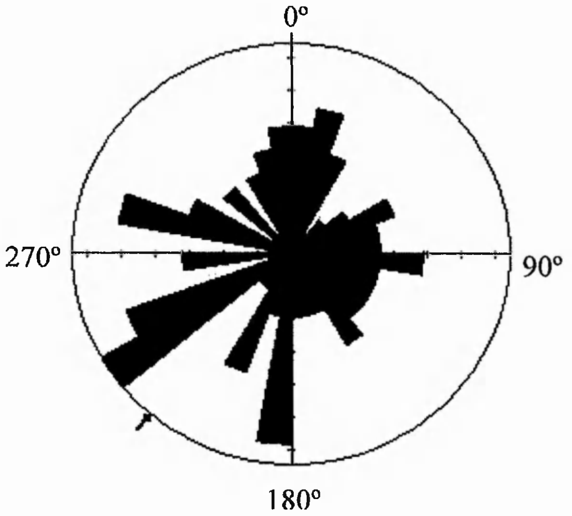


Figure 3.6. Rose diagram showing root orientations. The arrow indicates the mean root growth direction of 220 (± 2.6° s.d.). The divisions on each axis record the number of roots, (maximum of 10), for example, each sector has an angle of 10° and the angle 0-9° has 6 roots in this sector.

3.1.1.7 Root pull out resistance

Depending on the size of the plant, the root system around the stem was carefully excavated in the manner of an archaeological excavation, using pointing trowels and gardening tools to remove the soil. Soil was removed until the main lateral roots could be clearly seen (approximately 300 mm from the stem) and allowing sufficient room for access for secateurs, loppers or saws to cut the roots from the stem body.

After excavation, all roots were labelled using an alphabetical labelling system (i.e. A – Z then AA, BA, CA…) and the following parameters recorded on a datasheet (Figure 3.4): root diameters (see Section 3.1.3.2), root orientations (see Section 3.1.1.6) and exposed root length. Initial root diameter readings were taken within close proximity to the stem body. Photographs and sketch drawings were taken of the root system before conducting further tests and before cutting each root from the stem.

All roots were cut from the stem using secateurs, loppers or saw depending on the size of the root. Each root was cut as close to the stem body as possible so that the maximum area of root was exposed for the root clamps. The stem was weighed as part of the above ground mass.

The pull out resistance and extraction force of all roots was determined either manually or mechanically. Both methods and the design of root clamps are explained in Section 3.3. The labelled roots were clamped and pulled out of the ground in turn. Surface roots were pulled first to cause minimal soil disturbance to roots penetrating deeper into the ground.

Following pull out, the root diameters at the clamp and at either the root tip or failure point were recorded. When the root had multiple branches, all root tips or failure points were measured. The total length of each root (in mm), including all branches, was measured with a ruler or tape measure. A short description of the root morphology was made (see Table 8.1 for terminology). Each root was sketched and photographed. Figure 3.7 shows the features and notation associated with *in situ* root pull out testing. Maximum failure load and displacement were recorded for each test. Type of failure, whether tensile or slippage was also recorded. The maximum pull out stress of each root was calculated by using the formula:

$$\text{Maximum pull out stress (MPa)} = \frac{\text{Load (kN) (force to pull out root)}}{\text{Cross Sectional Area of root (mm}^2\text{)}} \qquad [3.3]$$

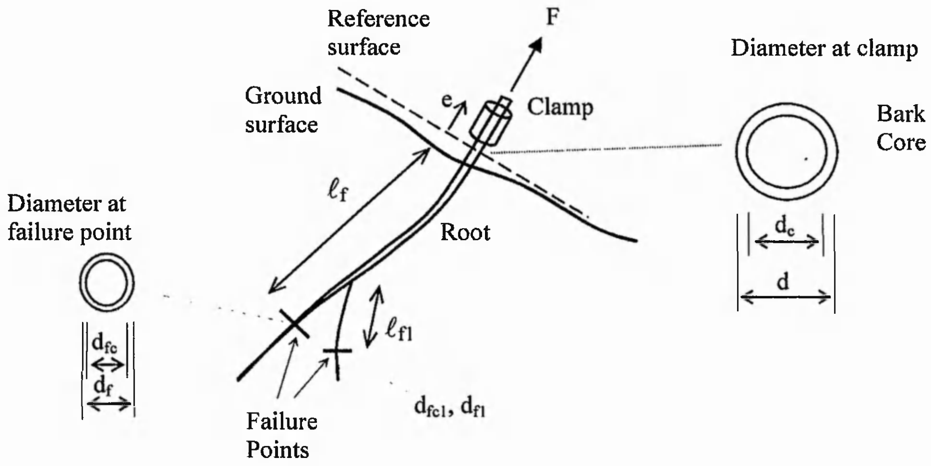


Figure 3.7. Features associated with root pull out testing.
Notation: F – Applied tensile force (kN); d – Mean diameter of root including bark at clamp (mm); d_c – Mean diameter of root core at clamp (mm); d_f – Mean diameter of root including bark at failure point (mm); d_{fc} – Mean diameter of root core at failure point (mm); e - Displacement (extension) relative to reference surface (mm); ℓ_f - Length of main (1st order) root pulled from ground (m); ℓ_{fl} - Length of branch (2nd, 3rd order) roots (ℓ_{fi}) (m).

Graphs of failure load and displacement were plotted for each root (Figure 3.8). Root moisture content (Section 3.1.2.4) and soil strength by hand vane tests (depths from 0-0.2 m bgl) (Section 3.1.1.3) were also determined as soon as possible after the tests.

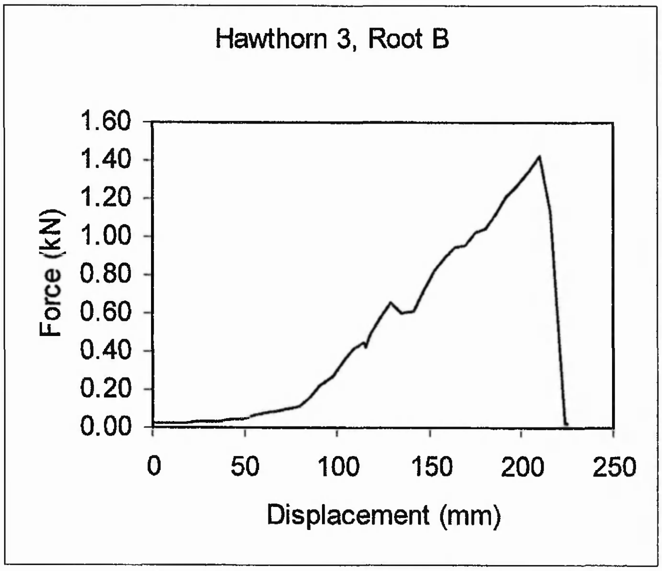


Figure 3.8. Example plot of recorded load against displacement observed during pull out of a hawthorn root.

3.1.2 Laboratory investigations

3.1.2.1 Soil classification

The collected soil samples were brought back to the laboratory and classified using the British Standard classification charts and methods (BS1377-2, 1990). Atterberg Limit tests and particle size distribution analyses were carried out when necessary to assist classification. 60 mm shear box tests were carried out in accordance BS1377-7 (1990). The methods of conducting these tests were carried out as directed by the British Standard and as such are not described further.

To determine the gravimetric moisture content of the soil samples, three specimen dishes of approximately 10 g of wet soil were oven dried at 105°C for 24 hours in accordance with BS1377-2 (1990). The mean of the three specimens was taken as the actual moisture content to 0.1 %.

3.1.2.2 Tensile strength tests of roots

Roots collected from shrubs and trees were given on site identifications and sealed in plastic bags to maintain natural moisture content as much as possible.

In the laboratory, all roots were washed to remove any soil. Roots were sketched, and the diameter at all ends measured (see Section 3.1.3.2), with the length and number of branches recorded. Each root and laterally branched root was subsequently cut, using secateurs, into ~150 mm lengths for testing in the Monsanto 20 Tensometer machine (Figure 3.9a).

Each cut length of root was given a new identification, and the diameter and length of the cut lengths of root were measured and recorded. Each cut length of root was kept in a sealed plastic bag and stored at a temperature below 10°C. All roots were tested within 4 – 5 days of excavation to ensure that the roots were as fresh as possible.

Each root was placed in the jaws of the Tensometer machine. Roots over 12 mm in diameter were trimmed using a Stanley knife, to enable them to fit into the jaws of the machine. Each root was pulled at a rate of 2 mm per minute, using either the 2 kN or 20 kN load cell depending on the diameter of the root. The Tensometer machine records graphically the applied force (y-axis) and extension (x-axis) (Figure 3.9b). The resulting maximum force and extension when each root failed was recorded. The peak force and corresponding extension were plotted in Microsoft Excel (see results in Section 4.5.2).

Roots that were deemed too strong for the capacity of the Monsanto Tensometer were tested in a Losenhausenwerk tensile testing machine (Figure 3.10).

After each tensile test, the length of the stretched root and the root diameter at the break point were recorded. The peak tensile strength of each root i.e. stress at break point was calculated using equation [3.3] and the corresponding percentage strain (extension) was determined. The relationships between tensile stress at break point and both root diameter and strain were determined (Section 4.5.2). The root moisture content was subsequently determined (Section 3.1.2.4).

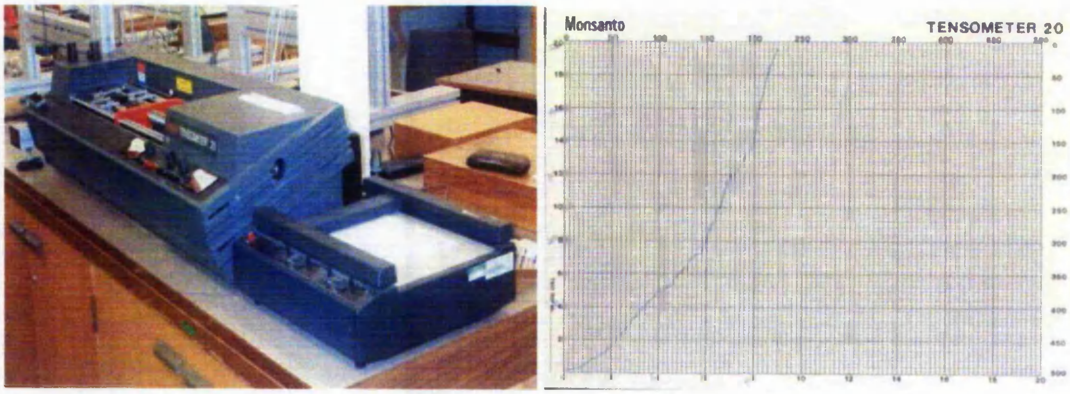


Figure 3.9. a).Monsanto Tensometer 20 tensile testing machine. b). Typical graphical output on designated plotting paper (plotting paper has multiple scale axes for a variety of applications).

Figure 3.10. The Losenhausenwerk tensile testing machine used for testing roots of diameters greater than 15 mm.

3.1.2.3 Root elasticity

When a material is is put under tension, the stress is linearly proportional to the strain during the initial portion of the stress-strain curve. This proportion of the curve is where the material exhibits elastic behaviour. Beyond the yield point or proportional limit the relationship no longer holds and the material undergoes plastic deformation. This relationship is true for roots and is known as root elasticity. Root elasticity can be calculated by using the familiar Young's Modulus or Modulus of Elasticity equation [3.4]

$$\text{Modulus of Elasticity, } E = \frac{\text{stress}}{\text{strain}} = \frac{F_p / A}{ext/ l_o} \qquad [3.4]$$

where F_p = force at the yield point, A = cross sectional area of the root, ext = extension, l_o = length of root between the clamps.

From the graphical results of the tensile tests (as described in Section 3.1.2.2), root elasticity (Young's Modulus) was calculated by drawing a tangent to the resulting stress-strain curve and the point where the tangent deviated from the curve was taken to be the position of the yield point. At the yield point, the equivalent stress and strain can be determined, and root elasticity can be calculated using equation [3.4].

3.1.2.4 Root moisture content

Root moisture content was determined by weighing the mass of each root, drying in an oven at 80°C (Schuurman and Goedewaagen, 1971) for 24 hours (or until a constant dry weight was achieved) and reweighed when dry. Large root diameter specimens took 3 – 5 days to dry.

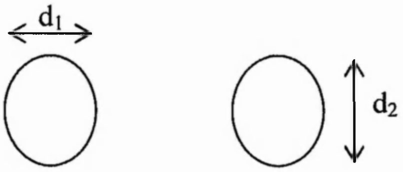
3.1.3 General practice

3.1.3.1 Location of vegetation on trial sites

A description of the general site details (slope angle, slope height, vegetation cover, location, soil type) and weather conditions were recorded. The location of all test pits and test plants were recorded using a handheld Global Positioning System (GPS) navigator, model Garmin GPS 12. All GPS positions were recorded using the latitude/longitude co-ordinate system (degrees, minutes, seconds or decimal degrees notation) e.g. N52°85'481" and E 001°17'616".

3.1.3.2 Root diameter measurements

Roots in cross section are generally not perfect circles, therefore root diameters were calculated by measuring the maximum width and height (d_1 and d_2) of the root (Figure 3.11). The average of the two measurements was taken to be the actual root diameter, d. All root diameters were measured using vernier callipers to an accuracy of 0.02 mm.



$$d = \frac{d_1 + d_2}{2}$$

Figure 3.11. Horizontal and vertical root diameter axes measurements.

3.1.3.3 Photography

Colour digital photographs were taken using either a Kodak DC3400 Zoom digital camera, with 2.0 Megapixels, 1760 x 1168 resolution, 2x optical plus 3x digital zoom and autofocus lens with macro facility or a Kodak DC5000, rugged and water resistant digital camera, with 2.1 Megapixels, 1760 x 1168 resolution, 2x optical plus 3x digital zoom, autofocus lens with macro facility and built-in flash.

The majority of photographs in this thesis were taken by the author, all other photographs are duly acknowledged.

3.2 ***In situ* shear apparatus**

3.2.1 A review of *in situ* shear boxes: their design features, development and associated problems

There are no commercially available standard *in situ* shear boxes developed for testing soils or in this particular case for analysing the strength of plant roots in soil. It has therefore been necessary for investigators to design and develop their own apparatus for measuring the *in situ* shear strength of both soil (e.g. Dijkstra *et al.*, 2000) and reinforced soil (e.g. Endo and Tsuruta, 1969; Endo, 1980; O'Loughlin, 1981; Wu *et al.*, 1988a; Norris and Greenwood, 2000b, 2003a).

Each *in situ* shear box (as reported by the authors in Table 3.3) is based on the standard laboratory shear box but, in general, has slight variations in size and design components. The basic principle for an *in situ* shear box is a metal box placed over a test block of soil, with a hand or hydraulic jack used to push or pull the box along a forced shear plane, a load cell is attached to record the force and weights placed on top to provide a normal compression load. Displacement meters are positioned on both sides of the box. Figure 3.12 shows the design of one of the early *in situ* shear boxes from which all later shear boxes were developed.

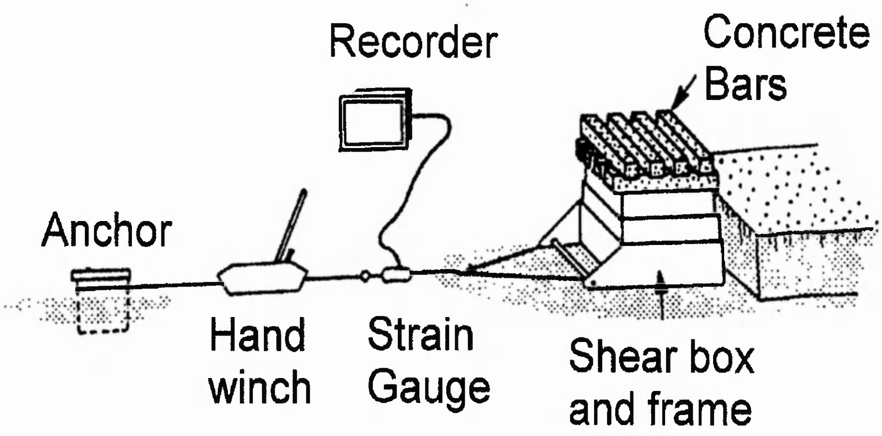


Figure 3.12. Schematic illustration of the *in situ* shear apparatus used by Endo and Tsuruta (1969) and Endo (1980) (modified from Endo 1980).

Norris and Greenwood (2000a) reviewed the design of *in situ* shear boxes, in order to design and develop an *in situ* shear box for use on root reinforced Gault Clay soil (Greenwood *et al.*, 2001; Norris and Greenwood 2000b; see Appendix 4). Table 3.3 highlights the different designs and variation in sizes of the *in situ* shear boxes used to test root reinforced soil.

There have been two distinct designs of the *in situ* shear box apparatus. The first is a closed shear box, initially designed by Endo and Tsuruta (1969) (Figure 3.12). In the closed shear box, roots can only extend undisturbed in the vertical direction, therefore

Table 3.3. Review of *in situ* shear box testing relating to root reinforced soil (updated from Norris and Greenwood, 2000a).

Author	**Location**	**Vegetation type tested**	**Shear box dimensions (w x l x h)**	**Comments**
Endo and Tsuruta (1969)	Japan	*Alnus glutinosa*	500 x 500 x 300-600 mm (adjustable height)	Roots 1 to 2 mm diameter pulled from the soil block during shearing.
O'Loughlin (1972)	British Columbia, Canada	*Pseudotsuga menziesii* *Thuja plicata* *Tsuga heterophylla*	Modified design of Endo and Tsuruta (1969)	Roots 5 mm in diameter pulled out of the soil block instead of shearing along the shear plane.
Endo (1980)	Japan	*Betula japonica* Sieb. *Alnus japonica* Steud.	500 x 500 x 300-600 mm	A simple design but made possibly impractical by the addition of two kinds of concrete sticks to provide additional load. Vertically aligned roots may pull out or break.
Ziemer (1981)	California	*Pinus contorta*	Open sided shear box 600 x 300 x 300 mm. Open side is 300 mm^2.	Designed so that the shear box shears along two parallel vertical planes. Shear rate 12.7 mm/minute. Roots lying horizontally and aligned normal to the shear planes are undisturbed by the shear box and continue into the soil either side of the box.
O'Loughlin (1981); O'Loughlin *et al.* (1982)	Maimai experimental catchment, New Zealand	Beech forest	Open sided and base shear box 300 x 300 x 150 mm	Similar design to Ziemer (1981) although on a reduced scale. Shear rate 13 mm/minute. During shearing, shear surfaces develop at the sides and base of the soil block; roots either stretch and break or pull out at these surfaces. See review by Phillips and Watson (1994).
Abe and Iwamoto (1986)	Chiyoda Experimental Branch Station nursery, Forestry and Forest Products Research Institute, Ibaraki Prefecture.	*Cryptomeria japonica* D. DON (sugi)	1 x 1 x 0.3-1 m (adjustable height)	Shear loading rate 0.98 kN per 20 minutes. A large tree root present in the soil can easily be sheared by the oil jack with a uniform pressure.
Barker in Hewlett (1987)	Jackhouse Reservoir, UK (steep grassed waterways)	Grass associated with concrete blocks and geotextiles	305-500 mm x 610 x 30-100 mm (variable width and height)	Saturated samples to represent in-service conditions.

Table 3.3 continued.

Author	Location	Vegetation type tested	Shear box dimensions (w x l x h)	Comments
Wu *et al*. (1988a)	Siuslaw National Forest Mapleton, Oregon	Western hemlock	undrained or quick direct shear tests 300 x 600 x 300 mm	Apparatus designed by Ziemer (1981). The dimensions of this box represent a compromise since increasing the length of the box would increase the number of roots that would be cut off and reducing the length would reduce the resistance developed by the root inside the box.
	Tongass National Forest Alvin Bay, Alaska	Western hemlock Alaska cedar		
	Tongass National Forest Peterson Cr., Alaska	Western hemlock		
	Ohio State University Columbus, Ohio	Silver maple		
Clark (1992)	Ghopa Camp, Nepal	*Pennisetum Purpeneum* (Napier grass)	250 x 250 x 100 mm	It was noted that the four sided shear box had tilting problems during shearing.
	Karkichap, Nepal	*Seteria anceps* (local Nepalese fodder grass)		
	Ambote, Nepal	*Themeda sp., Neyraudia sp., Cymbopogan Microtheca*		
	Dhankuta, Nepal	*Cymbopogan Microtheca,* Imperata.		
Tobias (1995)	Zurich, Switzerland	Grasses (*Alopecurus geniculatus, Poa pratensis, Agrostis stolonifera, Festuca rubra, Lolium multiflorum, Festuca pratensis*	500 x 500 x 150 mm	Marginal effects of roots cut by pushing in the metallic frame are minimised with these dimensions. Tests interpreted as unconsolidated and undrained.
Yatabe *et al*. (1996)	Japan	Chinese cedar, fir, shrub, bamboo, grass	300 x 300 x 120 mm	Normal stress applied by air cylinder, shear stress applied with a hydraulic jack.
Zhou *et al*. (1998)	Hutiaoxia Gorge, southwest China	Lateral roots of *Pinus yunnanensis*	400 x 350 x 200 mm	Roots were left connected to the stable soil mass behind the shear box to investigate the traction effects. Shear box assembled in place around soil cuboid.
Norris and Greenwood (2000b); Greenwood *et al*. (2001)	M20 Longham Wood Cutting, UK	Willow and alder	150 x 150 x 100 mm	No additional load.
van Beek *et al*. (2005)	Almudaina, Spain	Pine	600 x 600 x 400 mm	Soil saturated prior to testing.

allowing these roots to break or pull out of the soil. In the second design, the open sided shear box as developed by O'Loughlin (1981), horizontally aligned roots normal to the shear plane, can protrude undisturbed through the soil block and into the soil on either side of the shear box. These roots can only break when shearing takes place. The majority of authors used the closed shear box design for their investigations.

The review by Norris and Greenwood (2000a) highlighted the significant variation in size of shear box, from 0.15 m up to 1 m in length. The considerable variation in size is partly due to experimentation by the authors as to the best size of box but it is mainly due to the size of plant being tested and the extent of the root system. Large shear boxes are desirable to overcome local discontinuity effects within a soil-root system (Norris and Greenwood, 2000a).

The problems of *in situ* shear testing as recorded by Clark (1992), Tobias (1995) and Norris and Greenwood (2000a), raised questions regarding the reproduceability, repeatability and comparability of test results between investigators.

3.2.2 Apparatus design and development

The review of *in situ* shear boxes led to the development of an *in situ* shear box for testing reinforced clay soil on the Longham Wood Cutting bioengineering trial (Greenwood *et al.*, 2001; Norris and Greenwood, 2000a, b). The initial design was based on the closed shear box of Endo and Tsuruta (1969), with a push jack mechanism The shear box being enclosed within a steel frame located on two runners to prevent tilting during shearing (Norris and Greenwood, 2000b). A smaller shear box of a portable nature was favoured to a larger shear box (Norris and Greenwood, 2000b). The apparatus consisted of a 150 mm square sided by 100 mm in height steel box, 10 kN load cell, jack, displacement gauge and data-logger (Figure 3.13). The soil block was sheared until peak load had been obtained, further residual strength was recorded by repositioning the jack after every 50 mm movement. This *in situ* shear box worked reasonably well but problems with repositioning the jack after every 50 mm of displacement created problems with assessing the true failure stress. The apparatus was thus redesigned to ensure smooth shear failure during operation, by allowing for longer movements of the shear box and electronic data logging of load and displacement. Smooth shear failure was achieved by changing from a push jack mechanism to a pull mechanism. A larger capacity load cell was also used.

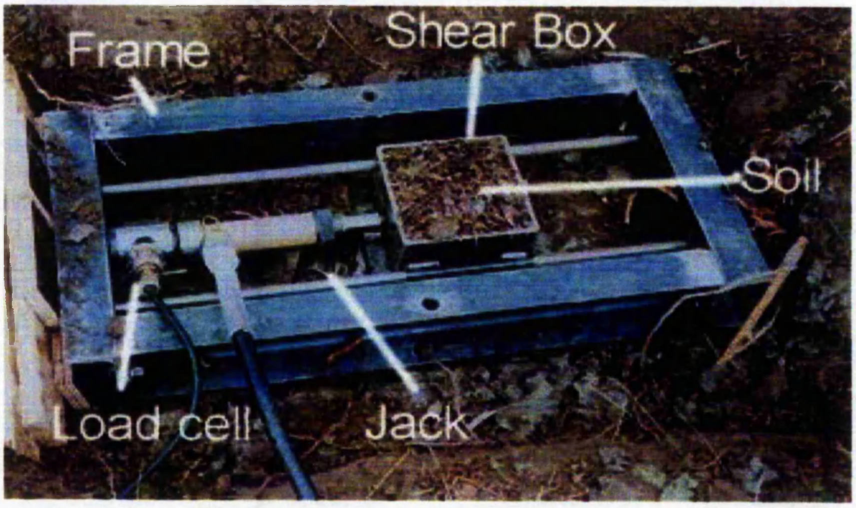


Figure 3.13. *In situ* shear box apparatus in operation on the bioengineering demonstration site, M20 motorway, Maidstone, UK (Norris and Greenwood, 2000b).

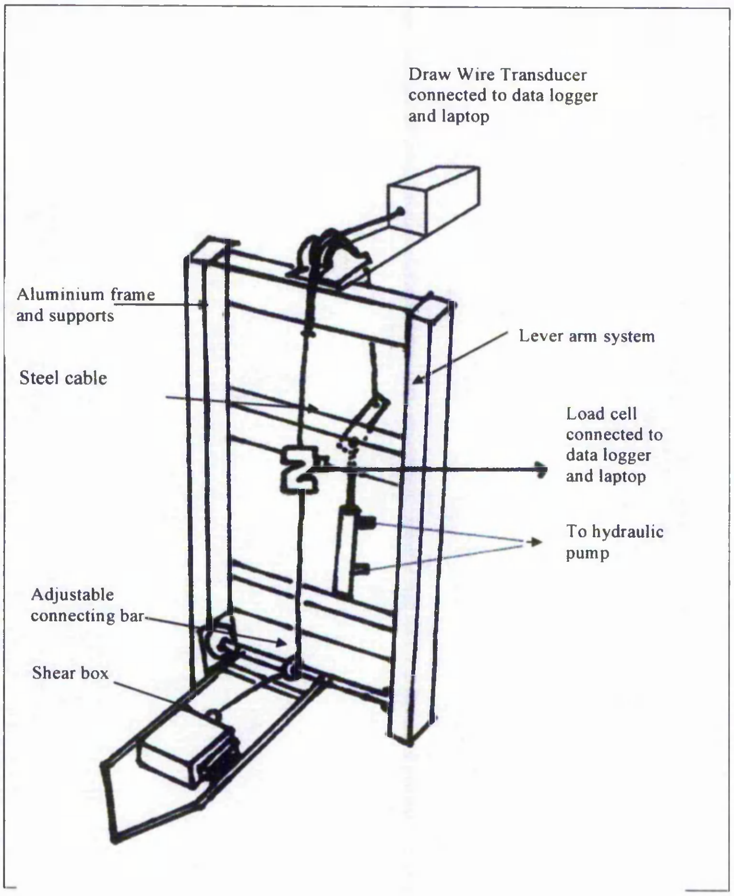


Figure 3.14. Field set up and lay out of the *in situ* shear box apparatus (Norris and Greenwood, 2003b).

The redesigned apparatus (Figure 3.14) consisted of a 150 mm by 150 mm by 100 mm steel plated shear box, an aluminium frame with running tracks, a 250 kg Z-type load cell connected to a steel cable and hydraulic cylinder, a draw wire transducer (type DWT-20-06-CR-1-E), datalogger (IOTech Data Acquisition System [USB 56]) and lap top computer (Norris and Greenwood, 2003b).

During shearing of the root-soil block, the running tracks control the movement of the shear box. The load cell measures tensile force. Force is applied through the hydraulic cylinder, which has a pulling force of 8.79 kN and is capable of 100 mm displacement. The cylinder is fully extended prior to the test. Displacement of the shear box is measured by the draw wire transducer, which is fixed to the top of the frame and the draw wire is clipped to the steel cable. Both the load cell and the draw wire transducer are electronically connected to the datalogger. The amount of displacement and tensile force are logged and recorded as an ASCII file. The draw wire transducer and the load cell were calibrated. Calibration factors for the draw wire transducer were $y = 64.14x + 0.08$ (where x is the original displacement reading and y is the calibrated displacement in mm) and load cell $y = -238.4x + 2.22$ (where x is the original load cell reading and y is the calibrated load in kN). The calibration scaling factors enabled the data to be logged in real time values of millimetres and kiloNewtons, respectively. The datalogger scanned the readings at 140 Hz per second, which gave an unmanageable number of data points. The data acquisition system was therefore set to block average the number of scans giving one reading per second.

3.2.3 Test procedure to measure the combined root-soil strength

A description of the general site details (soil, slope angle, slope height, vegetation cover, location) and weather conditions are recorded. The site is assessed for suitable test plot areas for carrying out unreinforced and reinforced *in situ* shear tests, i.e. an area with a combination of bare ground or grasses, shrubs and trees. An area of approximately 3 m long by 1 m wide is marked out with pegs. The type, density cover, height and spread of the vegetation within the test plot are recorded on a data sheet. The top growth of all the vegetation present within the plot is removed, as this may become a hazard during the testing procedure.

The shear box is positioned on the ground above the area of soil that is to be tested. The soil is carefully excavated around all four sides of the box maintaining an intact soil block inside the box, some pressure may need to be exerted on the box during emplacement. When testing a reinforced sample some roots protruding from the sides of the soil sample may need to be removed with sharp secateurs. Once the shear box is in place, i.e. at the required shearing depth from the ground surface, the soil surrounding the box can be removed to allow the shearing apparatus and frame to be assembled. The hydraulic pumping system and laptop are set up once the apparatus is assembled. The test is conducted at a constant rate of shearing. Load and displacement are recorded electronically by the datalogger. It is necessary during the shear test, to observe the mode of shear and to record any unusual events that may occur, for example, the presence of stones preventing the shear box from moving will cause a false peak in the failure curve.

On completion of the test, the soil in the shear box is explored and the number, locations and diameters of the roots (if present) are recorded. The moisture content of the soil in the shear box and below the shear plane is recorded. Any features present on the shear plane are also recorded.

The datalogger records all readings as ASCII files. Prior calibration of the load cell and displacement transducer results in real time values. The ASCII files can be exported into Microsoft Excel for processing and presentation of the data. Graphs of shear stress against displacement can be produced for each test (Figure 3.15). The peak (maximum) and residual shear strength can be determined from the graph.

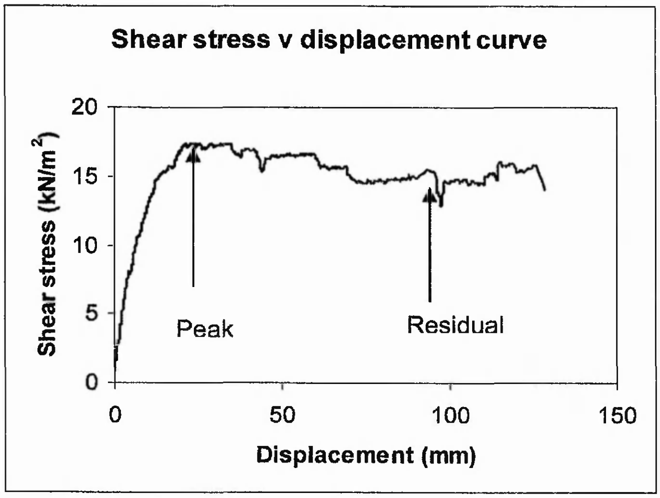


Figure 3.15. Example plot of shear stress test.

3.3 Root pull out techniques and apparatus design

3.3.1 Review of *in situ* root pull out apparatuses

The equipment necessary for finding the pull out resistance of roots from soil is relatively straightforward. A load cell to record force applied, a displacement meter to record the distance travelled and a simple jacking or cable pulley system is all that is required. The difficulty comes in how one is able to clamp the root securely to the pulley or jack since the relatively thin bark and the presence of sap between the bark and the root core can prevent gripping of the root during pull out.

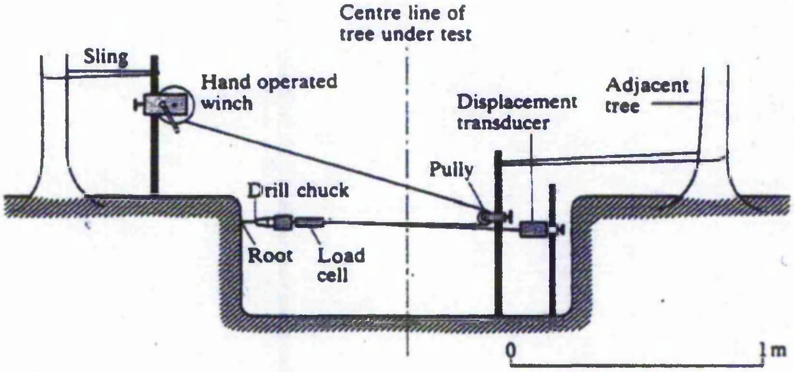


Figure 3.16. Set up of apparatus for measuring root extraction force and displacement (Anderson *et al.*, 1989).

In the literature, only two apparatuses for pulling roots out of the ground have been described. Anderson *et al.* (1989) measured root extraction force for Sitka Spruce roots using an adapted drill chuck with serrated jaws attached to a load cell (Figure 3.15). The method of extraction was extremely successful with ~350 roots being pulled out, however the diameter of roots was limited to between 4–20 mm due to the aperture of the drill chuck.

Operstein and Frydman (2000) designed an *in situ* pull-out apparatus using a jacking system with a proving ring for pull-out forces over 0.25 kN and used a hand-held spring balance for pull out forces less than 0.25 kN. The apparatus used by Operstein and Frydman (2000) was limited to a maximum root diameter up to 15 mm.

3.3.2 Root clamp design for *in situ* pull out tests

With no standard method of clamping roots available, it was necessary to design purpose made root clamps for roots of diameters 1–40 mm, and a root pulling apparatus. A number of designs were tried before a successful clamping technique was found.

3.3.2.1 Root clamp failures

A. Drill chuck

The adapted drill chuck method as used by Anderson *et al.* (1989) was initially tried but the roots were not gripped tight and pulled out of the chuck.

B. Bicycle inner tube clamp

The bicycle inner tube clamp (Figure 3.17) worked on the principle of an expanding airbag (or bicycle inner tube) exerting pressure onto the root to clamp it in place. Unfortunately, this clamping device had to be rejected due to only an applied maximum load of 1 kN before the root slipped out.

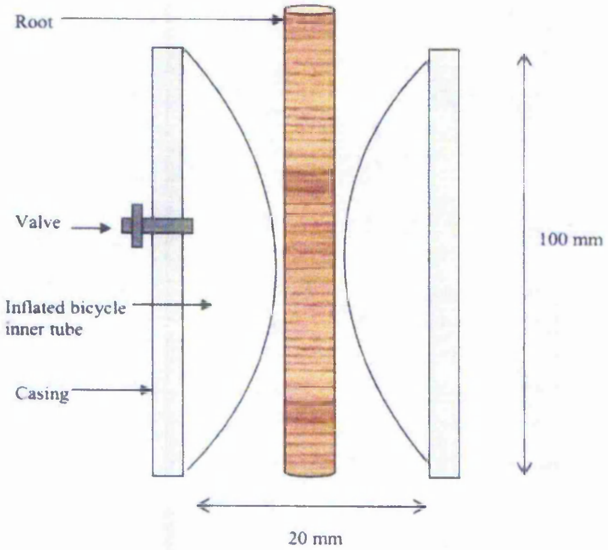


Figure 3.17. Root clamp designed using an inflatable bicycled inner tube.

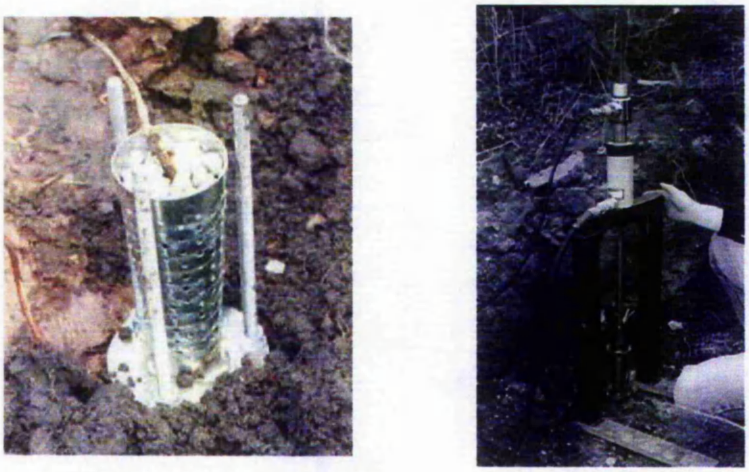


Figure 3.18. Gravel filled cone root clamp.

3.3.3.2 Root clamp successes

C. Gravel filled cone root clamp

A steel cone is placed over a protruding root and angular gravel (10–20 mm) is inserted into the cone around the root (Figure 3.18; Norris and Greenwood, 2000b). As the root is extracted from the ground, the gravel interlocks together and wedges against the root. In trials this clamp worked well but was not a very portable and efficient method.

D. Collet root clamps

Two collet root clamps with adjustable jaws and encased in a steel ring casing were designed for roots up to 28 mm. Figure 3.19 shows the collet clamp made of a steel ring with wedge shaped jaws (Norris and Greenwood, 2003b). The clamp in Figure 3.19 was suitable for roots 5–15 mm in diameter. Figure 3.20 shows the collet clamp with adjustable clamping screws that pushed on to screw rods to hold the root in position. Roots between 15–28 mm in diameter could be tested using the clamp in Figure 3.20.

Both collet clamps worked extremely well in clamping on to the root and were therefore used for the root pull out tests. However, the design of the clamps could be further improved as the adjustable screw rods kept falling out of the inner casing when trying to clamp the root.

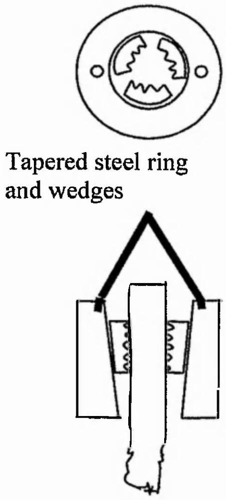


Figure 3.19. Root clamp made of a tapered steel ring with three wedge shaped jaws. Top. Plan view. Bottom. Cross section. (Norris and Greenwood, 2003b).

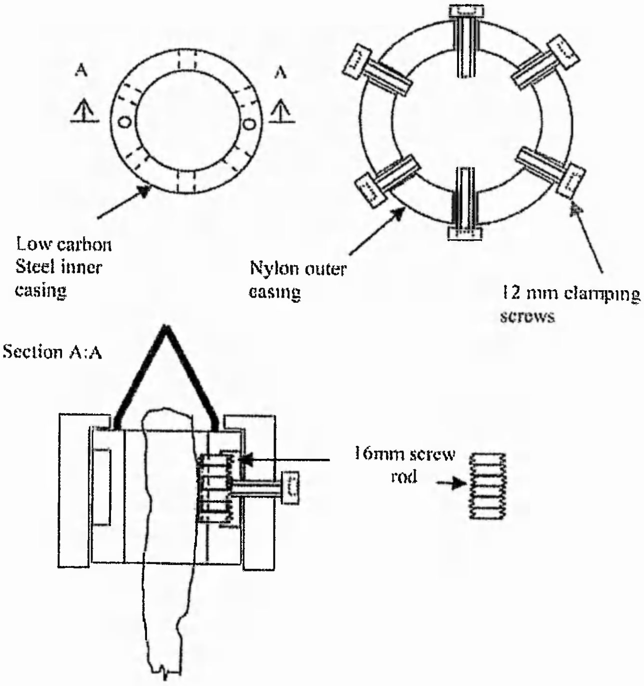


Figure 3.20. Screw clamp for roots 15 – 28 mm. Top. Plan view. Bottom Cross section through A:A. (Drawings by S. Goodman).

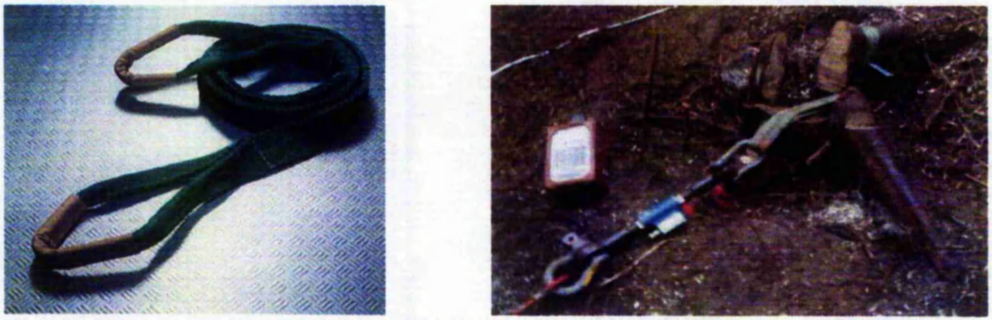


Figure 3.21. a). Tree lifting strop. b). Strop as a root clamp.

E. Strops

Tree lifting strops (Figure 3.21a), capable of lifting up to 3 tonnes were wrapped around the end of the root. A notch was carved into the root to prevent the strop from sliding off the end of the root (Figure 3.21b).

The strop clamping method was quick and efficient and is also portable. Further tests should be carried out using strops of different lengths and tensile strengths. Adjustable strops are used by professional arborists to climb trees and in the forestry and construction industry for lifting and winching.

3.3.3 Apparatus for extracting roots

3.3.3.1 Hand pull

Roots were pulled out by hand using a spring balance attached to a root clamp. Displacement was measured using a tape measure. Maximum pull out force and displacement were recorded manually.

This method worked reasonably well for small diameter roots but accurate simultaneous manual recording of load and displacement was problematic. An applied constant strain was also difficult to achieve.

3.3.3.2 Hand or tree winch

The basic principle of the method of winching is as given by Anderson *et al.* (1989) in Figure 3.16. Clark (2002) used a hand winch during root pull out experiments to measure the adhesion of the roots with the soil (Figure 3.22).

Figure 3.22. Simple root testing with spring balance and hand winch connected to cables anchored to a suitable 'in line' tree (method used by Clark, 2002).

3.3.3.3 Electronic mechanical apparatus

The *in situ* shear apparatus (Figure 3.14) was adapted for conducting root pull out tests. The root is clamped using either one of the collet clamps (Figures 3.19 and 3.20) and attached to a 500 kg Z-type load cell by a steel cable (Figure 3.23). The load cell measures tensile force. Force is applied through a hydraulic cylinder which has a pulling force of 21.5 kN and is capable of 400 mm displacement. Displacement is measured using a draw wire transducer (DWT-20-06-CR-1-E) attached to the steel cable. The load cell and draw wire transducer are electronically connected to a laptop via an IOTech Data Acquisition System (USB56) where the data is logged and recorded as an ASCII file. Calibration factors were $y = 0.5x - 0.02$ (where x is the original load cell reading and y is the calibrated load in kN) for the load cell and $y = 64.14x + 0.08$ (where x is the original displacement reading and y is the calibrated displacement in mm) for the draw wire transducer. The ASCII data file is imported to Microsoft Excel, where it can be manipulated and analysed (refer to Section 3.1.1.7).

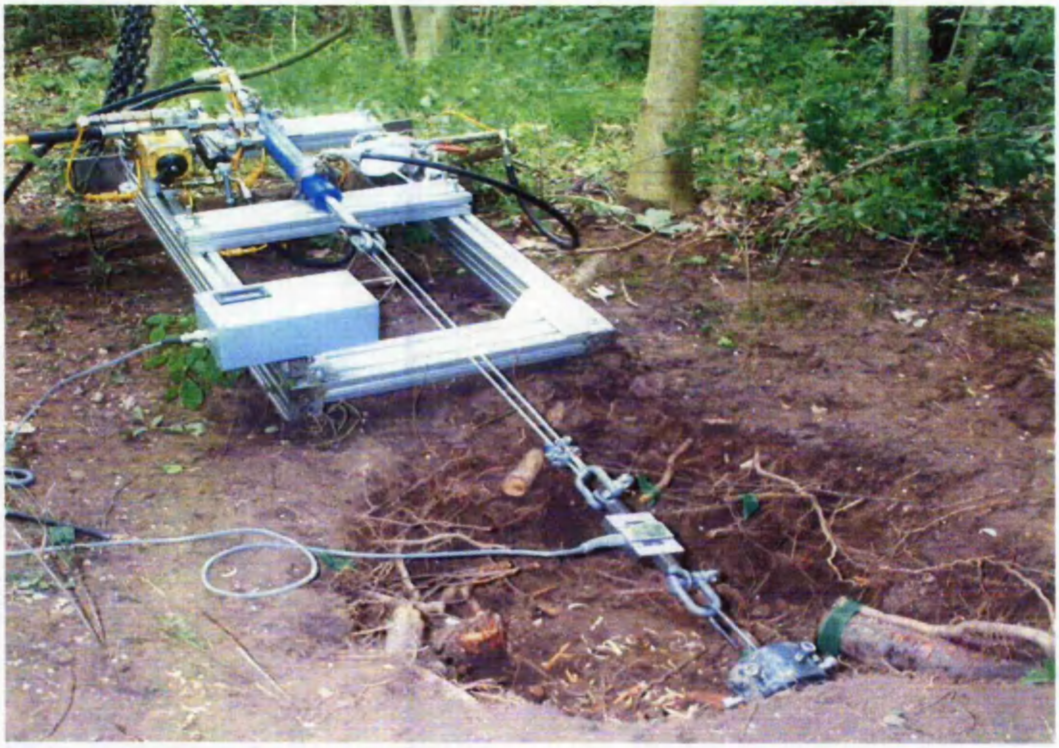


Figure 3.23. Root pull out apparatus.

3.3.4 Summary of root pull out apparatus

The development of the different methods of root clamping and pulling has allowed a greater number of roots to be tested. Initially, roots could only be tested at diameters less than 10 mm due to the size of the gravel filled cone and the collet diameter. As the testing proceded, it became apparent that valuable data was not being recorded by only restricting tests to these root diameters.

A combination of the hand pull method and the electronic mechanical method of testing the pull out resistance of roots was used in this thesis. This allowed for a wide range of root diameters (2–70 mm) to be tested.

The strop design (Figure 3.21) is probably the most efficient method of testing roots, since different size strops can be used for a range of root diameters. The strops are quickly installed and also resist slipping from the root during pulling which was a common problem with the other clamping techniques. This method also has the advantage of being lightweight and portable, and has the potential to be used on any field site.

3.4 Summary

The methods of investigation used on the study areas are described in this chapter, with a detailed description of the development, by the author, of the shear box and root pull out apparatus. The development of this apparatus was fundamental to the understanding of the interaction between roots and soil, enabling the quantification of root strength to be applied to slope stability analysis (see Chapters 5 and 9).

Chapter 4: Test Sites and Site Methodology

4.0 Introduction

In order to assess the contribution of roots to slope stability and to investigate root distribution and root system morphology, three study areas were selected on the transportation infrastructure in England. Two sites, selected for the ECOSLOPES project (Anon, 2004), were located on the M25 and M11 motorways, with an additional site local to Nottingham along the side of a railway. The three sites enabled a range of root investigations on different soil types to be carried out. This chapter provides details of each study area and describes the type of testing carried out on each site together with the results of these tests. The implications and further analysis of these tests are discussed in later chapters.

4.1 Site 1: M25 motorway embankment

4.1.1 Site description

Site 1 is located at Passingford Bridge, where the M25 is carried over the A113 (Chigwell to Chipping Ongar), adjacent to Epping Lane, Essex, southeast England (Grid ref: TQ504976) (Figure 4.1). This particular site was originally selected as a reference site in the ECOSLOPES project. It was chosen for its site accessibility, relative safety and for international recognition, as the M25 was perceived to be the motorway most commonly known to international researchers. This site was used for root-soil reinforcement investigations.

The site comprised of an embankment flanking an overbridge, which had an east-west trend. A small stream flowed from the north to the south under the embankment, which was culverted near the eastern boundary of the site. The north facing embankment slope was chosen as the study area in preference to the south facing embankment due to accessibility restrictions. The overall slope angle of the embankment was 26° (1:2), however the height varied from a maximum of 11 m at the east of the site to 3 m at the western margin. The site contained a wide variety of plants, from grasses to shrubs and young trees. A planted copse to the east of the site consisted of rowan, birch, oak, hawthorn and field maple (Figure 4.2). Natural regeneration of the vegetation was observed taking place, as young rowan and hawthorn were present. To the west of the copse, there was a grassed area consisting of mixed grasses, wildflowers and herbs.

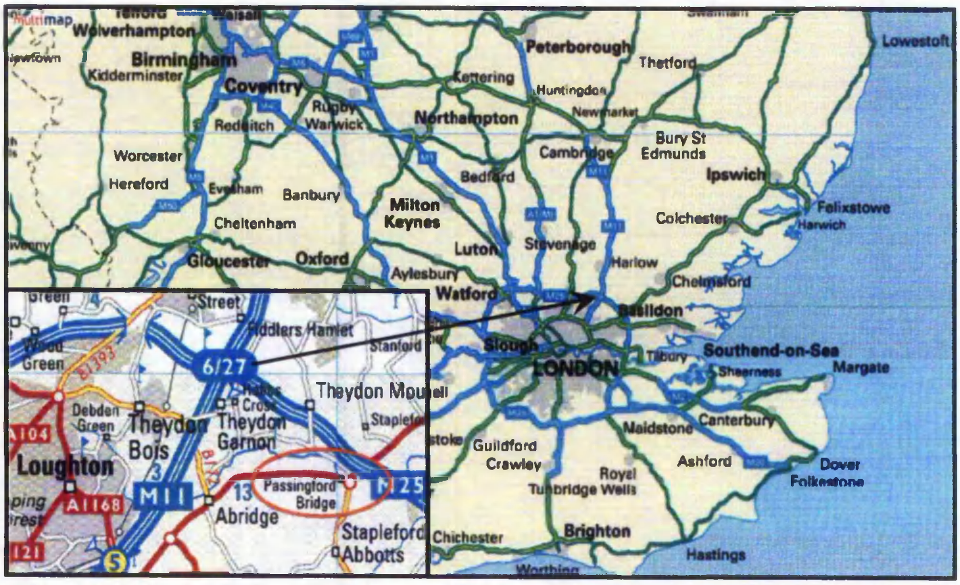


Figure 4.1. Site location plan. Inset: Passingford Bridge motorway embankment. (Source: Multimap, 2003).

Figure 4.2. View of the M25 embankment at Passingford Bridge looking north towards the copse and the culvert (by the railings). To the west of the copse is the grassed area of the embankment. (Photograph taken November 2002, J. Wint).

The site climate is temperate; displaying seasonality in temperature and precipitation, mean annual temperature 14.8°C and average annual rainfall of 583.6 mm (Met. Office, 2004a).

4.1.2 Site history

The embankment was constructed in 1981-82 and the motorway was opened to the public in 1983. Since then the site has suffered several shallow slip events, followed by a variety of remediation measures, such as the addition of geotextiles in the area to the east of the culverted stream.

4.1.3 Geology

The underlying geology comprised London Clay locally overlain by the Taplow Gravel (B.G.S., 1996). The Taplow Gravel outcrops at the brook and the nearby stream section to the east of the site.

The embankment is constructed mainly of London Clay with some lenses of Taplow Gravel. The construction material was covered by a topsoil layer approximately 150 mm deep.

4.1.4 Soil profile

The thin horizon of topsoil rests on firm grey fissured clay (fill) with local lenses of slightly sandy clay with occasional fine to coarse flint gravel and a few roots and rootlets. Further details of the soil and associated soil classification test results are given in Table 4.1. Natural soil moisture content and Atterberg Limit tests were carried out in accordance with the BS1377-2 (as described in Section 3.1.2.1), soil bulk and unit weight were measured in accordance with BS1377-2 (1990) using the core method for soils which are not too stony or dry (Blake and Hartke, 1986). The soil classification tests were carried out by J. Wint for the ECOSLOPES project.

Table 4.1. Soil profiles and results of soil classification tests from the trial pits in (a) the copse and (b) the grassed area of the M25 embankment (after Norris *et al.*, 2004a).

a) Copse

Soil Description	Depth (m)	Soil m.c. (%)	Atterberg Limits			Shear vane strength (kN/m^2)	Bulk density (Mg/m^3)	Unit weight (kN/m^3)
			LL (%)	PL (%)	PI (%)			
Moss over soft-firm grey brown slightly sandy clay with some fine to medium flint and brick gravel and a few roots and rootlets (0 – 0.25 m depth)	0.10	26.5	37.0	22.2	14.8	45		
	0.20	27.6						
Firm brown clay with occasional roots and rootlets (0.25 – 0.9 m depth)	0.30	32.6						
	0.40	31.0	63.7	28.1	35.6	61	1.34	13.0
	0.50	29.2						
	0.60	24.9						
	0.65						1.53	15.0
	0.70	22.5						
	0.80	20.9						
	0.90	21.1					1.50	14.7
Stiff orange brown slightly sandy clay with some fine to coarse flint gravel (0.9 – 1.1 m depth)	1.00	20.1	51.0	21.0	30.1	>120		
Stiff grey brown clay (1.1 – 1.2 m depth)	1.10	21.0	50.7	20.7	30.0	>120		

b) Grass

Soil Description	Depth (m)	Soil m.c. (%)	Atterberg Limits			Shear vane strength (kN/m^2)	Bulk density (Mg/m^3)	Unit weight (kN/m^3)
			LL (%)	PL (%)	PI (%)			
Grass and moss over soft to firm slightly sandy clay with occasional fine to coarse flint gravel and a few roots and rootlets (0 – 0.54 m depth)	0.10	24.1	38.0	19.5	18.5			
	0.20	21.5				37		
	0.30	19.4					1.64	16.0
	0.40	15.7						
	0.50	20.8	37.7	22.3	15.3			
Orange brown sandy clay with some flint gravel and sand lenses (0.54 – 0.67 m depth)	0.55						1.70	16.7
	0.60	15.4	21.6	16.1	5.5	42		
Stiff grey brown clay (0.67 – 1.0 m depth)	0.70	29.0						
	0.75						1.49	14.6
	0.80	16.9						
	0.90	20.6	57.8	25.9	31.9	>120		
	1.00	24.2						

Key: m.c. – natural moisture content; LL- liquid limit; PL-plastic limit; PI- Plasticity Index.
Note: Trial pits were dug and *in situ* soil analysis carried out in November 2002.

4.2 Site 2: M11 motorway cutting

Site 2 was originally selected for research activities in association with the ECOSLOPES project. This site proved suitable for investigating the *in situ* pull out resistance of hawthorn roots (Norris, 2005). The site was situated on a southbound slip road of the M11 motorway between junctions 4 and 5, near Chigwell, Loughton, Essex (Grid ref: TQ434943, GPS coordinates N 51°37′415″ E 000°04′117″), (Figure 4.3). The site provided ideal safe working conditions as the slip road was off the main motorway and had restricted access to normal traffic being an access road to a police and highway maintenance unit. It was also within close proximity to Site 1.

4.2.1 Site description

Site 2 was located on a road cutting, which had an overall slope angle of 20°, faces northwest, had a height of 15 m and the top of the cutting was at 40 m above sea level. The cutting contained a wide variety of plants, from grasses to shrubs and mature trees. Tree species present were silver birch, oak, hawthorn and pine. It was observed that natural regeneration of the vegetation was taking place as young oak trees (approximately 5 years old) were present.

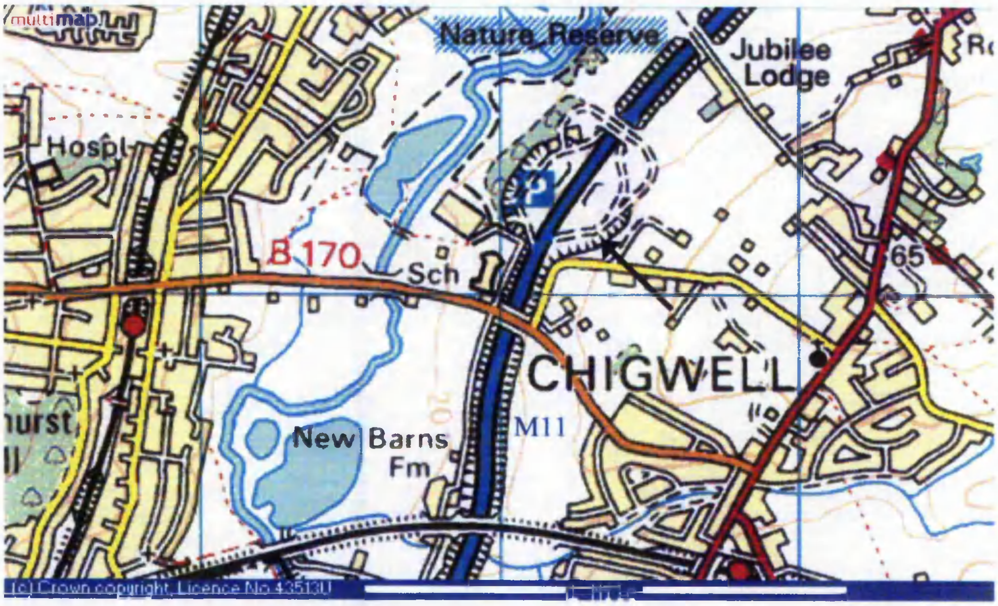


Figure 4.3. Field site location, M11, near Chigwell, Loughton, Essex. (Arrow points to site). 1:25 000 scale (Source: Multimap, 2003).

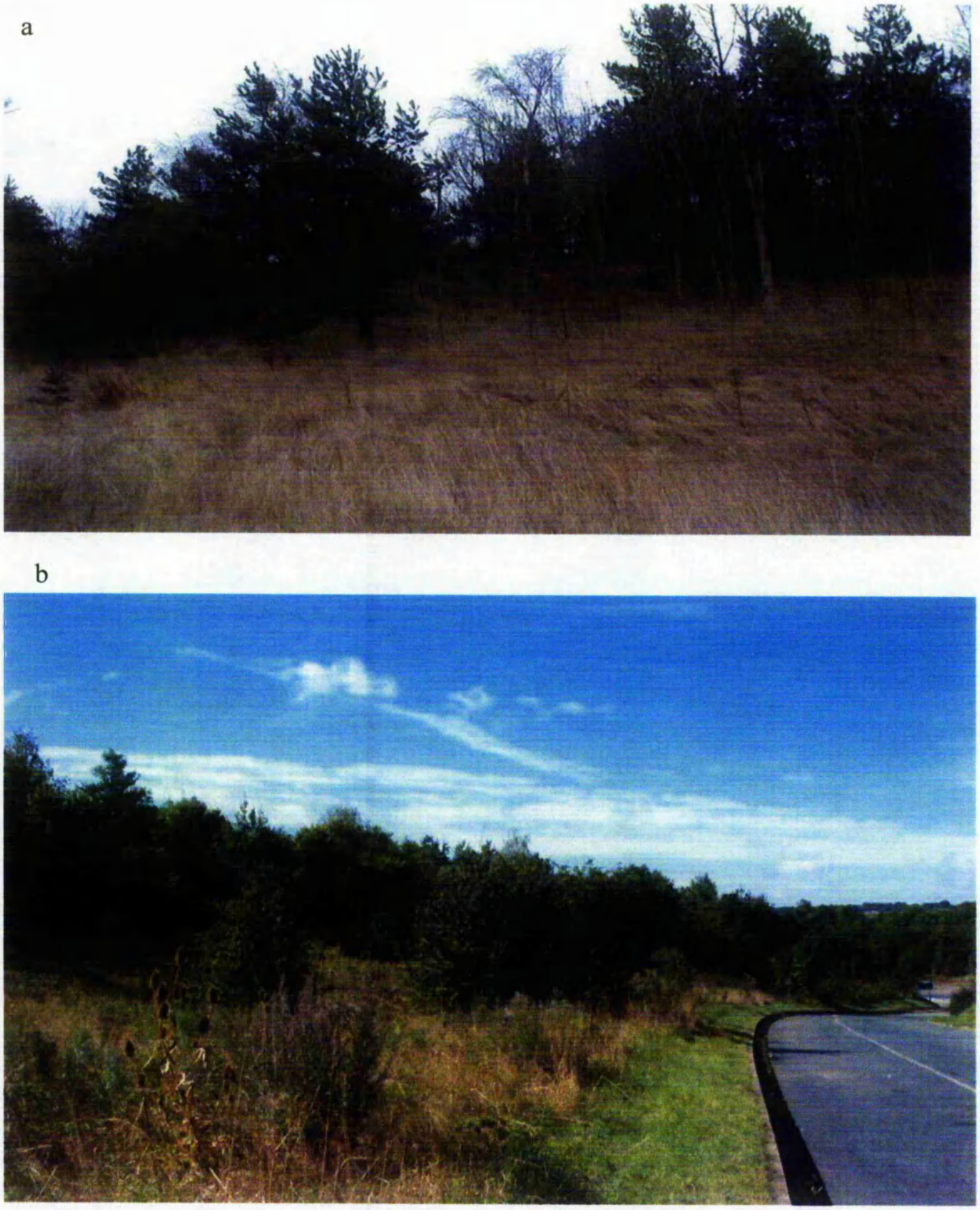


Figure 4.4. Photographs of site showing change in vegetation towards the top of the cutting and the access road to the Highways office and the Police unit on the M11 northbound. a). Taken in March 2002. b). Taken in September 2002.

Figure 4.5. Shallow landslide occurring in cutting section adjacent to field site. NB. Tree line is above top of landslide scar, landslide has occurred where there are no deep rooting plants. Taken September 2002.

There appeared to be a marked change in vegetation type approximately half way up the cutting with predominantly grass, shrubs and young trees towards the lower half of the slope and the upper half of the slope consisting of mature trees (Figure 4.4). The marked difference in vegetation was probably due to reprofiling of the lower part of the slope during construction of the access road and motorway (Kidd, A., pers. comm.).

The site climate is temperate; displaying seasonality in temperature and precipitation, mean annual temperature is 14.8°C and average annual rainfall of 583.6 mm (Met. Office, 2004a).

4.2.2 Site history

The motorway was constructed in 1976. The actual site had no history of failures (Kidd, A., pers. comm.) but there were recent failures (date of occurrence ~2001-2) on both sides of the motorway adjacent to the main carriageway. It is of note that these failures occurred where shrubs and trees were not present (Figure 4.5).

4.2.3 Geology

The geology of the cutting is predominantly London Clay with a thin cover of superficial deposits (Boyn Hill Gravel and Boulder Clay) (B.G.S., 1996). There was a topsoil layer present of approximately 150 mm depth.

4.2.4 Soil profile

The soil profile present in the cutting is a firm brown locally fissured clay with occasional brown silt partings overlain by a 150 mm layer of brown sandy clay with flint gravel and grass roots. The fissuring of the clay is typical of London Clay in this area. Further details of the soil profile and the associated soil classification tests are given in Table 4.2. Natural soil moisture content and Atterberg Limit tests were carried out in accordance with the BS1377-2 (as described in Section 3.1.2.1), soil bulk and unit weight were measured in accordance with BS1377-2 (1990) using the core method for soils which are not too stony or dry (Blake and Hartke, 1986). The soil classification tests were carried out by J. Wint for the ECOSLOPES project.

Table 4.2. Soil profile and results of soil classification tests on the M11 cutting (after Norris *et al.*, 2004b). (a) Trial Pit 1: lower slope, vegetation cover of grass. (b) Trial Pit 2: mid slope, vegetation cover of grass and shrubs. (c) Trial Pit 3: upper slope, vegetation cover of trees.

(a) Trial Pit 1: Lower slope

Soil Description	Depth (m)	Soil m.c. (%)	Atterberg Limits			Shear vane strength (kN/m^2)	Bulk density (Mg/m^3)	Unit weight (kN/m^3)
			LL (%)	PL (%)	PI (%)			
Grass over brown clayey sand and gravel with many roots and rootlets (0 – 0.15 m depth)	0.10	32.7	69.1	27.9	41.2	51		
Brown very sandy clay with occasional gravel and a few roots and rootlets (0.15 – 0.27 m depth)	0.20	35.3	70.5	25.3	45.1	56		
Brown fissured CLAY with occasional orange brown silt partings (0.27 – 0.80 m depth)	0.30	33.4						
	0.40	32.9						
	0.50	33.3					1.23	12
	0.60	33.3						
	0.70	33.6	66.4	27.3	39.1			
	0.80	35.6						

Table 4.2 continued.

(b) Trial Pit 2: Mid slope

Soil Description	Depth (m)	Soil m.c. (%)	Atterberg Limits			Shear vane strength (kN/m^2)	Bulk density (Mg/m^3)	Unit weight (kN/m^3)
			LL (%)	PL (%)	PI (%)			
Grass over soft sandy clay with some fine to coarse flint gravel and occasional roots and rootlets (0 – 0.22 m depth)	0.00	30.7	60.2	23.3	37.0	40	1.42	14
	0.10	32.9						
	0.20	41.3						
Firm brown locally fissured clay with occasional orange brown silt partings and a few roots (0.22 – 0.80 m depth)	0.30	37.5	78.1	26.8	51.3	68	1.15	11
	0.40	36.9						
	0.50	40.3						
	0.60	35.9						
	0.70	35.0						
	0.80	36.9						

(c) Trial Pit 3: Upper slope

Soil Description	Depth (m)	Soil m.c. (%)	Atterberg Limits			Shear vane strength (kN/m^2)	Bulk density (Mg/m^3)	Unit weight (kN/m^3)
			LL (%)	PL (%)	PI (%)			
Scrub over brown sandy clay with occasional fine-medium flint gravel and some roots and rootlets (0 – 0.15 m depth)	0.10	23.3	42.0	22.4	19.6	97		
Brown fissured sandy clay with orange brown silt partings and occasional flint gravel and roots (0.15 – 0.64 m depth)	0.20	11.2	36.4	19.9	16.6	96	1.47	14.4
	0.25	19.1						
	0.30	17.7						
	0.40	26.7						
	0.50	20.3						
	0.60	28.4						
Orange brown sandy clay with occasional gravel (0.64 – 0.8 m depth)	0.70	18.0	38.9	15.9	23.1	89		
	0.80	17.5						

Key: m.c. – natural moisture content; LL- liquid limit; PL-plastic limit; PI- Plasticity Index.
Note: Trial pits were dug and further *in situ* soil analysis carried out in May 2003.

4.3 Site 3: Railway embankment

Site 3 was selected as a study area for its range of different vegetation types from the motorway sites, for its close proximity to Nottingham and to investigate the variation in root architecture of one type of vegetation and the reduction in strength of roots after vegetation clearance.

4.3.1 Site description

Site 3 is situated on the preserved Great Central Railway, near Bunny Lane, East Leake just north of the East Leake British Gypsum Works, Nottinghamshire, Grid Reference: SK 555288 (Figure 4.6). This section of the Great Central Railway is owned by the Nottingham Heritage Transport Centre based at Ruddington, Nottingham. The site is a 200 m stretch of embankment along the west side of the single track railway line (Figure 4.6), the site forms part of a much longer length of embankment. The embankment had an overall slope angle of 25° and a height of 8.6 m.

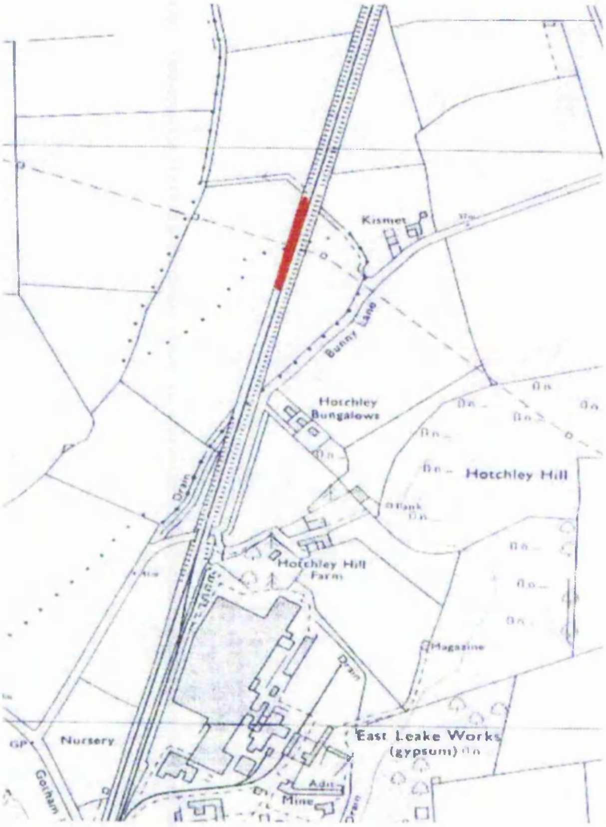


Figure 4.6. Extract of 1:10 000 Ordnance Survey Sheet SK52NE showing railway embankment at East Leake (embankment is highlighted as shaded section).

Prior to investigations on this site, the embankment had had a general clearing of vegetation in the summer of 2001 (Freebury, A., pers. comm.). The observed vegetation throughout the investigation was predominantly grasses and weeds or wildflowers (e.g. nettles, thistles, brambles, cowslips, blackthorn, moss, Great

Mullein or Aaron's Rod) with elder and hawthorn shrubs, ash and sycamore trees (Figure 4.7). The majority of the shrubs had multi-stems due to the previous vegetation clearing regimes. During the period of investigative work on the embankment, there was little change in vegetation type although the size of the shrubs had shown an average 30 % seasonal increase in growth. A considerable proportion of the ground surface was covered by dead leaves, twigs and branches, ballast from the railway track or was bare ground.

The site climate is temperate; displaying seasonality in temperature and precipitation, mean annual temperature is 14.5°C and an average annual rainfall of 613 mm (Met. Office, 2004b).

Figure 4.7. View of railway embankment looking north towards Ruddington. Vegetation along the embankment consists of ash and sycamore trees with an understory vegetation cover of elder and hawthorn shrubs, grasses, nettles and brambles (Photograph A. Swift).

4.3.2 Site history

The embankment was constructed between 1894 and 1898 as part of the Great Central Railway northern extension works. The works connected railway lines in Derbyshire near Annesley to Rugby through Nottingham, Loughborough and Leicester (Bidder, 1900). The new lines formed a direct freight only railway to London and the south. Between Nottingham and Loughborough, the railway proceeded through undulating country passing by the villages of Ruddington and East Leake. It was necessary to construct deep cuttings, a short tunnel, a long embankment and a viaduct to traverse this undulating country (Bidder, 1900). The long embankment, on which Site 3 is situated, has a gradient of 1 in 176 between Gotham Branch sidings and East Leake station (Bidder, 1900).

Bidder (1900) reports that during construction, by the tipping method, of the embankment several slips of minor importance occurred due chiefly to the heavy rains following the remarkably dry weather but he failed to record whereabouts along the line these slips occurred. No other records of slips have been found for this embankment.

The main Great Central Railway line was operational until 1969 when it closed due to Beeching's closures of the railways. Although the section between Rushcliffe Halt at the British Gypsum works and Loughborough was largely protected by the fortune of continued freight traffic to the British Gypsum works.

The 10 mile section between Ruddington and Loughborough, as with the rest of the line down to London was built for high speeds with no gradient steeper than 1:176 and curves having a minimum radius of 1 mile. North of Loughborough the line cuts uncompromisingly through the topography of the land after leaving the high embankments and viaduct at Loughborough Meadows. Driving straight through the Normanton Hills via one of the largest cuttings on the line, the formation proceeds to Barnstone Tunnel and East Leake Station. Following Rushcliffe Halt the line passes through Gotham Junction, it was built with a 5 mile straight section to allow for fast sprints into Ruddington, Nottingham and beyond.

Today this part of the Great Central Railway line is owned by the Nottingham Heritage Transport Centre. It consists of a single-line track from the Midland mainline at Loughborough to Fifty Steps Footbridge at Ruddington (close to the former Ruddington station site). Plans are in progress to return the preserved single track railway back to double track.

4.3.3 Geology

The underlying geology of the area is Mercia Mudstone with a capping of peat near the River Soar (B.G.S., 2003). Bidder (1900) reports that the geology of the railway line south of Nottingham is for some distance in the 'keuper marl', 'rhaetic shale' being met with near East Leake. The Keuper Marl, now known as the Mercia Mudstone Group is of Triassic age and is widely recognised as an unfossiliferous red-brown mudstone derived from sedimentation in an arid inland basin with sterile lakes and inland seas (Chandler and Forster, 2001). At the end of the Triassic, a transgression of the sea took place and the red mudstones (marls) gave way to blue-green mudstones, then brown to black mudstones and shales of the Penarth Group (formerly known as the 'rhaetic shale'). Along the section of the embankment as outlined in Figure 4.6, there is a progressive change from red mudstone in the north to blue mudstone in the south with the red mudstones commonly containing angular gravel sized pieces of blue mudstones.

4.3.4 Soil profile

The soil profile consisted of weathered Mercia Mudstone used to fill the embankment, with a variable covering of topsoil consisting of organic debris and railway ballast. Further details are given in Figure 4.8.

Soil classification tests were conducted on soil samples associated with trees investigated for tensile root strength and from the trial pit. Table 4.3 provides summary data of the results of the soil classification tests.

Depth (m)	Soil description	Log
0 0.3	Topsoil: loose fine-coarse brown sand with subangular red and blue gravel-sized particles of mudstone and many rootlets. Abundant surface leaf litter and ballast. Variable thickness of topsoil up to 0.3 m	▨
0.4 0.7	Made Ground (fill): variable from orange-red medium-coarse sand to very stiff-hard blocky red and blue-green silt-clay of MERCIA MUDSTONE origin.	▷

Figure 4.8. General soil profile of the railway embankment.

Table 4.3. Summary data of soil classification tests for Site 3.

Date	Sample location	Sample No.	Depth (m)	Soil m.c. (%)	Atterberg Limits			Shear strength parameters*		Soil description
					LL (%)	PL (%)	PI (%)	c′ (kN/m^2)	ϕ′ (°)	
Apr 2004	Rud7	2	0.1	27						Black sandy topsoil
		1	0.2	24						Black silt/clay with hard blue clay gravel pieces
Apr 2004	Rud13	2	0.1	36						Black sandy topsoil
		1	0.15	18						Red-brown clay
Apr 2004	Rud23	1	0.1	30						Brown-red clay
Jul 2003	TP	1	0.1	11						Topsoil
		2	0.33	7						Red blocky clay
		2	0.33	21	29	17	12			Red clay – rehydrated
		3	0.4	5						Red-orange gravelly sand
		3	0.4	6				8	43	
Nov 2003	RudH2	1	0.1	27						Brown sandy clay (topsoil)
		2	0.2	17						Red and blue clay with brown sandy topsoil
		3	0.3	18						Red clay with blue silt
Jan 2004	RudH3	1	0.12	31						Brown organic rich peaty soil
		2	0.32	19	32	20	12			Weathered green silt-clay with topsoil
		3	0.5	15						Green blocky silt
Apr 2004	RudH4	1	0.1	34						Black sandy clay topsoil

Key: m.c. – moisture content; LL - liquid limit; PL - plastic limit; PI - Plasticity Index; c′ - apparent cohesion, ϕ′ - friction angle, * determined by laboratory shear box test; refer to Figure 4.12 for sample locations.

4.4 Site activity: experimental work carried out at each site

4.4.1 Selection of vegetation

The species selected for the root strength and distribution experiments were hawthorn, oak, rowan and elder. These species were selected mainly for their common occurrence along the transportation network. Of the four species chosen, only the oak had published values of root strength and detailed information on its root architecture (Lyford, 1980). It was therefore hoped that the new information gained during this research would contribute to the dataset available in the literature. The characteristics of the four species are discussed below:

4.4.1.1 Hawthorn, Crataegus monogyna (Rosaceae)

The hawthorn is a deciduous tree or shrub that can be found growing in North America, Europe and western Asia. It is common in hedgerows, woodland margins and scrub throughout England on all but the poorest soils up to about 500 m above sea level (British Native Trees and Shrubs, 2002). The tree can reach 15 m in height but is more commonly about 6 m tall, they can vary greatly in size.

Hawthorn grows in a wide range of soil and climate conditions. It grows in sun or semi shade, but not dense shade and is tolerant of all but the poorest acid soils. It is a hardy plant. Young trees can be planted in permanent positions after one or two years where they rapidly become established (British Native Trees and Shrubs, 2002).

Hawthorn trees have many uses both living and as wood products: e.g. hedges, thorny, stock-proof fences, firewood – a slow burning fuel and wood-engravers' blocks and tool handles. They are important habitats for all types of wildlife.

4.4.1.2 Elder, Sambucus nigra (Caprifoloaceae)

Elder is one of the most vigorous and productive English trees. Elder is widespread in woods, hedgerows, scrub and rough ground throughout England. It can be grown as a shrub or a free-standing tree, in the wild or as a hedge. It will grow in sun or semi shade and on most moist but well drained soils. It may be damaged by very hard frosts but will regenerate quickly. It can be pruned back to keep it under control.

Elder is readily propagated and raised from seeds. Elders can grow up to 15 m in height.

4.4.1.3 Oak, Quercus robur (Fagaceae)

The pedunculate oak is found in woodland, open ground and in pollarded form in hedgerows throughout England on heavy clays and loams, especially on neutral or lime-rich soils, rarely above 300 m. It is dominant in woods in lowland areas, where the soil is suitably deep and rich. It is a deciduous tree, growing up to 30 or 40 m in height. It grows in sun or semi-shade and likes deep, fertile soils, tolerating those that are damp but not waterlogged. Oak is reasonably drought tolerant but does not thrive on dry, shallow soils. It does not like salty winds in coastal sites (British Native Trees and Shrubs, 2002).

The oak tree is very important for wildlife attracting many insects, butterflies, fungi and birds (British Native Trees and Shrubs, 2002).

4.4.1.4 Rowan, Sorbus aucuparia (Rosaceae)

Rowan is found in woodlands, moors and scrub (waste) lands on light, free-draining soils in the lowlands throughout most of England, but it is also widespread on rocks and in acid peat in the mountains where it ascends to over 850 m. It prefers a sunny, open position but will grow in semi-shade and it grows in most moist, free-draining soils, preferably neutral to acid. It is wind-resistant and grows fast when young. It rarely grows higher than 15 m (British Native Trees and Shrubs, 2002). Rowan trees are attractive to insects who feed on the flowers and provide berries for birds during the winter (British Native Trees and Shrubs, 2002).

4.4.2 Measurements of root-soil strength

To investigate the contribution of roots to the stability of the clay slopes, *in situ* shear box and root pull out resistance tests were carried out. The methods of testing are described in Sections 3.2 and 3.3. The following describes the tests carried out on each site.

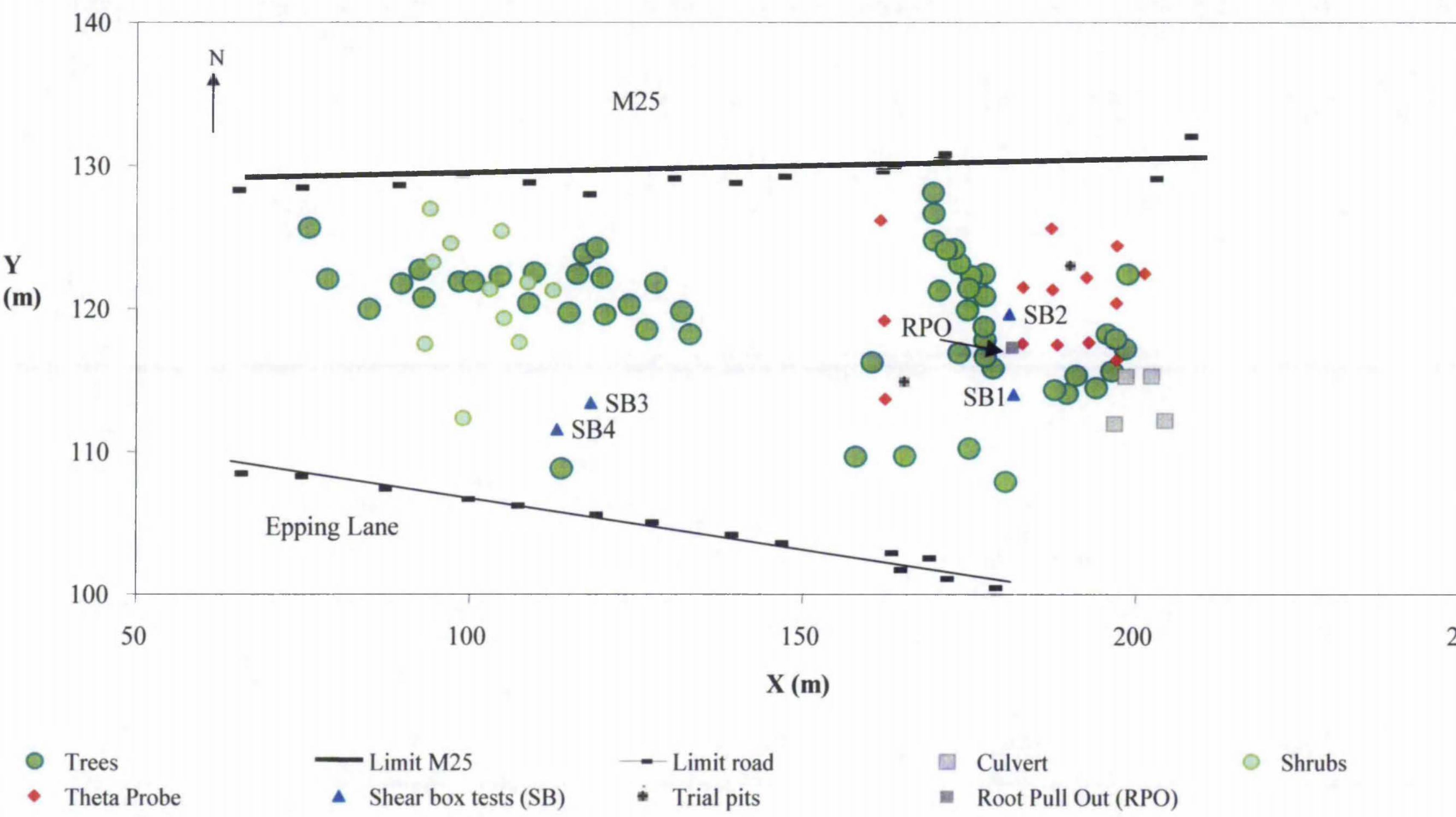


Figure 4.9. Layout of Site 1 the M25 embankment, including positions of shear box and root pull out tests (modified from Anon, 2004).

4.4.2.1 *In situ shear box tests*

On Site 1, four *in situ* shear box tests (SB1-SB4) were carried out, using the method given in Section 3.2.3, on the grassed/herbaceous cover area at four locations on the slope (Figure 4.9). All tests were conducted at depths of between 100 and 200 mm, at the natural slope angle. SB1 and SB2 were carried out within close proximity (<2 m) to the copse, SB1 was within 1 m distance of the *Sorbus aucuparia* tree which was used in the root pull out tests. SB3 and SB4 were carried out 110 m to the west of the copse, in the grassed area.

On Site 2, two *in situ* shear box tests were carried out (Figure 4.10). In the first test (M11A), an oak sapling (0.5 m in height) was sheared (Figure 4.11). In the second test (M11B), an area of grass was sheared. Both tests were carried out near the base of the slope at the natural slope angle of 8°, within the topsoil layers at a depth of 100 mm.

No *in situ* shear box tests were carried out on Site 3, due to the inaccessible nature of the railway embankment.

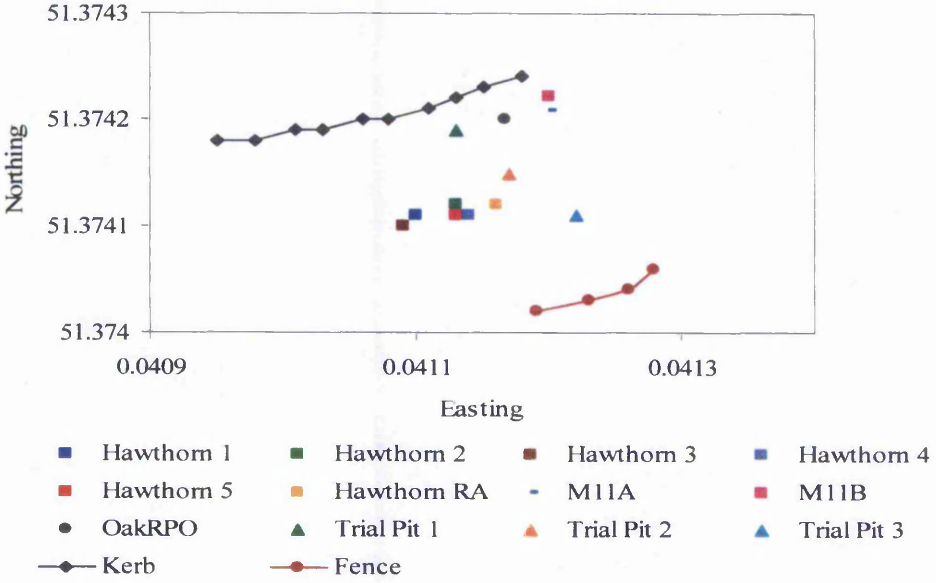


Figure 4.10. Layout of Site 2 the M11 cut-slope, showing positions of the hawthorn trees which were tested for root pull out resistance (hawthorn 1,2,3,5), root strength (hawthorn 4) and root architecture (hawthorn RA), the oak tree for root pull out resistance and the shear box tests (M11A and M11B).

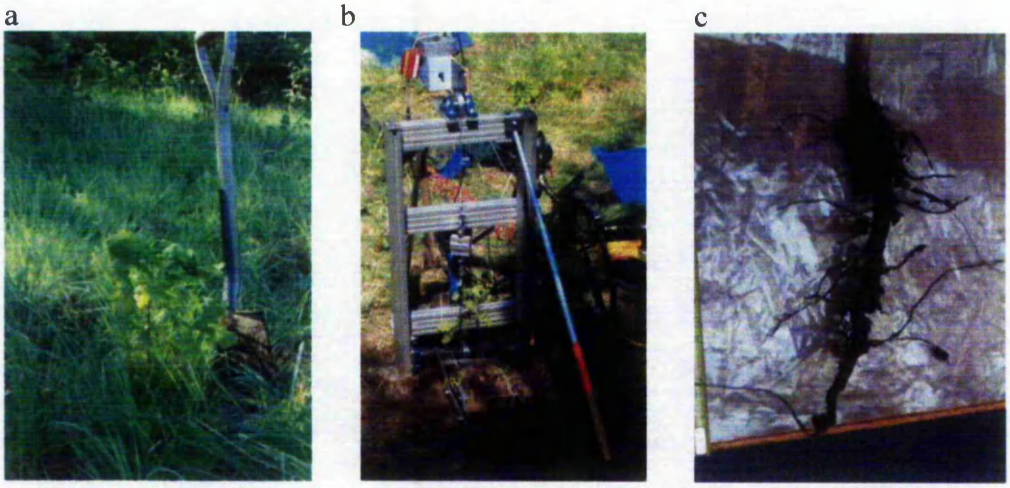


Figure 4.11. (a) Oak sapling before and (b) during *in situ* shear test (M11A). (c) Root system of the sheared oak sapling.

4.4.2.2 Root pull out resistance tests

The potential contribution of roots to slope stability can be assessed by carrying out root pull out resistance tests as described in Chapter 3. The species tested on Sites 1 and 2 are given in Table 4.4. The characteristics of each species are detailed in Table 4.5. The location of the root pull out tests are shown on Figures 4.9 and 4.10. No root pull out resistance tests were carried out on Site 3, due to the inaccessible nature of the railway embankment.

Table 4.4. Species and location of root pull out resistance tests.

Location	Species	No. of trees tested	No. of roots tested	Method of test
Site 1: M25	Rowan (*Sorbus aucuparia*)	One	11	Manual (hand pull)
Site 2: M11	Oak (*Quercus robur*)	One	10	Manual (hand pull)
Site 2: M11	Hawthorn (*Crataegus monogyna*)	Four	42	Mechanical

Table 4.5. Characteristics and location of species used for root pull out resistance tests.

Test date	Location	Species	Slope angle/ aspect (°)	Plant height (m)	Stem diameter (mm)		Soil m.c. (%)	Shear vane strength (kN/m^2) @ ~0.3 m depth
					Ground level	dbh		
May 2002	Site 1: M25	Rowan	30/240	1.8	16.7 ± 0.8	5.6 ± 0.5	27	NR
May 2002	Site 2: M11	Oak	18/204	1.5	34.6 ± 0.2	4.9 ± 0.3	39	47
Sep 2002	Site 2: M11	Hawthorn H1	18	4.1	150.0	54.7	NR	80
Sep 2002	Site 2: M11	Hawthorn H2	18	7.4	170.0	100.0	NR	98
May 2003	Site 2: M11	Hawthorn H3	18	NR	131.0	79.0	19	59
May 2003	Site 2: M11	Hawthorn H5	17	4	148.0 ± 8.0	105.0 ± 15.0	23	55

Key: dbh – diameter of trunk at breast height (1.3 m), m.c. – moisture content, NR – not recorded.

4.4.3 Root tensile strength tests

Roots were collected from hawthorn and elder trees on Sites 2 and 3 for testing of their tensile strength in the laboratory, as described in Section 3.1.1.7 (Tables 4.6 and 4.7). The location of the trees are shown on Figures 4.10 and 4.12. Roots were stored in sealed plastic bags prior to testing. Roots greater than 150 mm in length were cut up into sections so that multiple tests could be carried out. Each length of root was cut to approximately 150 mm to fit within the jaws of the testing machine.

Table 4.6. Species selected for root tensile strength tests.

Location	Species	No. of trees tested	No. of sections of roots tested
Site 2: M11	Hawthorn (*Crataegus monogyna*)	One	10
Site 3: Railway	Hawthorn (*Crataegus monogyna*)	Four	60
Site 3: Railway	Elder (*Sambucus nigra*)	Three	43

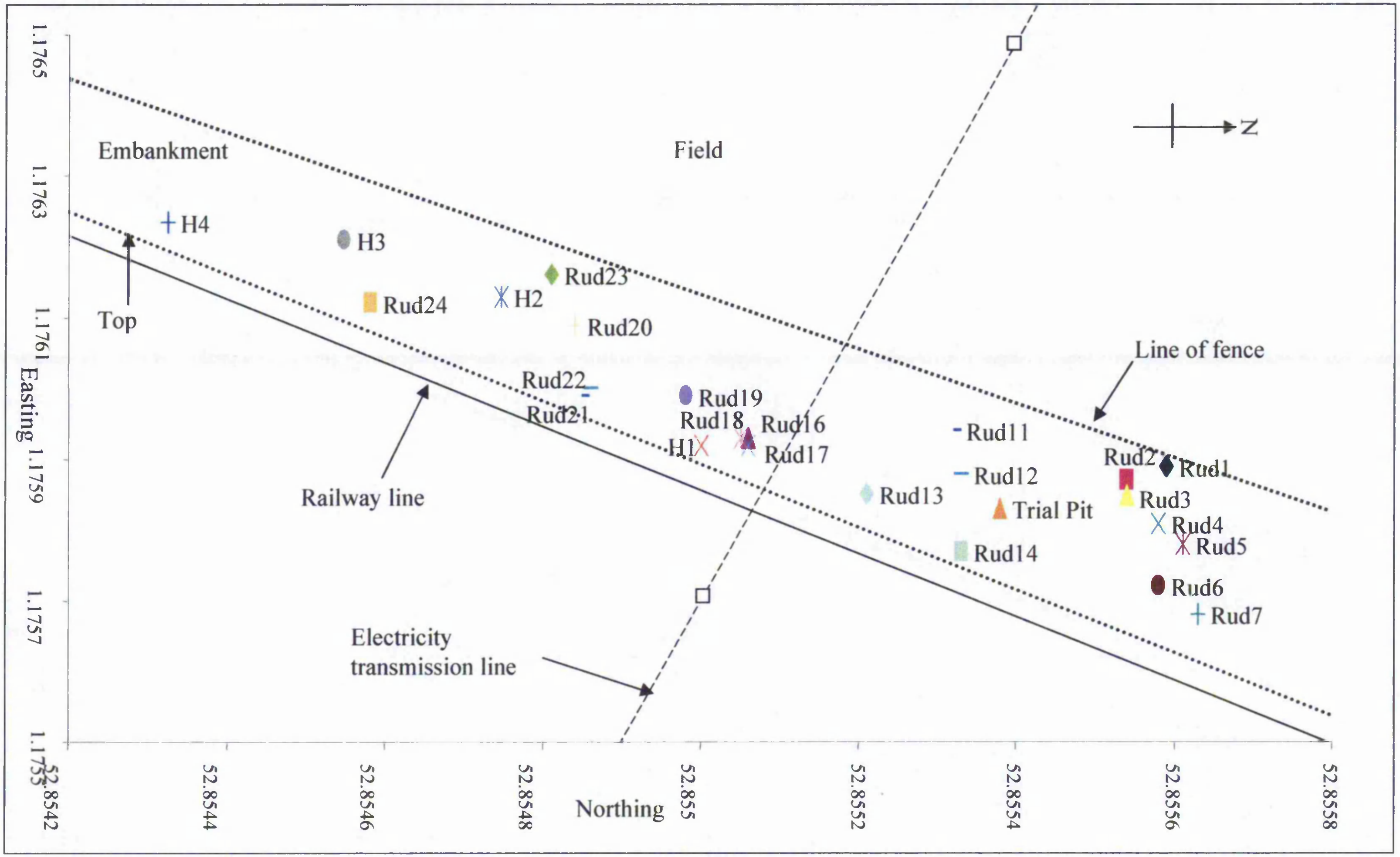


Figure 4.12. Location of elder (Rud1-24) and hawthorn (H1-4) shrubs on Site 3 (railway embankment).

Table 4.7. Characteristics of the species selected for root tensile strength tests.

Test date	Location	Species	Slope angle (°)	Plant height (m)	Stem diameter (mm)		Soil m.c. (%)
					g.l.	dbh	
May 2003	M11	Hawthorn H4	18	7.0	175	75	32
Sep 2003	Railway	Hawthorn RudH1	45	1.7	37.3	*	21
Nov 2003	Railway	Hawthorn RudH2	34	1.55	14.9	*	20
Jan 2004	Railway	Hawthorn RudH3	42	1.2	35.1	*	22
Apr 2004	Railway	Hawthorn RudH4	25	1.07	40.3	*	34
Apr 2004	Railway	Elder Rud7	38	1.5	31.4	*	25
Apr 2004	Railway	Elder Rud13	28	0.75	17.9	*	28
Apr 2004	Railway	Elder Rud23	20	1.6	54.09	*	30

Key: dbh – diameter at breast height of stem (1.3 m); * - no single stem at this height; g.l. – ground level; m.c. – moisture content.

4.4.4 Root distribution

Root counts were carried out in all trial pits on each site. The quadrat method was used on Site 1, wheras the lithological boundary method was used on Sites 2 and 3 (see description in Section 3.1.1.4). On Site 2, the root counts were carried out by J. Wint.

4.4.5 Root architecture

Root architecture measurements (i.e. root diameter and orientation) were recorded for all shrubs and trees on all sites before being tested for either root pull out resistance, tensile or shear strength, as described in Section 3.1.1.6. More detailed root architecture measurements of hawthorn and elder were carried out for information on branching, root distribution and relationship patterns.

On Site 2, one hawthorn root system was excavated using a combination of an airspade (www.airspade.com) and hand tools to a circumference of 2 m from the trunk of the tree. The characteristics of this tree are given in Table 4.8.

Table 4.8. Characteristics of the hawthorn tree excavated for root architecture measurements on Site 2: M11.

Date of excavation	Species and Identification No.	Slope angle/ aspect (°)	Plant height (m)	Mean stem diameter (mm)		Soil m.c. (%)	Shear vane strength (kN/m^2)
				g.l.	dbh		
May 2003	Hawthorn HRA	14/260	~6	175 ± 5	113 ± 7	27	77 @ 0.1 m depth 49 @ 0.3 m depth 58 @ 0.4 m depth

Key: dbh – diameter at breast height of stem (1.3 m); g.l. – ground level; M.C. – moisture content.

Table 4.9. Characteristics of the elder shrubs on the railway embankment.

Ident. No.	Alt. (m)	Height (m)	Spread		Stem diameter at g.l. (mm)	Slope angle/ aspect	Position on slope
			up-down slope (m)	lateral (m)			
Rud1	45	1.9	1.6	1.97	165	0/296NW	base
Rud2	47	2.22	1.72	1.65	150	8/296NW	base
Rud3	48	1.06	0.77	0.65	49.96	22/294NW	lower slope
Rud4	49	2.2	2.0	1.75	15.91	24/293NW	lower middle
Rud5	50	1.3	0.9	1.1	35.58	28/280NW	lower middle
Rud6	52	1.4	0.92	0.5	32.38	28/298NW	mid-upper
Rud7	54	1.5	0.7	0.7	31.37	38/302NW	upper
Rud11	45	1.4	0.9	1.15	86.2	4/292NW	base
Rud12	46	1.0	0.72	0.56	51.87	24/288NW	lower middle
Rud13	47	0.75	0.66	0.48	17.87	28/270NW	middle
Rud14	50	1.3	0.66	0.96	22.695	26/294NW	upper
Rud16	46	0.95	0.9	0.9	29.36	40/293NW	lower middle
Rud17	46	1.0	0.55	0.7	25.4	28/306NW	middle
Rud18	47	1.75	0.9	0.9	60.77	30/288NW	upper middle
Rud19	47	0.7	0.65	0.7	24.915	30/307NW	middle
Rud20	49	0.95	0.5	0.68	33.66	42/303NW	middle
Rud21	53	1.53	0.77	1.0	77.48	18/295NW	top
Rud22	53	1.25	0.83	1.1	58.925	35/300NW	top
Rud23	45	2.1	1.24	1.45	54.09	20/293NW	base
Rud24	51	0.95	0.35	0.3	17.24	36/310NW	top

On Site 3, twenty elder shrubs at varying positions along the railway embankment slope (i.e. top, middle, base) were identified and the root system hand excavated. The root system of each shrub was thus photographed, sketched and the root diameter and orientation recorded. The twenty shrubs were initially mapped in August 2002. Excavation of the root systems was completed in stages between October 2002 and September 2003. The location of the shrubs are shown in Figure 4.12. Characteristics of the shrubs are given in Table 4.9.

4.5 Test Results

The results of the experimental work, as illustrated in Section 4.4, on each site are now described. The implications of these results will be discussed in Chapters 5 and 7-9.

4.5.1 Root-soil strength test results

The results of the root-soil strength work are divided into two sections: the *in situ* shear box tests and the root pull out resistance tests.

4.5.1.1 In situ shear box test results

The results of the six *in situ* shear tests are shown in Figure 4.13 with associated data in Table 4.10. Peak *in situ* shear stress was achieved rapidly, with relatively small displacements of 10-20 mm occurring in all tests except M11A. Tests SB1 and SB4 had similar failure curves with peak shear stresses of approximately 25 kN/m^2. Tests SB2 and SB3 showed similar failure curves with peak shear stresses of 13 kN/m^2. M11A shows a peak shear stress of 77 kN/m^2 before the oak tree root contained within the soil block failed with a shear break. M11B shows a peak shear strength of 17 kN/m^2 and a residual strength of 15 kN/m^2.

Tests SB1-4 were severely affected by the presence of the gravel along the shear plane. The gravel increased the loads recorded by the load cell and created ‘false’ slip planes. In test SB1, the soil sample built up shear stress very quickly with minimal displacement, then sheared rapidly, although there was no clearly defined shear plane. The soil on the shear plane was considerably drier (by approximately 10%) than the soil at the surface due to the lithological changes in the soil (i.e. gravels enhancing drainage). Tests SB2 and SB3 were both affected by the presence of large rounded

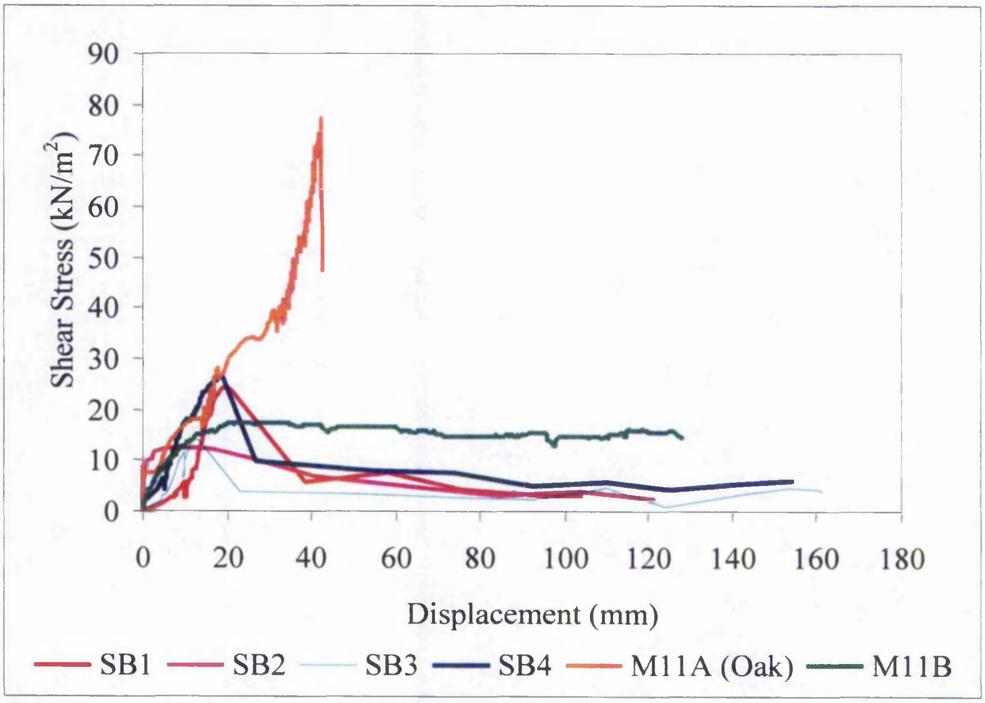


Figure 4.13. *In situ* shear tests on root reinforced London Clay at Sites 1 and 2.

gravels (30 x 20 mm in size). In SB3 the gravel cut grooves into the soil during the shearing process. Test SB4 sheared on an orange sandy oxidised layer with 30 x 30 mm gravels.

During shear testing of the oak tree (M11A), the oak tree became wedged in the apparatus therefore the test was stopped at this point before the residual shear strength of the soil could be obtained.

In tests SB1-4, the low *in situ* shear stress values and low undrained shear strength values, recorded by the hand vane, are indicative of the observed soft ground.

Undrained shear strength measurements, recorded using the hand vane, varied between 22-27 kN/m^2 for the soil in M11A and 17-32 kN/m^2 in M11B. Moisture content of the clay was 29 and 35% respectively. The lower moisture content of the clay around the oak tree may indicate uptake of moisture by the oak roots, producing a desiccated zone around the tree root.

The low shear stress value of M11B, reflects the observed high moisture content of the soil in the motorway cutting. Some fine rootlets were observed on the shear plane but these probably had little effect on shear strength of the soil as a whole.

Table 4.10. Data associated with the *in situ* shear box test results.

Test ID	Type of test	Alt (m)	Slope angle/ aspect	Soil description	Depth of *in situ* shear test (mm)	Mass of sheared soil block including roots (kg)	Shear vane strength (kN/m^2)		*In situ* shear strength (kN/m^2)		Soil m.c. (%)	Root content
							Ground level (depth 0-30 mm)	On shear plane†	Peak	Residual		
SB1	Grass	37	60°S	Thin layer of stiff grey London Clay above orange brown sandy clay with rounded gravel.	120	2.04	>140		24.5	3.0	27.6	Fine rootlets
SB2	Grass	40	45°S	Thin layer of humus. Soft brown clay with rounded gravels, high plasticity.	200	2.47	23	39	12.9	3.5	26.5	Rare fine rootlets
SB3	Grass	44	38°S	Soft-firm brown sandy clay with abundant gravel.	100	2.99	36	52	13.8	2.5	21.8	Rare fine rootlets
SB4	Grass	46	28°S	10 mm layer of humic material; 35 mm layer of dark grey clay, 120 mm layer of brown gravelly clay, thin layer of soft-firm orange brown sandy clay at 165 mm depth	165	NR	NR	42	26.7	5.6	15.0	Rare fine rootlets
M11A	Small Oak shrub*	33	8°NW	Soft, brown grey clay, highly plastic, (London Clay)	100	3.23	NR	25	76.9	NR	28.6	One main tap root, length 297 mm. Root tip diameter 6.3 mm. Multiple roots from main tap root (see Fig. 4.13)
M11B	Grass	35	8°NW	Very soft-soft, brown grey clay, highly plastic, (London Clay)	100	2.97	18	30	17.0	15.0	34.6	Fine roots

Key: m.c. – moisture content; NR – not recorded. * Oak characteristics: Height 0.51 m; Spread = 0.25 x 0.3 m; Stem diameter at ground level = 11.96 mm, at top of tree = 3.06 mm.
† Depth of hand vane tests on the shear plane is equivalent to the depth of the *in situ* shear test.

The presence of fine rootlets in the clay soils had very little effect on soil strength. The apparent difference in strengths between results SB1/4 and SB2/3 is due to the gravel. However, the presence of the oak root system (Figure 4.11) significantly increased the soils resistance to shear by increasing the shear stress over larger displacements (up to 60 mm) (Figure 4.13).

4.5.1.2 Root pull out resistance test results

The root pull out resistance tests of hawthorn, oak and rowan roots carried out on Sites 1 and 2 are shown graphically as force to pull out against displacement plots in Appendix 1. Some of the plots show repeated pull outs of the root e.g. H3A, this was necessary as the amount of extension on the hydraulic pump was limited to 400 mm. From these graphs, the peak pull out force was determined and the pull out stress calculated for each root, as described in Chapter 3. For the three species, the range of pull out forces and mean pull out stresses are given in Table 4.11. The test data for each individual tree root is summarised in Table 4.12, where the pull out stress is based on the root diameter at the clamp.

When root pull out force is compared with root diameter (Figure 4.14) there is a positive relationship for all three species. The hawthorn roots show a much wider spread of data points than the oak or rowan due to the greater number of roots tested and also the wide variation in root morphology (root branching) (Figure 4.15). All three species show a positive relationship between root pull out force and extracted root length (Figure 4.16). A negative relationship is apparent when root pull out stress at failure (based on diameter at the clamp) is compared with root diameter (Figure 4.17), thus large pull out stresses equate with small root diameters. The root pull out resistance test results are further analysed and discussed in Chapter 5.

Table 4.11. Summary test data of root pull out resistances of rowan, oak and hawthorn.

Species	Range of root diameters (mm)	Range of force to pull out the roots (kN)	Range of pull out stress (MPa)	Mean pull out stress (MPa)
Rowan (*Sorbus aucuparia*)	2.4 – 9.2	0.06 – 0.43	2.5 - 22.6	10.7
Oak (*Quercus robur*)	1.7 – 9.3	0.03 – 0.44	2.2 – 14.0	7.4
Hawthorn (*Crataegus monogyna*)	7.1 – 61.8	0.16 – 11.53	1.9 – 25.3	8.1

Table 4.12. Individual root pull out resistance test data for all species.

Species	ID	Root incln (°)	Mean root diam. (mm)	Root length (mm)	Force to pull out (kN)	Max. displ. (mm)	Pull out stress (MPa)	Root moisture content (%)
Rowan *(Sorbus aucuparia)* [PBT1]	A	19/300	2.8	154	0.10	58	10.8	NR
	B	20/070	3.1	297	0.29	168	13.2	NR
	C	11/354	2.1	140	0.06	140	12.5	NR
	D	48/220	2.0	230	0.17	15	22.6	NR
	E	16/092	5.8	63	0.42	63	11.3	NR
	F	8/340	2.2	185	0.09	90	18.8	NR
	G	22/160	4.4	220	0.10	52	2.5	NR
	H	42/200	2.5	120	0.10	30	10.8	NR
	I	31/130	3.7	188	0.18	52	4.3	NR
	J	48/044	4.2	84	0.17	84	7.8	NR
	K	66/151	6.7	68	0.20	36	2.9	NR
Oak (*Quercus robur*) [MO1]	A	18/102	9.1	673	0.39	650	6.04	3.8*
	B	6/160	8.9	546	0.44	500	7.10	8.3*
	C	11/045	2.7	73	0.03	73	5.14	25.0*
	D	4/236	5.2	369	0.17	320	7.86	11.1*
	E	18/348	3.5	395	0.07	350	7.35	16.1*
	F	18/108	9.3	140	0.15	120	2.17	0*
	G	16/130	4.2	492	0.10	330	7.08	9.1*
	H	21/032	1.7	465	0.03	150	12.97	0*
	I	16/200	6.9	244	0.15	140	3.96	7.14*
	J	12/258	2.5	170	0.07	60	13.99	0*
Hawthorn (*Crataegus monogyna*) [H1]	B	223/20	22.5	381	1.53	156	3.87	68.6
	C	315/25	19.6	245	1.13	91	3.76	53.9
	D	052/1	31.2	1380	7	55	9.15	71.3
	F	122/6	21.9	717	3.01	116	8.00	66.1
	H	308/0	48.0	2561	6.41	48	3.54	66.0
Hawthorn (*Crataegus monogyna*) [H2]	2A	233/1	18.5	840	2.24	193	8.31	58.1
	2C	006/9	26.7	1610	3.99	98	7.14	65.8
	2D	017/8	18.2	450	0.51	55	1.97	75.0
	2F	080/12	24.5	967	2.62	89	5.54	77.5
	2G	006/9	19.2	575	2.03	96	6.99	68.5
	2H	050/32	19.9	800	2.15	40	6.92	63.6
	2J	046/15	23.6	1210	1.9	35	4.34	78.7
Hawthorn (*Crataegus monogyna*) [H3]	3A	046/22	25.1	943	3.08	180	6.24	79.0
	3B	078/7	13.3	762	1.42	210	10.29	78.7
	3E	100/2	7.4	745	0.35	126	8.19	74.2
	3F	146/10	21.3	2010	2.23	125	6.24	81.7
	3G	186/+30	7.1	224	0.33	50	8.43	81.8
	3H	161/+26	9.3	922	0.49	45	7.28	89.8
	3J	212/6	7.3	127	0.16	161	3.81	34.5
	3L	240/0	15.0	362	1.51	73	8.55	73.9
	3M	268/+10	15.3	250	1.63	130	8.88	75.4
	3N	246/12	11.2	885	1.23	191	12.40	73.2
	3O	264/18	16.9	964	4.06	133	18.19	79.4
	3R	358/11	11.8	853	2.15	66	19.57	71.8
	3T	318/+2	10.4	680	2.16	23	25.32	79.6
	3V	350/0	35.3	1155	5.88	207	6.00	82.6
	3X	264/4	8.6	165	0.34	17	5.92	72.8
	3Y	187/+24	10.9	310	0.75	123	8.01	73.7
	3Z	182/14	11.6	2033	1.24	170	11.70	63.6

Table 4.12 continued…

Species	ID	Root incln (°)	Mean root diam. (mm)	Root length (mm)	Force to pull out (kN)	Max. displ. (mm)	Pull out stress (MPa)	Root moisture content (%)
Hawthorn (*Crataegus monogyna*) [H3]	3AA	200/10	22.2	4197	3.41	218	8.83	76.9
	3BA	206/8	10.0	1940	0.91	108	11.65	72.3
	3CA	216/18	19.8	550	1.57	117	5.12	80.0
	3DA	240/0	20.3	7094	4.31	154	13.34	75.8
	3EA	358/44	55.8	488	11.53	239	4.73	92.6
Hawthorn (*Crataegus monogyna*) [H5]	5A	268/+4	61.8	6141	11.1	1000	3.70	72.9
	5B	293/0	21.6	2809	3.08	426	8.41	58.8
	5C	337/10	28.2	1167	4.15	126	6.63	67.9
	5D	344/18	26.8	762	1.22	105	2.17	64.7
	5E	006/+2	19.1	189	3.15	122	11.04	61.9

Key: diam. – diameter; displ – displacement; incln – inclination, + – roots growing in an upwards direction; Max – maximum; NR – not recorded; * – roots had partially dried out before moisture content was recorded.

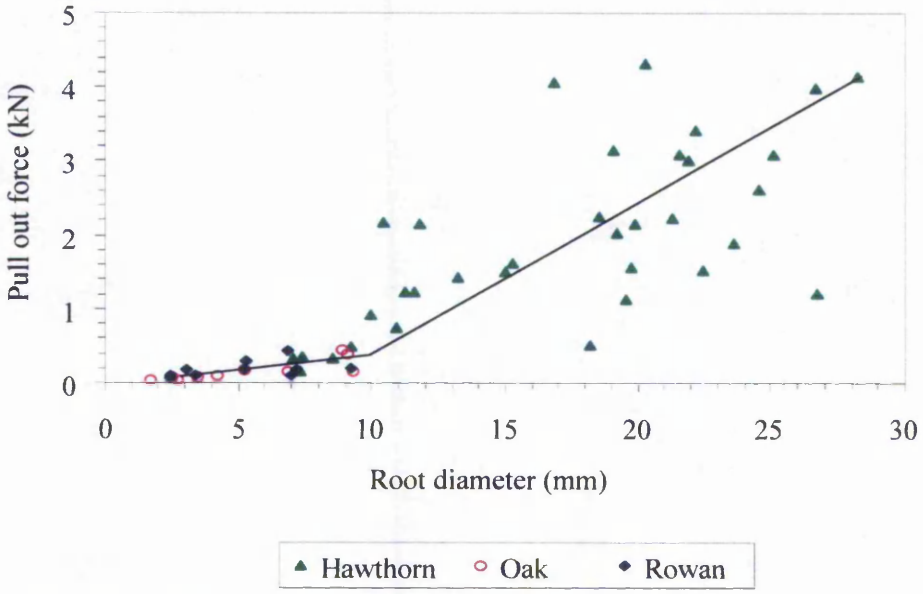


Figure 4.14. Root pull out force increases with root diameter (at the clamp) for hawthorn, oak and rowan roots.

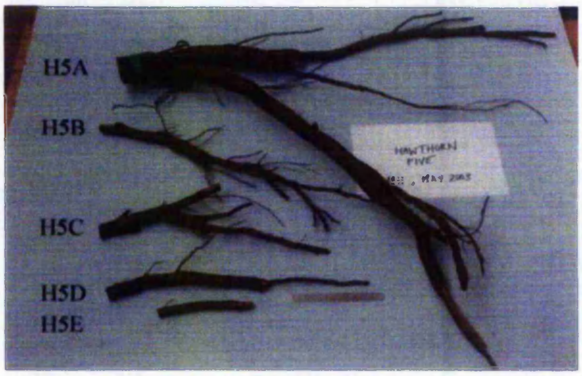


Figure 4.15. Root morphology of hawthorn [H5] roots from Site 2.

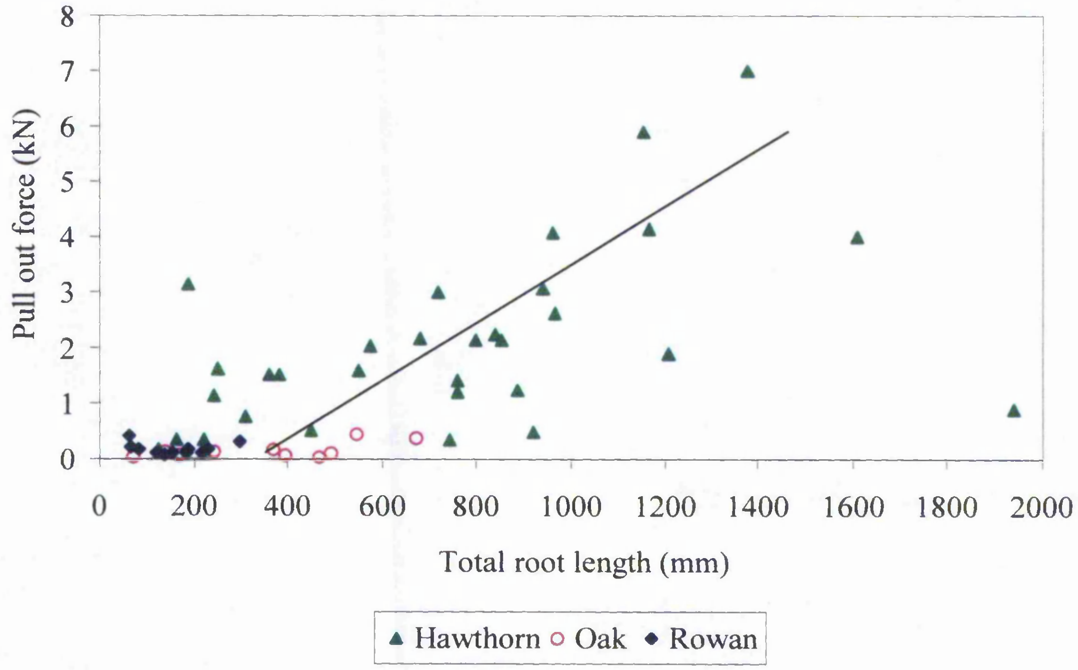


Figure 4.16. Variation of root pull out force with extracted root length.

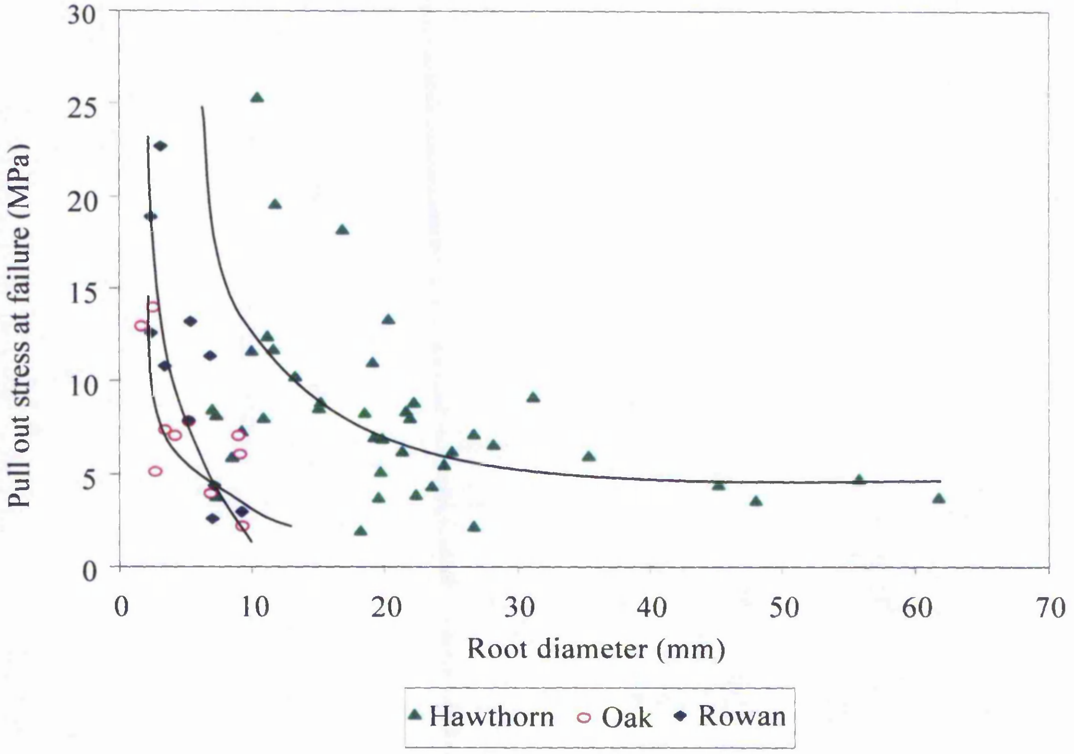


Figure 4.17. Root pull out stress at failure shows a decreasing trend as root diameter (based on diameter at the clamp) increases.

4.5.2 Results of laboratory root tensile strength tests

The data obtained from the tensile strength tests (see Section 4.4.3) of hawthorn roots from Sites 2 and 3 and elder roots from Site 3 are now presented.

4.5.2.1 Site 2: Hawthorn [H4] results

Seven roots from hawthorn tree H4 were collected from Site 2 (Figure 4.18) and tested in the tensometer for their tensile strengths (see Sections 3.1.2.2 and 4.4.3 for method and descriptions). One root was divided into three sections prior to testing. The morphology of each root and the associated breaking strengths are described in Table 4.13. The roots were woody with thin barks.

Figure 4.18. Hawthorn [H4] roots prior to tensile testing. From left to right, roots are 4E, 4I, 4C, 4F, 4L, 4D and 4H. Root 4L was divided into three sections.

In each test, there was an increase in tensile force with extension (Figure 4.19a), showing that the root has some elastic properties. The calculated value of elasticity (Young's modulus, E) for the ten roots varied from 24 – 123 MPa with a mean E value of 57 MPa. Root moisture content was over 95 % in all roots tested. The tensile force required to break the roots ranged from 0.24 – 8.9 kN (Figure 4.19b) over a root diameter range of 3.9 – 26.6 mm. The increase in tensile force with root diameter is a positive linear relationship.

Table 4.13. Summary tensile test data of hawthorn [H4] roots from Site 2 (M11).

Root ID	Root description	Original length (mm)	Final length (mm)	Force (N)	Ext. (mm)	Mean diameter at break point (mm)	Tensile stress at break point (MPa)	Root moisture content (%)	Young's Modulus, E (MPa)
4C	Lateral – straight woody root, few rootlets	170	177	1860	59	10.1	23.2	104	52
4D	Lateral – long, woody root with few rootlets	154	156	2000	61	10.9	21.2	102	34
4E	Lateral – straight root, rootlets at distal end, ridges on bark	150	164	505	50	8.1	9.9	113	30
4F	Lateral – straight woody root, branch at distal end	160	168	1020	56	9.7	13.9	107	40
4H	Upslope – long, woody root with rootlets	153	158	1100	56	11.4	10.9	120	24
4I	Upslope – sinuous woody root with rootlets	165	175	830	50	8.7	14.1	100	32
4L1	Lateral – very long thin woody root, few rootlets mainly at distal end, tapers towards terminus. Root cut into 3 sections.	170	180	240	28	3.9	20.2	100	123
4L2		195	203	352	47	4.2	25.0	108	104
4L3		200	203	290	33	5.3	13.0	98	76
4M	Downslope – long, straight, thick woody root, 4 branches, daughter roots (1-3mm thick) at distal end	395	395	8980	—	26.6	16.2	95	—

Key: Ext. – extension, maximum distance root was extended during tensile test.

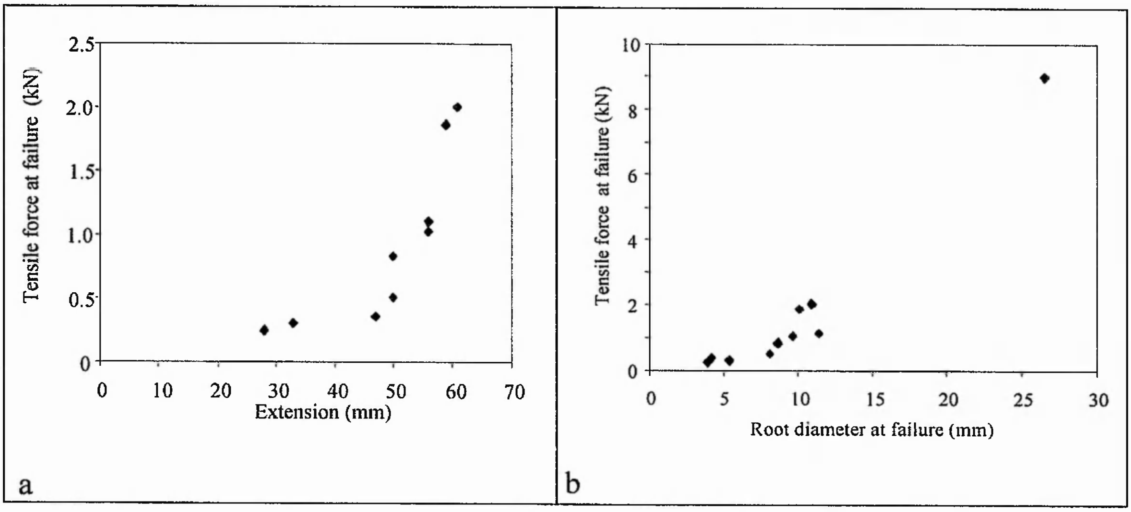


Figure 4.19. Tensile strength test results of hawthorn [H4] roots. (a) Positive correlation between tensile force and extension at failure; (b) Positive correlation between tensile force and root diameter at failure.

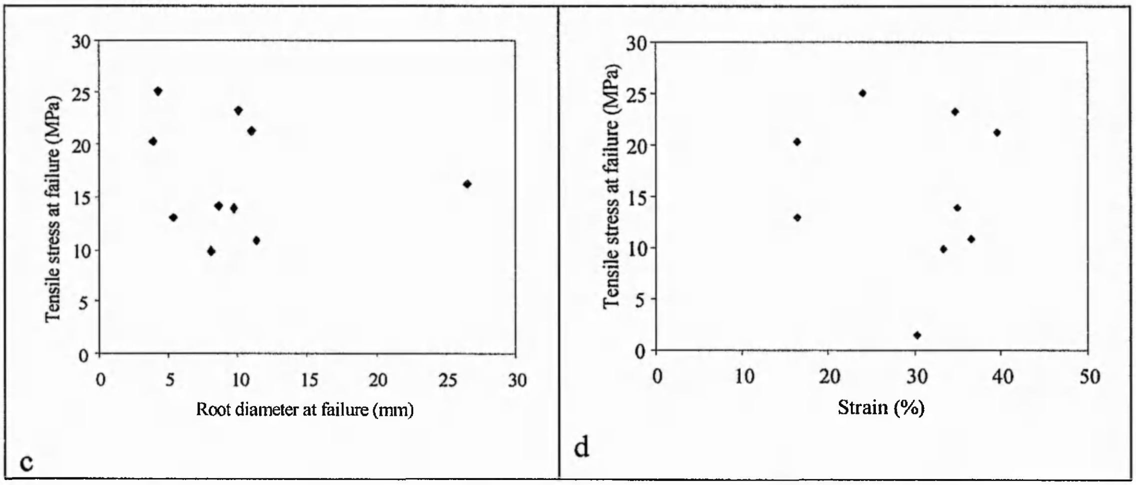


Figure 4.19 continued. Tensile strength test results of hawthorn [H4] roots. (c) Negative correlation between tensile stress and root diameter at failure; (d) No correlation between tensile stress and strain at failure.

Tensile stress at failure varied between 10 – 25 MPa, with a mean tensile stress of 16.8 MPa. There appears to be a negative correlation between tensile stress at failure and root diameter (Figure 4.19c), although due to the small data set this trend can not be confirmed. There is no correlation between tensile stress and percentage strain at failure (Figure 4.19d).

4.5.2.2 Site 3: Hawthorn results

Hawthorn roots from Site 3 were tested for their tensile strength. Table 4.14 provides summary information of the 60 hawthorn roots tested. The roots were taken from four hawthorn trees (Section 4.4.3) and cut into sections for testing. Seven roots were rejected from the analysis for three reasons: (a) the roots slipped out of the clamps of the tensometer [roots Rud: H1.2, H2UD, H2UE, H2UH, H2DJ] ; (b) were too brittle to test [RudH4B] due to drying and (c) Root RudH1.3 was to thick to test in the Tensometer but too short to test in the Losenwark machine. The roots were woody and had very thin barks.

The hawthorn roots from Site 3 showed the same increase in tensile force with extension (Figure 4.20a) as the hawthorn roots from Site 2. Young's modulus, E varied from 2 – 205 MPa with a mean E value of 75 MPa, a much greater range than the roots from Site 2. Root moisture content varied between 50 – 175% (Table 4.14). The range of E values

Table 4.14. Summary of tensile strength test data of hawthorn roots from Site 3.

Root ID	Root description	Original length (mm)	Final length (mm)	Force (N)	Ext. (mm)	Mean diameter at break point (mm)	Tensile stress at break point (MPa)	Root moisture content (%)	Young's Modulus, E (MPa)
RudH1.1	Taproot. Cut into 3 sections.	163	163	42	25	1.5	25.4	50	166
RudH1.2		80	80	41	12	---	---	54	---
RudH1.3		220	---	---	---	---	---	58	---
RudH2UA	Upslope – long straight root. Cut into 17 sections.	180	185	18	26.8	4.1	1.3	93	9
RudH2UB		122	125	170	27.7	3.7	15.5	100	46
RudH2UC		152	160	280	37.1	5.1	13.6	89	45
RudH2UD		156	162	340	44	---	---	91	41
RudH2UE		95	95	260	24	---	---	88	8
RudH2UF		215	235	220	31	7.0	5.7	90	40
RudH2UG		140	144	81	19.1	2.3	19.4	108	101
RudH2UH		95	95	20	27	---	---	89	2
RudH2UI		177	184	104	20.7	3.0	14.3	86	175
RudH2UJ		108	113	131	16.8	3.7	11.9	83	77
RudH2UK		83	85	118	20.6	2.7	20.1	83	107
RudH2UL		127	131	213	25.8	4.5	13.6	93	74
RudH2UM		125	128	241	27.4	3.6	23.9	91	110
RudH2UN		164	166	94	24.7	2.4	21.6	80	144
RudH2UO		134	138	220	25.9	4.4	14.7	89	76
RudH2UP		145	148	345	36.8	5.4	15.0	92	67
RudH2UQ		398	398	1100	NR	16.6	5.1	80	---
RudH2DA	Downslope – long straight root. Cut into 11 sections.	208	225	618	65	7.0	16.1	93	29
RudH2DB		137	138	890	84.9	7.9	18.0	109	12
RudH2DC		131	132	490	54.3	8.6	8.5	98	12
RudH2DD		155	156	585	37.6	8.5	10.4	92	18
RudH2DE		160	164	882	109.1	9.7	12.0	117	22
RudH2DF		162	164	432	52	8.9	7.0	98	15
RudH2DG		160	162	948	70.5	8.0	18.6	104	26
RudH2DH		138	142	1010	62.1	10.3	12.1	96	9
RudH2DI		139	145	993	59.7	9.7	13.5	107	13
RudH2DJ		122	120	790	49	---	---	97	4
RudH2DK		81	83	82	12.3	2.6	16.1	80	106
*RudH3.1	Lateral – long, sinuous root with fibrous branches	179	181	42	33.1	2.0	13.4	112	73
RudH3.2	Lateral – long, sinuous root with fibrous branches	181	189	79	36.3	2.2	20.7	116	104
RudH3.3	Lateral – long, sinuous root with a right angle bend	250	263	55	77.3	4.5	3.5	139	11
RudH3.4	Lateral – long straight root	196	198	48	30	2.0	15.8	90	103
RudH3.5	Lateral – short, multiple bends	130	135	87	26	4.4	5.8	93	28
RudH3.6	Lateral – long, bended root	260	265	63	24.6	3.1	8.4	86	89
RudH3.7	Lateral – short root with minor branch	85	86	30	14	3.0	4.1	102	25
RudH3.8	Lateral – long, sinuous root with forked branch	183	182	22	21.7	3.2	2.8	105	24

Table 4.14 continued.

Root ID	Root description	Original length (mm)	Final length (mm)	Force (N)	Ext. (mm)	Mean diameter at break point (mm)	Tensile stress at break point (MPa)	Root moisture content (%)	Young's Modulus E (MPa)
RudH3.9	Lateral – long, fibrous branch	130	134	284	41.5	5.3	13.1	99	39
RudH3.10	Lateral – short, sinuous	80	84	21	20.1	1.2	18.6	157	54
RudH3.11	Lateral – long, sinuous	160	161	15	25.5	1.2	13.1	133	40
RudH3.12	Taproot	300	300	6540	NR	25.6	12.8	75	---
RudH4A	Long sinuous root with one side branch	161	162	242	37	4.8	13.5	81	59
RudH4B	Short woody root with prominent bend	90	---	---	---	---	---	86	---
RudH4C	Multibranched with many fine roothairs	136	138	46	14	1.9	16.4	135	160
RudH4D	Sections cut from roots H4A, B and C and rootball	161	165	181	35	4.6	10.7	83	25
RudH4E		182	184	15	16	3.7	1.4	83	16
RudH4F		205	206	21	14	1.2	17.6	78	115
RudH4G		180	184	47	15	2.5	9.6	76	115
RudH4H		213	216	20	20	0.9	30.8	64	328
RudH4I		184	184	34	30	1.2	28.6	79	176
RudH4J		130	131	10	0.7	1.6	5.1	73	94
RudH4K		144	145	49	15	1.7	20.7	81	199
RudH4L		149	149	36	23	3.1	4.9	75	31
RudH4M		155	161	21	18	1.1	23.8	62	205
RudH4N		134	135	46	19	1.7	19.5	75	138
RudH4O		120	89	46	12	1.9	16.8	175	168
RudH4P		148	155	12	20	0.9	18.1	58	134
RudH4Q		145	153	421	32	12.7	3.3	45	15

Key: Ext. – extension, maximum distance root was extended during tensile test; *H3.1-11 roots cut from two side branches from main taproot.

and root moisture contents is sufficient that the hawthorn roots from Site 2 can be encompassed within the larger dataset from Site 3.

The tensile force required to break the hawthorn roots from Site 2 ranged from 0.012 – 6.54 kN over a root diameter range of 0.9 – 25.6 mm (Figure 4.20b). Figure 4.20b shows that as tensile force increases, root diameters also increase. There is a wide range of tensile stress values (1.3 – 30.8 MPa), which clearly show a negative correlation with root diameters (Figure 4.20c). This relationship confirms the apparent negative correlation of tensile stress at failure with root diameter of the hawthorn roots from Site 2 as shown in Figure 4.19c. The mean tensile stress of the hawthorn roots from Site 3 was 13.7 MPa. There is no apparent correlation between tensile stress at failure and percentage strain (Figure 4.20d).

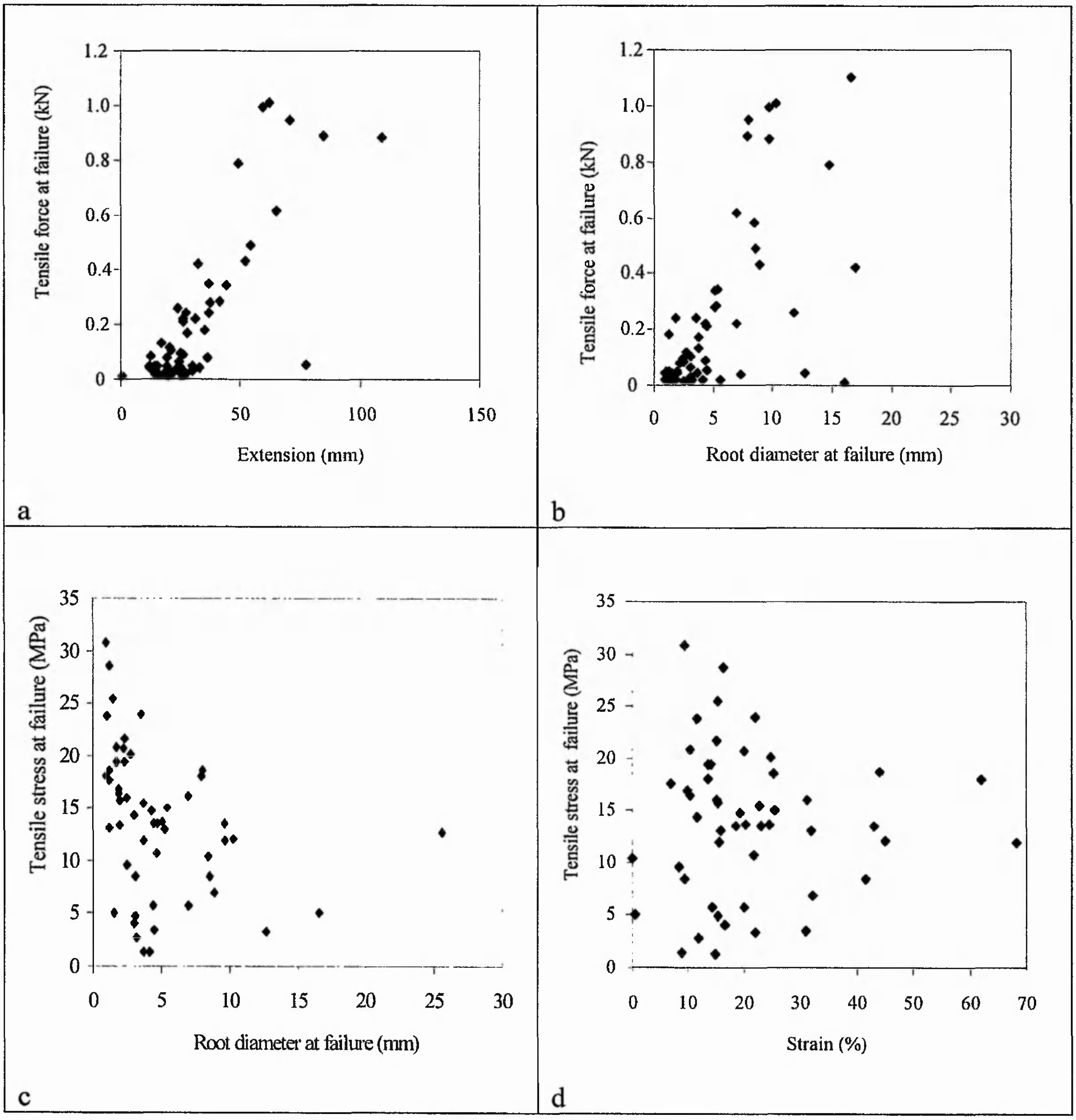


Figure 4.20. Tensile strength test results of hawthorn roots from Site 3. (a) Positive correlation between tensile force and extension at failure; (b) Positive correlation between tensile force and root diameter at failure; (c) Negative correlation between tensile stress and root diameter at failure; (d) No correlation between tensile stress and strain at failure.

4.5.2.3 Site 3: Elder root results

Fifteen elder roots from three elder shrubs on Site 3 were tested in the tensometer for their tensile strengths (Sections 3.1.2.2 and 4.4.3). Of the fifteen roots collected for testing, nine roots were subsequently cut into further sections, making a total of 43

Table 4.15. Summary tensile strength test data of elder roots from Site 3.

Root ID	Root description	Original length (mm)	Final length (mm)	Force (N)	Ext. (mm)	Mean diameter at break point (mm)	Tensile stress at break point (MPa)	Root moisture content (%)	Young's Modulus E (MPa)
7A1	Upslope - long root with few side rootlets, rubbery outer layer, tough woody inner core. Cut into 3 sections.	140	146	13	20	---	---	228	---
7A2		175	180	21	15	0.4	136.6	262	1861
7A3		150	152	5	15	0.6	16.6	250	166
7B1	Lateral – long rubbery root with many branches and feathery roots at the end of the branches. Cut into 6 sections.	177	180	142	38	1.9	52.6	250	306
7B2		103	107	65	20	1.6	31.6	388	163
7B3		166	171	25	30	1.5	14.8	352	82
7B4		164	166	20	18	1.4	12.8	358	116
7B5		170	172	9	15	0.8	16.3	283	185
7B6		138	141	26	26	2.0	8.1	376	43
7C1	Lateral – long rubbery root with one main branch which splits into 4 branches along its length. Cut into 8 sections.	155	153	255	28	2.4	58.6	233	178
7C2		174	179	62	32	1.6	30.9	402	173
7C3		149	149	6	20	0.8	12.2	314	91
7C4		95	102	18	20	0.9	26.4	87	125
7C5		152	152	22	25	1.4	14.5	230	88
7C6		129	134	9	15.8	1.0	12.4	75	106
7C7		160	163	13	16	1.0	18.3	44	183
7C8		135	139	10	11	0.8	18.7	80	230
7F1	Downslope – long, straight rubbery root. Cut into 3 sections.	150	153	51	33	3.3	5.8	383	26
7F2		155	155	820	25	4.6	50.2	143	311
7F3		125	125	122	28	---	---	331	---
7G1	Taproot. Cut into 2 sections.	206	214	180	22	4.7	10.2	329	96
7G2		160	163	30	20	1.3	24.3	350	194
7I1	Upslope - long sinuous root, daughter branch at proximal end, 3-way split at distal end. Cut into 4 sections.	130	130	30	20	1.6	15.5	323	101
7I2		106	113	215	24	3.9	17.8	241	44
7I3		145	146	153	29	3.5	15.7	108	59
7I4		112	117	240	23	2.5	47.5	128	155
13A1	Downslope - multiple branched taproot. Cut into 3 sections.	180	185	52	38	2.9	7.8	272	42
13A2		165	165	102	37	1.9	36.0	300	179
13A3		110	107	10	30.3	0.4	77.7	300	285
13B1	Upslope - long root forks into two at approx. 2/3rds of its length. Cut into 3 sections.	160	160	115	18.5	1.5	61.6	269	547
13B2		120	120	20	12	2.8	3.2	293	32
13B3		125	130	32	22	2.1	9.2	317	52
13C1	Lateral - long root forks into two at distal end. Cut into 5 sections.	180	182	17	20.5	0.8	30.7	358	276
13C2		160	158	20	23.3	0.8	40.6	342	282
13C3		160	167	52	17	1.5	28.6	343	269
13C4		146	150	146	16.8	1.3	51.5	340	570
13C5		160	160	242	28	2.9	36.9	303	224
23UPNE1	Upslope – tapering root with two short daughter branches	136	136	23	24	---	---	261	---
(retest)		136	140	25	27	2.2	6.4		32
23UPNE2	Upslope – short, thick root, (outer core 1.8 mm thick)	140	151	580	53	9.8	7.7	240	11
23UPSE3	Upslope – rubbery, irregular ridged bark surface	148	148	130	50	2.3	31.3	226	93
23SL4	Lateral – with one branch, thick outer core (2.5 mm)	195	200	920	41	13.3	6.7	200	8
23UPE5	Upslope – short length of root, striations on inner core, bark damaged during excavation	117	123	800	28	5.4	34.5	92	48
23S6	Lateral – twisted, irregular surface, thick inner core (6.7 mm) and thick outer bark (2 mm)	150	152	383	38	5.8	14.7	236	38

Key: E – Young's Modulus (root elasticity); Ext. – extension, maximum distance root was extended during tensile test. Note a reduction in length of the root specimen is due to either loss of root during breaking or inaccurate measurements of the two parts of the root after tensile tests.

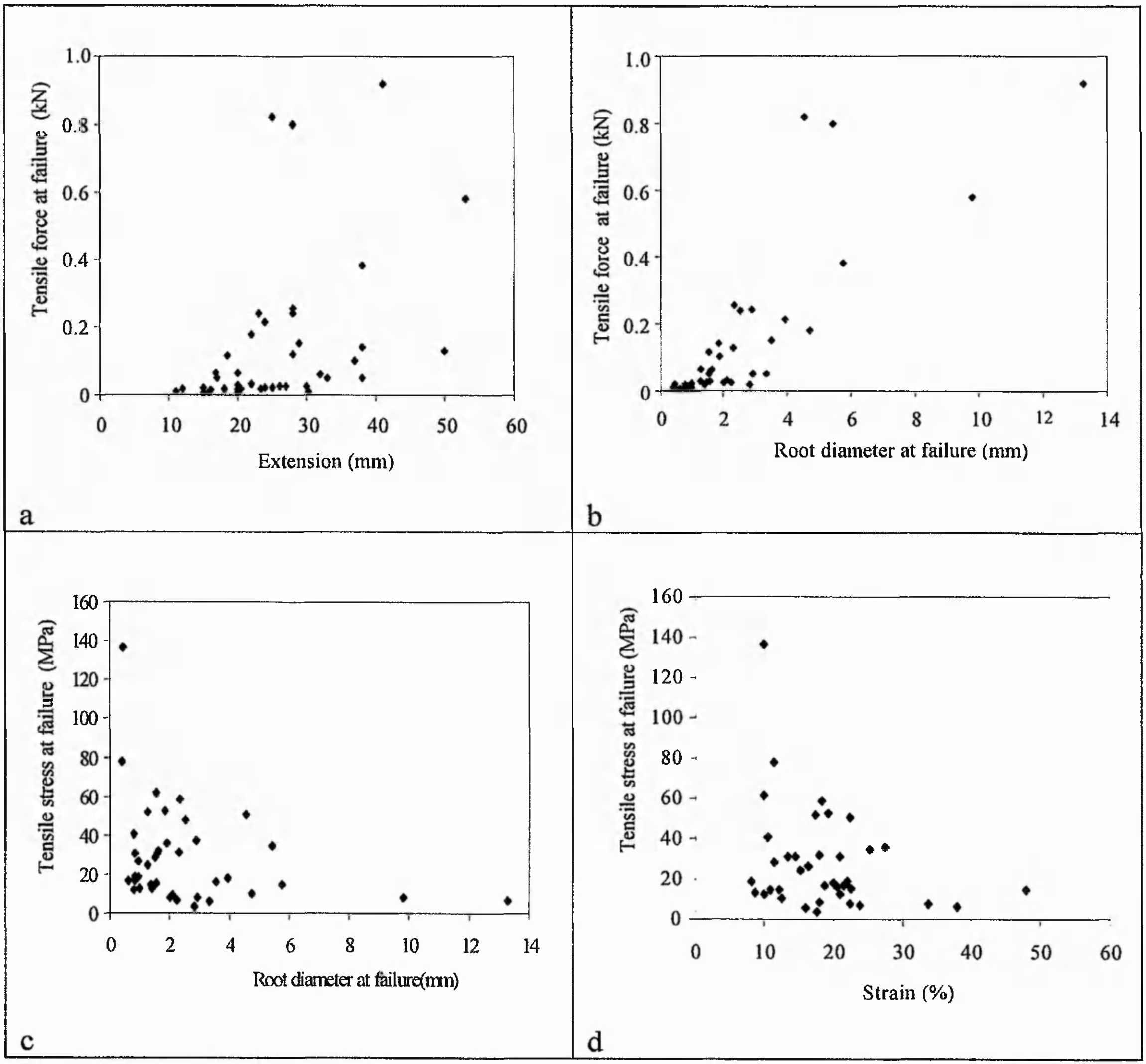


Figure 4.21. Tensile strength test results of elder roots from Site 3. The plots show relationships between (a) tensile force and extension at failure; (b) tensile force and root diameter at failure; (c) tensile stress and root diameter at failure; (d) tensile stress and strain at failure.

roots as described in Table 4.15. The elder roots were less woody than the hawthorn roots and had a thick outer rubbery core and a small inner woody core.

The elder roots showed a positive linear relationship between tensile force at failure and extension (Figure 4.21a). Young's modulus, E for the elder roots varied from 8 – 1861 MPa, with a mean E value of 188 MPa, showing that elder roots are very elastic properties. Root moisture content varied between 44 – 402% in all roots tested (Table 4.15). The tensile force required to break the roots ranged from 0.005 – 0.92 kN (Figure 4.21b) over a root diameter range of 0.4 – 13.3 mm. The increase in tensile force with root diameter is a positive linear relationship, whereas the relationship between tensile stress and root diameter appears to be negative (Figure 4.21c). Tensile stress varies between 3 – 136 MPa, although the mean tensile stress is much lower at 28.1 MPa. There is no apparent correlation between tensile stress at failure and percentage strain (Figure 4.21d).

4.5.3 Root distribution and Root Area Ratio

Root counts were carried out in the trial pits on all three sites. Some disturbance of the ground surface at the top of the trial pit prevented root count data from being collected at each 0.1 m interval. The number of roots in each trial pit was then converted into a Root Area Ratio (see Section 3.1.1.4).

On Site 1, Figure 4.22a shows root distribution with depth for the trial pit (TP1) situated in the copse to the east of the embankment and Figure 4.22b for the trial pit (TP2) situated on the grassed area of the west embankment. In TP1, small – medium-sized (0–10 mm diameter) roots were observed penetrating depths up to 1 m. Large-sized (>10 mm diameter) roots were only observed to depths of 0.5 m (Figure 4.22a).

In TP2, small-sized (<5 mm diameter) roots were counted at depths up to 0.8 m, with a high concentration between 0.2 and 0.5 m. Medium-sized (5–10 mm diameter) roots penetrated to depths up to 0.6 m, with only one large-sized (>10 mm diameter) root count existing at 0.2–0.3 m depth.

The corresponding root area ratios for trial pits TP1 and TP2 are shown in Tables 4.16 and 4.17. The root area ratio values are used in the slope stability analysis methods in Chapter 9.

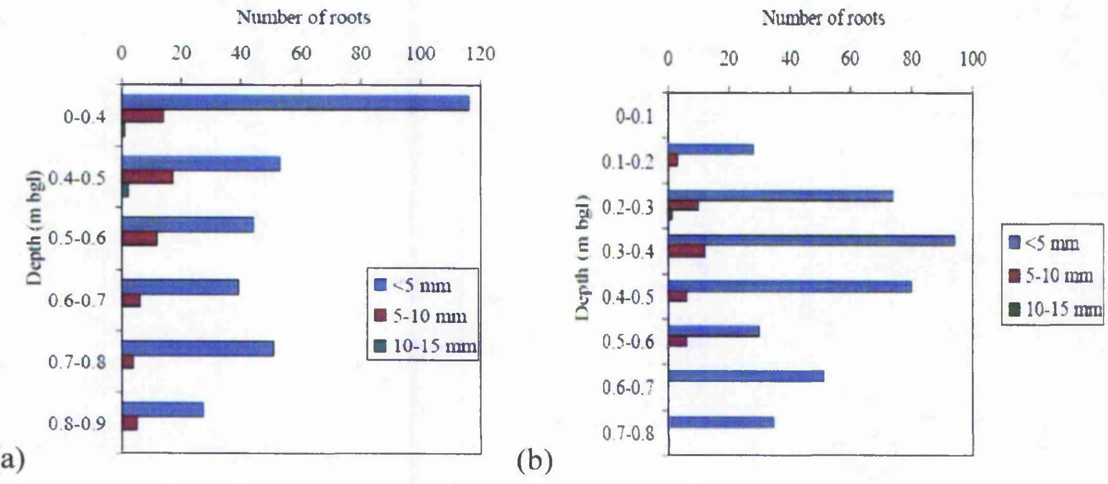


Figure 4.22. Variation of root distribution on Site 1 (a) within the copse (TP1) and (b) within the grass (TP2).

Table 4.16. Percentage root area ratios for the copse on Site 1 (TP1).

Root diameter Depth (m)	<5 mm	5-10 mm	10-15 mm	All roots
0-0.4	0.08	0.09	0.02	0.16
0.4-0.5	0.15	0.42	0.14	0.34
0.5-0.6	0.12	0.30	0.00	0.27
0.6-0.7	0.11	0.15	0.00	0.22
0.7-0.8	0.14	0.10	0.00	0.26
0.8-0.9	0.07	0.12	0.00	0.15

The total area represented is 1.61 m^2.

Table 4.17. Percentage root area ratios for grass on Site 1 (TP2).

Root diameter Depth (m)	<5 mm	5-10 mm	10-15 mm	All roots
0-0.1	NR	NR	NR	NR
0.1-0.2	0.10	0.09	0.00	0.14
0.2-0.3	0.25	0.31	0.09	0.39
0.3-0.4	0.32	0.37	0.00	0.49
0.4-0.5	0.27	0.19	0.00	0.40
0.5-0.6	0.10	0.19	0.00	0.17
0.6-0.7	0.18	0.00	0.00	0.24
0.7-0.8	0.12	0.00	0.00	0.16

The total area represented is 1 m^2.

Table 4.18. Percentage root area ratios for Site 2 – lower slope, grass.

Root diameter / Depth (m)	<5 mm	5-10 mm	10-15 mm	All roots
0-0.15	1.07	0.00	0.00	1.07
0.15-0.27	0.03	0.00	0.00	0.03
0.27-0.7	0.00	0.00	0.00	0.00

The total area represented is 0.35 m^2.

Table 4.19. Percentage root area ratios for Site 2 – midslope, grass.

Root diameter / Depth (m)	<5 mm	5-10 mm	10-15 mm	All roots
0-0.22	0.25	0.04	0.00	0.26
0.22-0.70	0.01	0.00	0.00	0.01

The total area represented is 0.35 m^2.

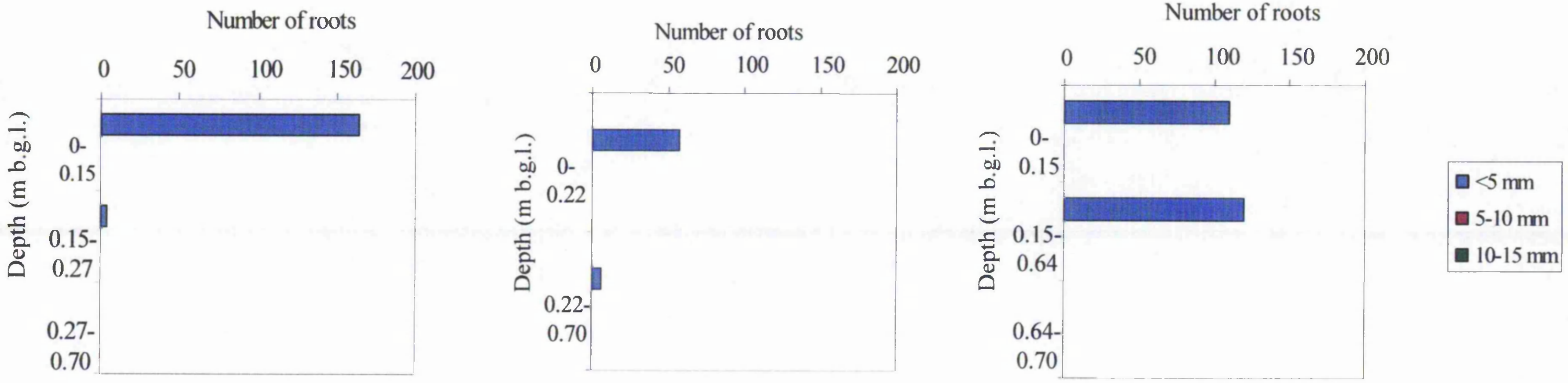
Table 4.20. Percentage root area ratios for Site 2 – upper slope, trees.

Root diameter / Depth (m)	<5 mm	5-10 mm	10-15 mm	All roots
0-0.15	0.72	0.06	0.16	0.73
0.15-0.64	0.24	0.02	0.00	0.24
0.64-0.70	0.00	0	0.00	0.00

The total area represented is 0.35 m^2.

On Site 2, Figure 4.23 shows the variation in root count with changing vegetation type up slope. It can be seen that the majority of roots of less than 5 mm diameter are concentrated in the top 150 mm of soil with very few roots being observed at depths greater than 150 mm. One medium-sized root and three medium–large-sized roots were counted in the mid and upper slope trial pits. The low number of medium–large-sized roots may be indicative of the location of the trial pits under vegetation cover of grass, for example lower and mid-slope; the trees are only shallow rooting in this particular location due to the stiffness of the clay preventing root penetration, and most probably the siting of the trial pit missed the location of the roots in the ground. It is feasible that the roots at depth may were following fissures in the clay, for easier root penetration.

Tables 4.18-4.20 show the percentage root area ratios for the corresponding root distribution; again the extremely low ratios indicate the low abundance of roots with depth.



(a) Lower slope - grass

(b) Mid slope – grass on edge of woodland

(c) Upper slope - woodland

Figure 4.23. Variation in root distribution on Site 2, (a) lower slope with grass vegetation cover; (b) mid slope – grass vegetation cover within close proximity to trees; (c) upper slope with tree vegetation cover.

Figure 4.24 shows the root distribution on Site 3. There is a high abundance of small diameter roots up to 0.5 m depth. Medium diameter roots occur in small numbers to depths of 0.5 m with only one large diameter root observed in the top layer. The percentage root area ratios are shown in Table 4.21.

The root area ratios are applied in the slope stability analysis models discussed in Chapter 9.

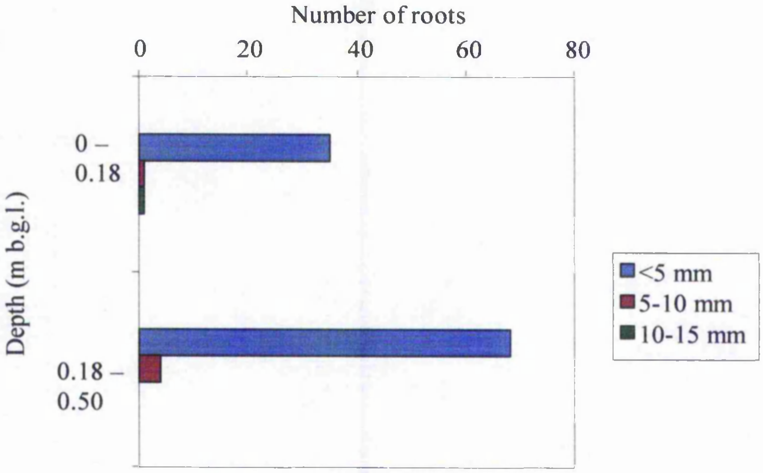


Figure 4.24. Variation of root distribution on Site 3.

Table 4.21. Percentage root area ratios for Site 3 – within close proximity to an elder shrub.

Root diameter / Depth (m)	<5 mm	5-10 mm	10-15 mm	All roots
0-0.18	0.19	0.05	0.14	0.20
0.18-0.50	0.21	0.11	0.00	0.22

The total area represented is 0.25 m^2.

4.5.4 Root architecture results

Root architecture measurements were carried out prior to root pull out resistance tests on Sites 1 and 2, tensile strength tests on Sites 2 and 3 and as a means of investigating the variation in architecture with slope angle on Site 3 (Section 3.1.16). The root architecture of the trees used in the root pull out tests is described in Section 4.5.4.1 and the variation of architecture with slope is described in Section 4.5.4.2.

4.5.4.1 Root architecture of vegetation subject to root pull out resistance tests

The root architecture measurements of angle of dip, direction of dip and root diameter provide information on the growth directions and distributions of roots within the ground. The root architecture of the rowan, hawthorn and oak trees on Sites 1 and 2 are now described.

4.5.4.1.1 Root architecture of rowan

The rowan, *Sorbus aucuparia*, tree (Figure 4.25) shows an asymmetrical distribution of roots around the stem (Figure 4.26), with a mean growth direction of 110°. There appears to be no preferential direction to roots growing either upslope or downslope. Each root was relatively short in length (63-297 mm) with a concentration of fine roots near to the stem.

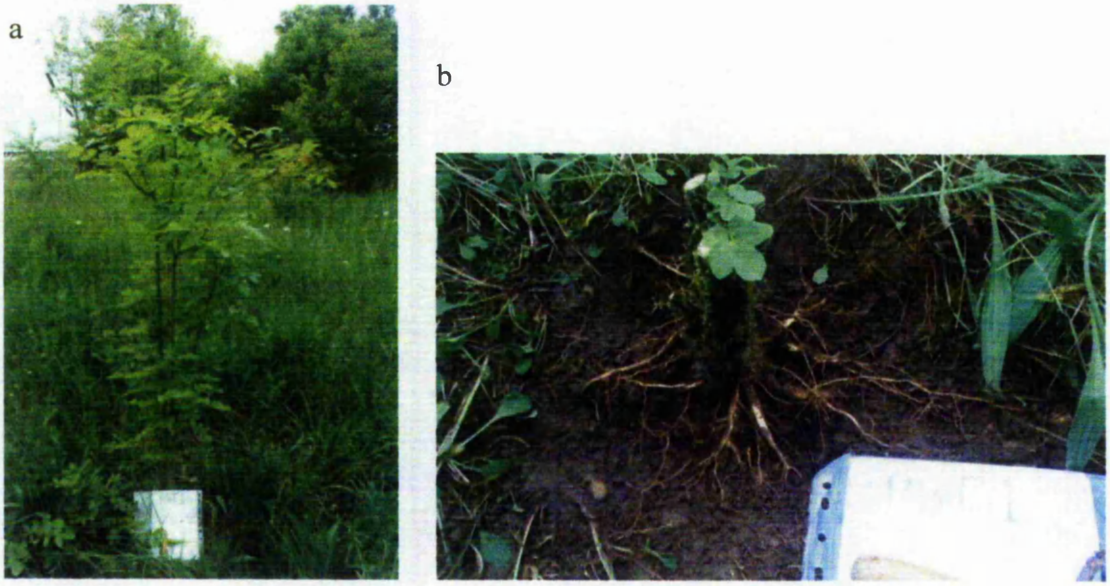


Figure 4.25. Tree and root characteristics of Rowan (*Sorbus aucuparia*) (a). Tree height 1.79 m. (b). Shallow root system with root diameters between 2 – 10 mm, looking in the upslope direction (330°).

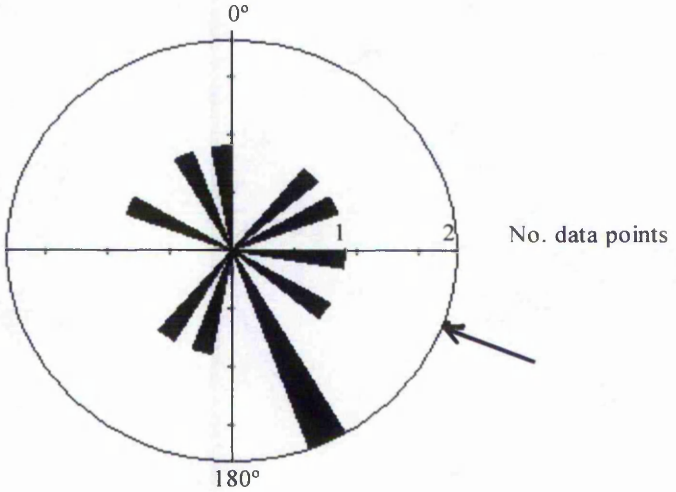


Figure 4.26. Root growth direction of the rowan (*Sorbus aucuparia*) tree. The length of each sector is equivalent to the number of roots occurring in that sector (e.g. 3 roots occur in the sector 1-10° where each sector angle is 10°). The arrow indicates mean root growth direction of 110° (±1.8° s.d.). Upslope direction of the embankment is 330°.

4.5.4.1.2 Root morphology and architecture of hawthorn (Site 2).

Figure 4.27. Root distribution of an 80 year old Hawthorn (*Crataegus monogyna*) tree [HRA]. Arrow shows upslope direction of 150°.

The hawthorn root system [HRA] as shown in Figure 4.27, had roots to depths of 0.5 m below the trunk of the tree. The root system showed no obvious tap root directly below the trunk, but had many lateral roots which radiated from the base of the trunk. Roots were ellipsoidal in cross section and tapered gradually. Some lateral roots divided into multiple branches along their length. It was not possible to determine what happened to the lateral roots at their termini since the root system had to be cut at 1.5 m from the centre of the trunk to enable the root system to be removed from the ground. The roots plunged shallowly into the soil at angles of 10–20°.

Figure 4.28 shows the radial distribution of roots around the trunk of the tree with the greatest number of roots occurring at a distance of 0.3 m from the central point of the trunk. There is also a high abundance of fine roots at all distances from the trunk. The peak at 0.3/0.4m is coincident with root branching at this point and the gradual tapering of the roots and reduction in number of roots is observed with increasing distance from the trunk. Chiatante *et al.* (2003b) report that the presence of a high incidence of root branching near the stem allows for more rapid dissipation of forces, avoiding a higher investment in strength further along the root (Stokes and Guitard, 1997). The mechanical role played by root branching is demonstrated by the fact that mechanically stressed plants presented a higher number of lateral roots than those of the controls (Goodman and Ennos, 2001).

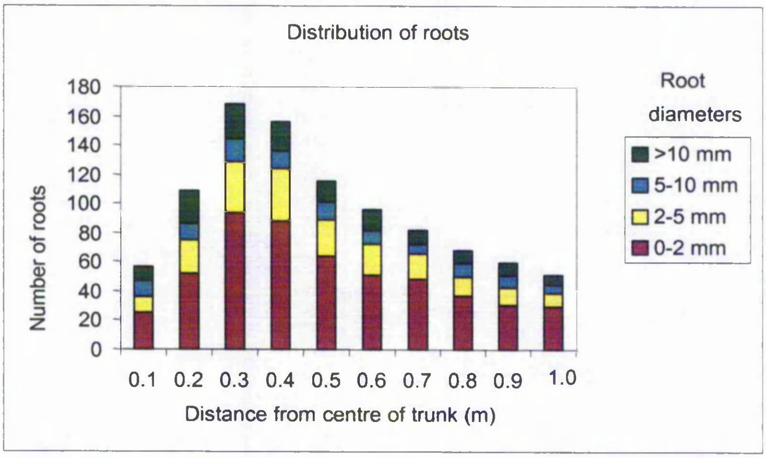


Figure 4.28. Number and size of roots at 10 cm intervals from the centre of the trunk.

Figure 4.29 shows the direction of all hawthorn roots from all the measured trees [H1-H5 and HRA]. The roots show an asymmetric distribution around the trunk, with a preference for growing laterally across the slope. Very few roots were observed growing in the upslope direction. The mean growth direction of the hawthorn roots was 299°.

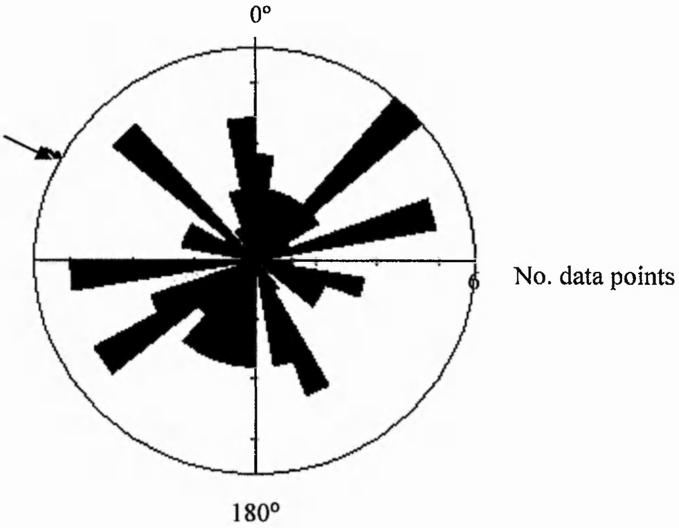


Figure 4.29. Root growth direction of hawthorn (compilation of 6 trees) on Site 2. The length of each sector is equivalent to the number of roots occurring in that sector (e.g. 3 roots fall in the sector 1-10° where each sector angle is 10°). The arrow indicates the mean root growth direction of 299° (± 2.8° s.d.). Upslope direction of the cut-slope is 150°.

4.5.4.1.3 Root morphology and architecture of oak

The variation in oak root morphology is shown in Figure 4.30. Generally the oak roots were long and straight with many short rootlets along their length. Some roots forked into two or more branches near the root tips. Some showed right angle bends where they had obviously had to grow around an obstruction. All roots showed a gradual taper along their length. Many of the oak roots lost the cortex or outer bark during pull-out. The oak showed an asymmetrical distribution of roots, with no preferential growth direction on the slope (Figure 4.31).

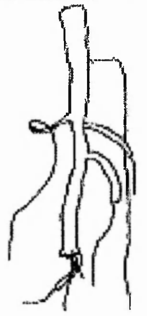
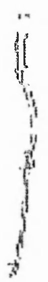
Oak root morphology				
Description	Long, highly branched root system	Multiple branched root system	Single straight root	Straight root with minor root branches
Diameter Total root length	d = 9.1 mm ℓ_T = 673 mm	d = 9.3 mm ℓ_T = 140 mm	d = 6.88 mm ℓ_T = 244 mm	d = 2.5 mm ℓ_T = 170 mm

Figure 4.30. Schematic drawings of oak root morphology. d is diameter at the top of the root in each drawing), ℓ_T is total root length including root branches (Norris, 2005).

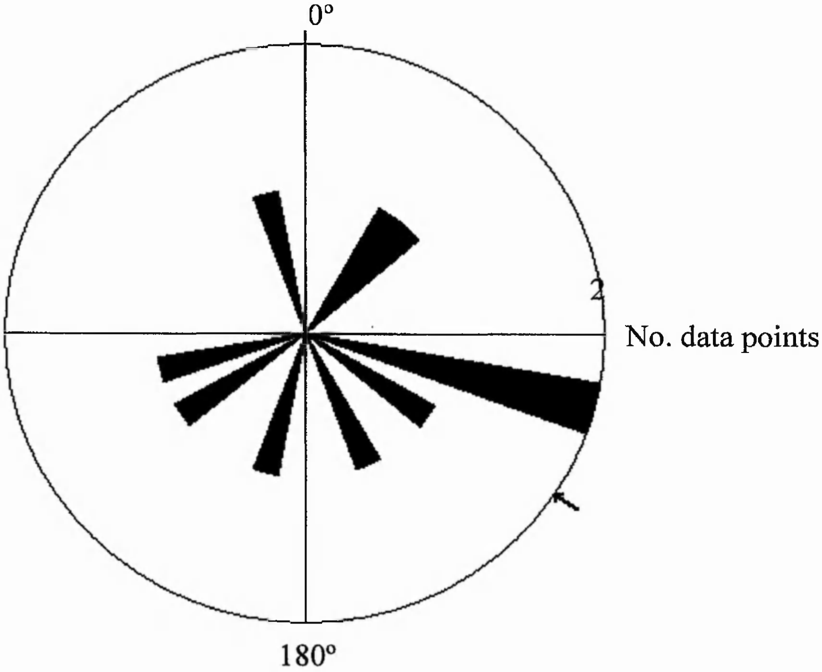


Figure 4.31. Root growth direction of oak. The length of each sector is equivalent to the number of roots occurring in that sector (e.g. 2 roots fall in the sector 100-110°, where each sector angle is 10°). The arrow indicates the mean root growth direction of 124° (± 1.7° s.d.). Upslope direction of the cut-slope is 150°.

4.5.4.1.4 Root architecture of hawthorn (Site 3)

The four hawthorn trees excavated for root tensile strength tests (RudH1-H4) showed a preference for growing in the lateral and downslope directions (Figure 4.32). The root systems showed an asymmetrical distribution of roots around the stem. The mean root growth direction was 077°.

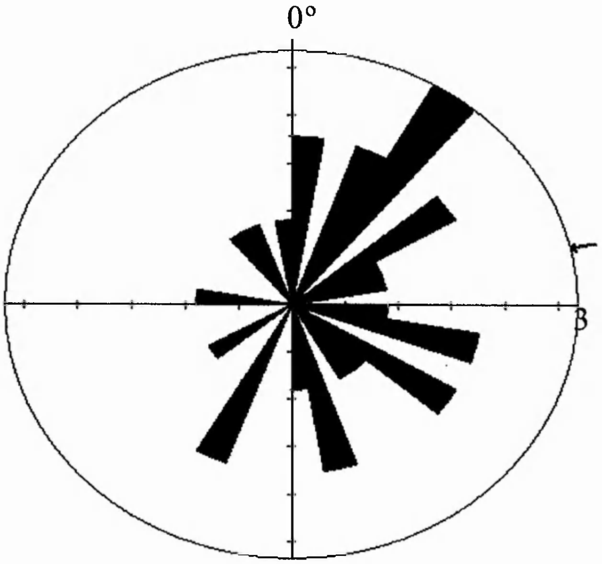


Figure 4.32. Root growth direction of hawthorn roots on Site 3. The arrow indicates the mean root growth direction of 077° (± 1.5° s.d.). The length of each sector is equivalent to the number of roots occurring in that sector (e.g. 2 roots fall in the sector 0-10°, where each sector has an angle of 10°. Upslope direction of the embankment is 295°.

4.5.4.2 Root morphology and architecture of elder

Elder roots have a thick outer core and are less woody in nature than other species. The inner core being the woody part of the root. Figure 4.33 shows some of the variation in root morphology of elder roots. Elder roots tended to be white in colour, soft and rubbery.

The elder shrubs growing on sloping and non-sloping ground showed substantial variation in root architecture, as illustrated in Figure 4.34. The slope angle of the embankment varied from top to bottom, with a gentle slope at the base (0-8°), a mid

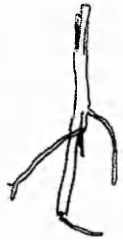
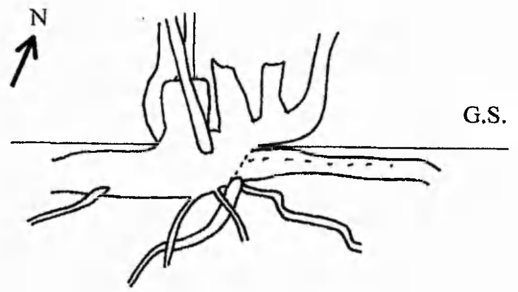
Elder root morphology							
Root ID	Rud7B	7I	23S6	23SL4	23UPNE1	23UPS5	23UPSE3
Description	Long rubbery root with many branches and feathery roots at the end of the branches.	Long rubbery root, forked at end.	Short, twisted root with irregular outer surface, inner core 6.7 mm thick, bark 2 mm thick	Short root with one small branch. 2.5 mm bark	Rubbery tapering root with two small branches	Bark stripped off during excavation to reveal striations on inner core and a radial pattern on cut transverse section.	Rubbery root with irregular ridged bark surface
Diameter, d	5.85 – 1.64 mm (root tips)	7.14 – 5.85 mm (at root tip)	9.01 – 8.39 mm	14.31 – 11.58 mm	5.02 – 3.38 mm	8.93 mm with bark 7.22 mm without bark	6.05 – 4.57 mm
Total root length, ℓ_T	835 mm	499 mm	150 mm	195 mm	179 mm	117 mm	148 mm

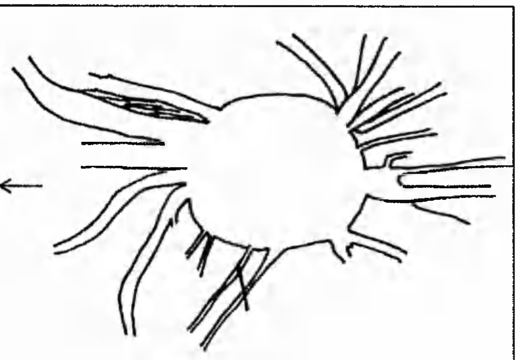
Figure 4.33. Variation in root morphology of elder.

slope of 18-30° and the top part of the embankment varying between 35-42°. Root architecture of the elder shrubs on flat/gently sloping ground generally showed a symmetrical distribution of roots around the stem, albeit with two dominant directions of 185 and 235 degrees (Figure 4.35a). One of the three trees (Rud11) was prevented from growing in the uphill direction due to a substantially thick root from a sycamore tree. On slopes greater than 8° (mid-upper slope), the root architecture of the elder showed a tendency for a 90 degree bend at the root – stem junction e.g., Rud14, Rud19, Rud24, producing a vertical taproot with very few lateral roots (Figures 4.34 and 7.8a). The single taproot was not evident on the non-sloping ground trees. In general, the root architecture of the elder on slopes showed an asymmetrical distribution of lateral roots around the taproot.

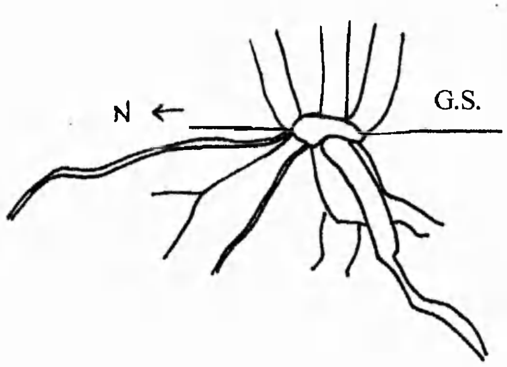
The mid slope elder shrubs have an approximately even distribution of root growth in both the up-down and across slope directions (Figure 4.35b), while the upper slope shrubs show a preference for roots in the across slope direction (Figure 4.35c). When all shrubs are compared together, the preferential root growth direction appears to be diagonally across the slope, with a mean of 220° (± 2.6° s.d.).



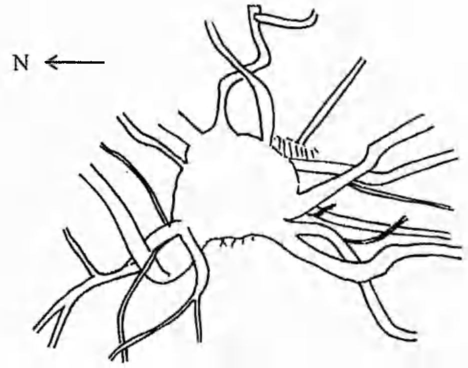
Rud1. Front view. Stem diameter 180 mm. Slope angle 0°.



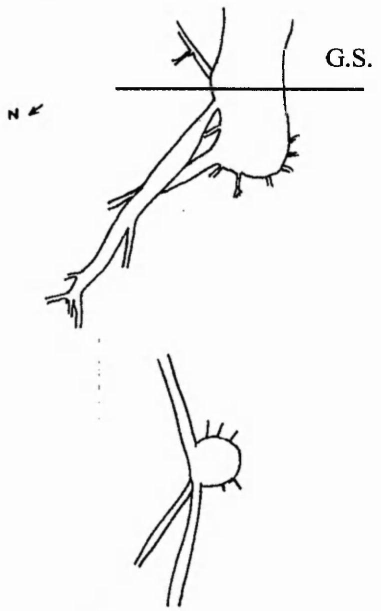
Rud2. Plan view. Stem diameter 170 mm. Slope angle 8°.



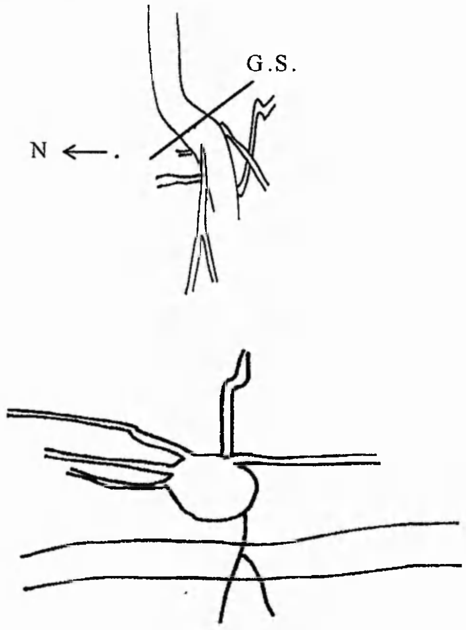
Rud3. Front view. Stem diameter 43.6 mm. Slope angle 22°.



Rud4. Plan view. Stem diameter 200 mm. Slope angle 24°.

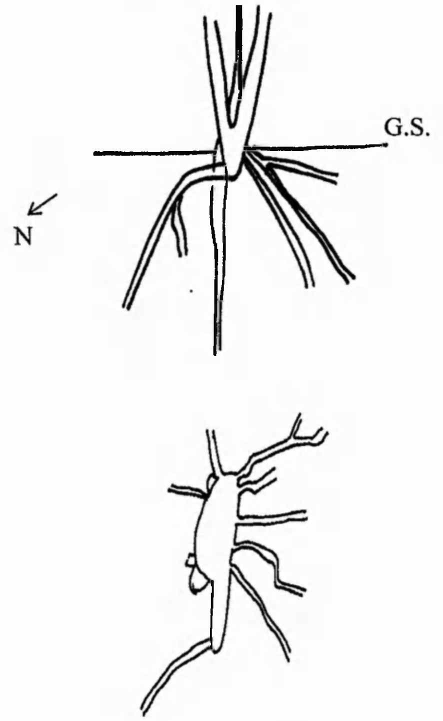


Rud5. Front and plan views. Stem diameter 35.3 mm. Slope angle 28°.

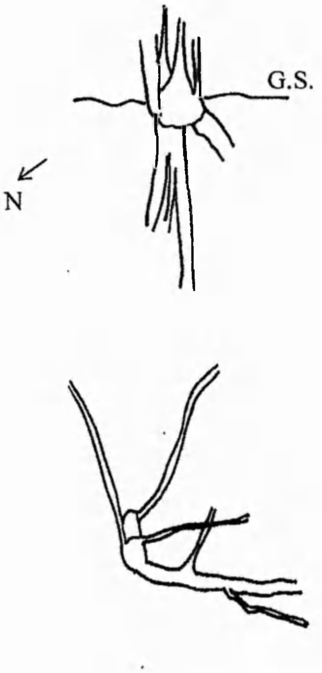


Rud6. Front and plan views. Stem diameter 32.0 mm. Slope angle 28°.

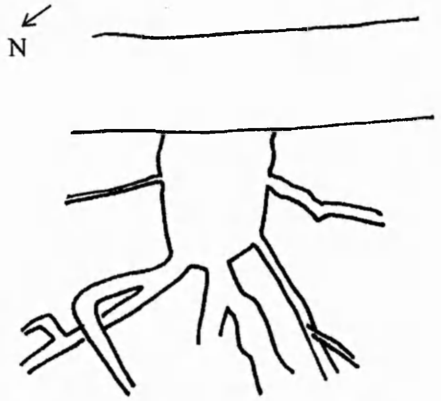
Figure 4.34. Schematic drawings of the twenty elder shrubs, showing wide variation in shape and form of the root systems. Key: G.S. – ground surface. Note: The stem diameter is the average diameter of the vertical and horizontal readings taken just above ground level.



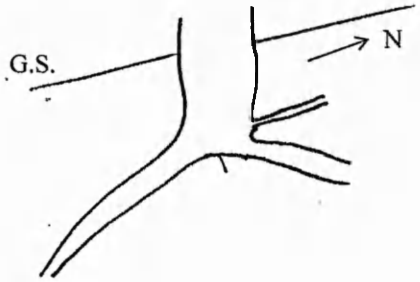
Rud7. Front and plan views. Stem diameter 27.4 mm. Slope angle 38°.



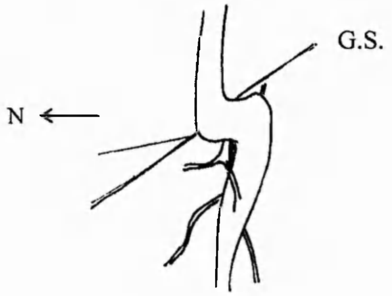
Rud12. Front and plan views. Stem diameter 51.87 mm. Slope angle 24°.



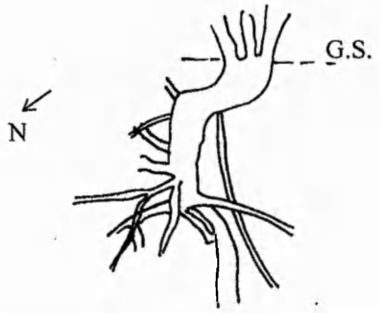
Rud11. Plan view. Stem diameter 86.2 mm. Slope angle 4°.



Rud13. Lateral view. Stem diameter 18.0 mm. Slope angle 28°.



Rud14. Front view. Stem diameter 22.4 mm. Slope angle 26°.



Rud16. Front view. Stem diameter 28.3 mm. Slope angle 40°.

Figure 4.34. continued.

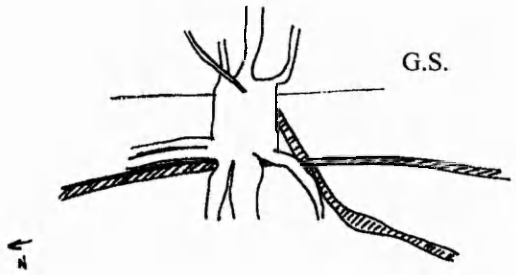
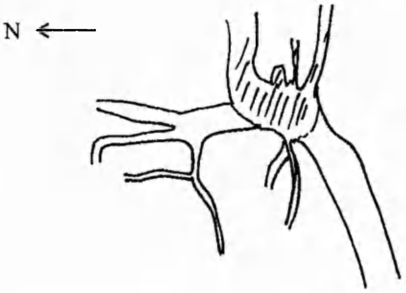
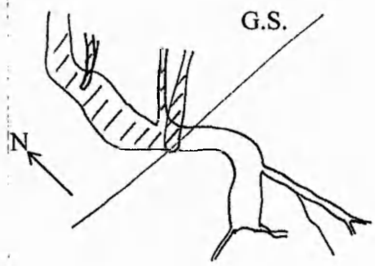
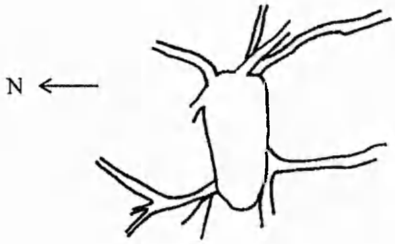
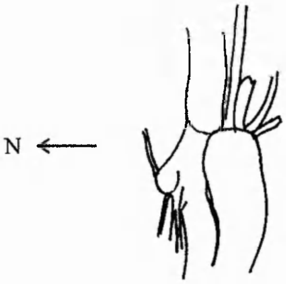
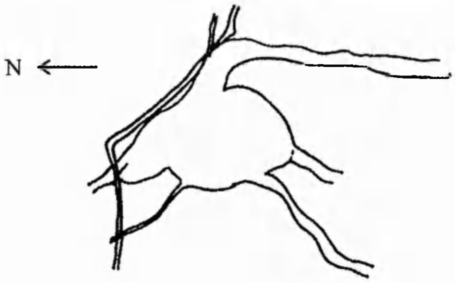
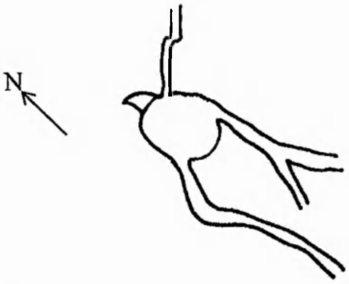
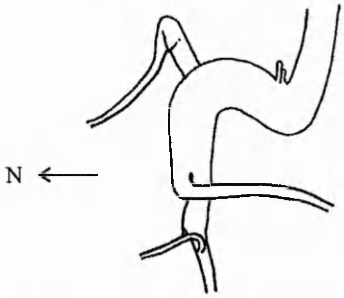
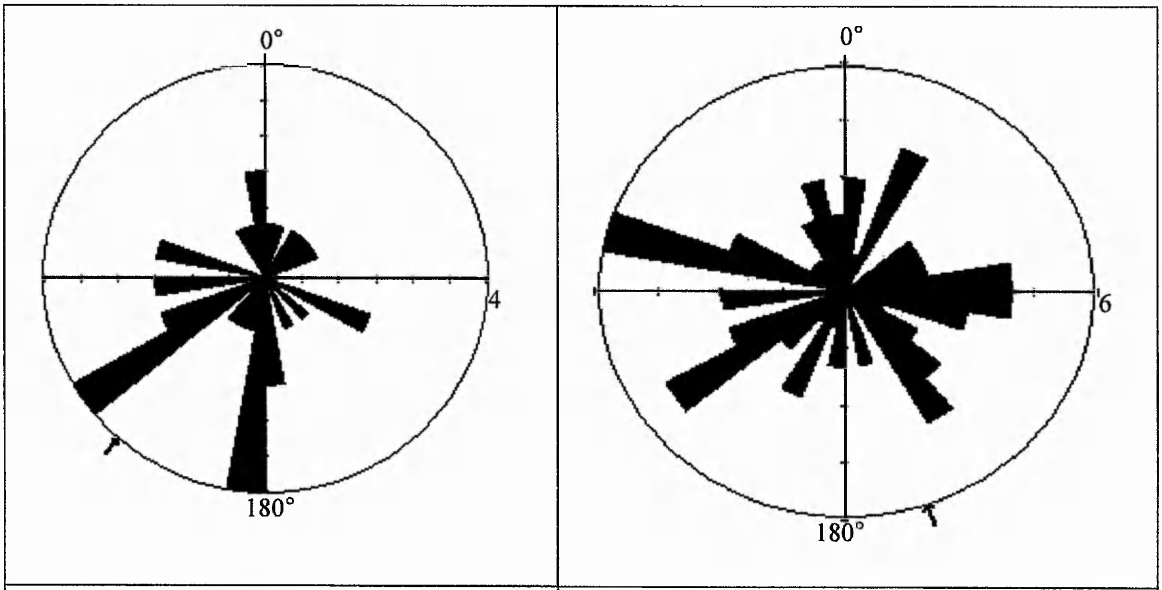
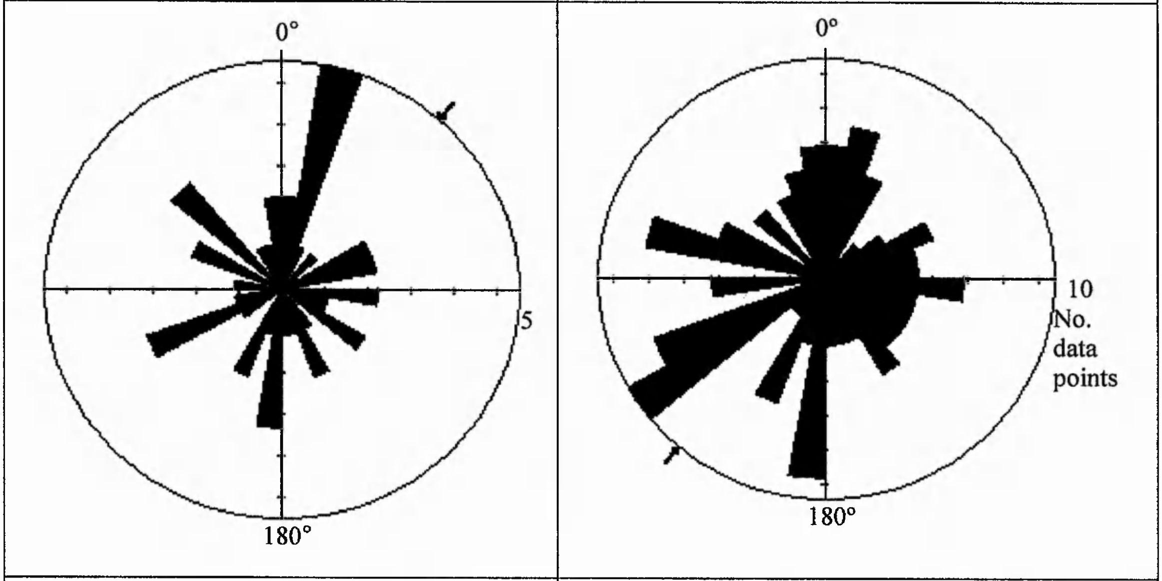
	
Rud17. Front view. Stem diameter 25.6 mm. Slope angle 28°.	Rud18. Front view. Stem diameter 64.6 mm. Slope angle 30°.
	
Rud19. Lateral view. Stem diameter 24.8 mm. Slope angle 30°.	Rud20. Plan view. Stem diameter 29.6 mm. Slope angle 42°.
	
Rud21. Front view. Stem diameter 82.1 mm. Slope angle 18°.	Rud22. Plan view. Stem diameter 63.5 mm. Slope angle 35°.
	
Rud23. Plan view. Stem diameter 53.1 mm. Slope angle 20°.	Rud24. Front view. Stem diameter 17.4 mm. Slope angle 36°.

Figure 4.34. continued.



(a) Flat slope (0-8°). Root direction of 3 shrubs. Mean root growth direction is 221°.

(b) Midslope (18-30°). Root direction of 12 shrubs. Mean root growth direction is 161°.



(c) Steep slope (35-42°). Root direction of 5 shrubs. Mean root growth direction is 041°.

(d) All shrubs. Mean root growth direction is 220°.

Figure 4.35. Variation of root growth direction of elder with slope angle. Arrows indicate the mean growth direction. Each sector has an angle of 10°. Upslope direction of the embankment is 295°.

4.6 Summary

Three study areas were selected for root strength and root architecture measurements. The location and soil parameters of the three study areas are described. The activity carried out on the three study areas is discussed and the results of this activity are presented. The factors and mechanisms of the root pull out resistance testing and laboratory tensile strength tests are discussed further in Chapters 5 and 6. The *in situ* shear tests are related to the well established root reinforcement models in Chapter 7. The patterns of root architecture in slopes are further discussed in Chapter 8. The results of the *in situ* shear tests, root pull out resistance tests, laboratory tensile strength tests and root distributions are applied to the limit equilibrium stability model in Chapter 9.

Chapter 5: The Uprooting Resistance of Roots

5.1 Introduction

The ability of plants to resist uprooting is vital for their own stability within the ground and also for the stability of the soil slope. In agriculture, uprooting or dislodging (uprooting by wind) is a common problem and has therefore seen a considerable amount of investigation (e.g. Ennos, 1990; Koinuma *et al.*, 1990; Ennos *et al.*, 1993; Goodman *et al.*, 2001; Bailey *et al.*, 2002). Forestors have investigated the uprooting resistance of trees to explain why some trees in forest stands uproot during gales (e.g. Stokes *et al.*, 1995, 1996; Cucchi *et al.*, 2004). The uprooting of vegetation on embankments or cut slopes is not in itself a major problem since there is no reason why the plants in these types of environments should pull out of the ground in this manner. However, many of these types of slopes are prone to shallow-seated landslides due to the unstable nature of the soil. Although plant roots have been shown to have a major reinforcing effect by providing tensile resistance to the soil slope (e.g. Gray and Sotir, 1996) and thus preventing landslides, very little investigation has been done to determine the pull out resistance of vegetation on landslides (Riestenberg, 1994; Schmidt *et al.*, 2001). If the tensile strength or pull out resistance of the roots of the plants can be determined, then valuable information may be obtained, which can be used in slope stability analysis methods, to thus provide greater certainty in the determination of the Factor of Safety of these types of slopes (see Chapter 9).

This chapter discusses the mechanics of uprooting and the factors associated with the variation in root strength and the behaviour of the root during uprooting.

5.2 Root anchorage

Roots play an important role in the reinforcement of soil especially on slopes, by providing tensile resistance and frictional or adhesive properties (O'Loughlin and Watson, 1979; Gray and Leiser, 1982; Greenway, 1987; Watson *et al.*, 1999). Shear stresses in the soil mobilise tensile resistance in the roots, which in turn imparts greater strength to the soil. Lateral roots in the soil mass transfer the shear stresses and solidify the soil matrix by preventing soil movement (Greenway, 1987).

The efficiency of tree roots in reinforcing a soil mass depends on the root tensile strength, the strength of the soil, the strength of the root-soil bond and the root system morphology. The mechanics of uprooting single roots and complex root systems are explained and the relationships to root system morphology and architecture are now discussed.

5.2.1 Mechanics of uprooting single roots

In its simplest form, a plant may have one root, the tap root, connected to its stem. When the root is pulled upwards, the top part of the root is stretched and shear stresses are set up between the root and the soil (Figure 5.1). Failure of the root-soil bond or of the soil itself will take place depending on their relative strengths. During pull out, tension is transferred from the root to the soil mass and uprooting is resisted through the soils' shear resistance. The greater the tension applied to the root, the greater the area of the root-soil bond that must be broken to resist uprooting, and the greater the length of root which will be stressed (Ennos, 1990). During pull out, the tensile strength of roots must be fully mobilised during failure, such that the frictional bond between the roots and the soil matrix exceeds the tensile strength of the roots. If the root is too short it will slip or pull out before mobilising the maximum tensile resistance and breaking in tension (Ennos, 1994). If the root system is subjected to sliding or pulling forces greater than the maximum resistance by the roots, roots will either break (failure in tension) or be pulled out of the soil (bonding failure). A residual shear force caused by friction between the root and the soil, or within the soil, occurs after failure (Clark, 2002).

In the Ennos (1990) model (Figure 5.1), the rate at which tension is transferred from the root to the soil is proportional to the area of the bond broken per unit length, i.e., the perimeter of the root, $2\pi R$ (perimeter of a cylinder). It is also proportional to the strength of the root-soil bond or soil, $\alpha\tau$ where α is the relative strength of the root-soil bond, α varies from 0 where no bond occurs to 1 (fully bonded) when the bond is stronger than the soil and the soil itself fails; τ is the soil strength. The tension in the root, T decreases with soil depth, X, such that:

$$dT/dX = 2\pi R\,\alpha\tau \qquad [5.1]$$

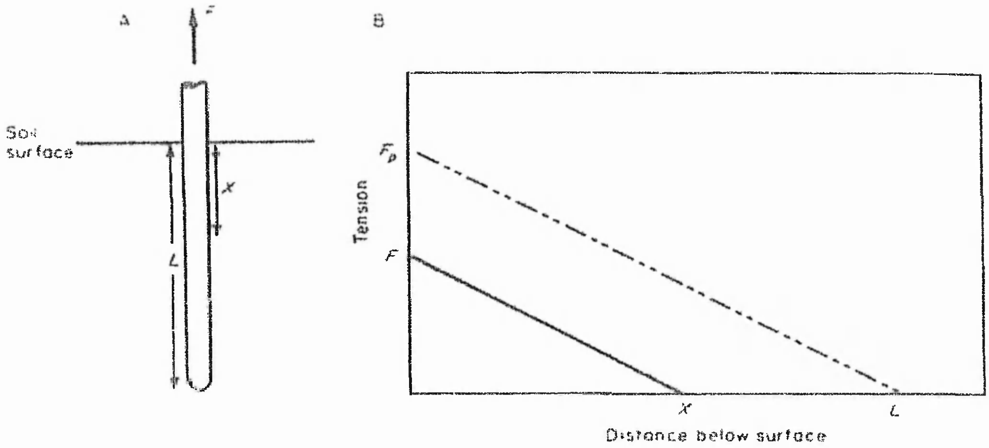


Figure 5.1. A. Mechanics of uprooting single roots. When a root is pulled upwards with a force F, the root-soil bond is initially broken to a depth X below the surface and tension is evenly transferred to the soil via shear. L is the total length of the embedded root.
B. Graph of the tension in the root against the distance below the soil surface when two different forces are applied. When a force F is applied (—) only a fraction of the root-soil bond is broken (X) and distal root areas are unstressed. When the root breaks along its entire length, L the maximum force, F_P (- - -) occurs (Ennos, 1990).

therefore the force, F required to break the root-soil bond to a depth X is given by

$$F = 2\pi R\ \alpha\tau X \qquad [5.2]$$

and the force, F_p required to break the bond along the entire root length, L and pull the root out is

$$F_p = 2\pi R\ \alpha\tau\ L \qquad [5.3]$$

Equation 5.3 implies that pull out resistance is greater for long thick roots embedded in strong soil.

Some roots cannot withstand the force required to pull out along their entire length, resulting in root breakage. The tensile breaking strength, F_B is proportional to the cross sectional area πR^2 and the tensile breaking stress, σ of the root, i.e.

$$F_B = \pi R^2\ \sigma \qquad [5.4]$$

Roots break rather than pull out when $F_p > F_B$ i.e. when $2\pi R\ \alpha\tau\ L > \pi R^2\ \sigma$, thus roots break when their length is greater than a critical length L_{crit}, where

$$L_{crit} = \sigma R / 2\alpha\tau \qquad [5.5]$$

The uprooting model of Ennos (1990) was based on the uprooting resistance of leek seedlings. This model assumed that the root had a constant radius with elastic properties (Young's modulus, E) and the soil behaves as a rigid/plastic solid with infinitely high shear stiffness and shear strength. The model predicts that:

a) the anchorage force provided by roots will be proportional to their length but only up to a critical length (L_{crit}) above which the roots will break before lower regions are stretched. Short roots will pull out while long ones will break (Figure 5.2).

b) roots in weaker soil should provide less anchorage force per unit length than those in stronger soil, where L_{crit} will be greater.

c) the critical length of roots is proportional to their radius.

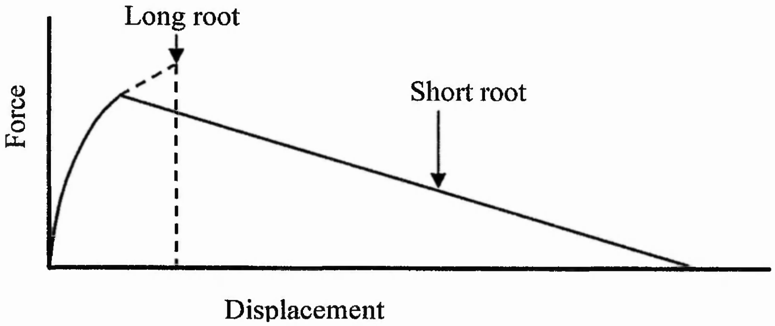


Figure 5.2. Predicted shape of the force-displacement curve for a long and a short root. Long roots break while short roots are pulled out and maintain residual force (pull out resistance) until they are pulled fully out of the ground (after Ennos, 1990).

5.2.2 Mechanics of uprooting complex root systems

Ennos' (1990) model only addressed the mechanics of uprooting single (non-branching) roots of leek seedlings. In reality, most plants have a complex root system of single and branching roots. Stokes *et al.* (1996) and Hamza *et al.* (2006) have modelled the uprooting resistance of different branching patterns of roots by using root analogues. Stokes *et al.* (1996) used wire models buried in wet sand while Hamza *et al.* (2006) used Vitron rubber (diameter 1.7 mm, Youngs' Modulus 7 MPa) in agricultural soil. The forces acting on branched roots are shown in Figure 5.3.

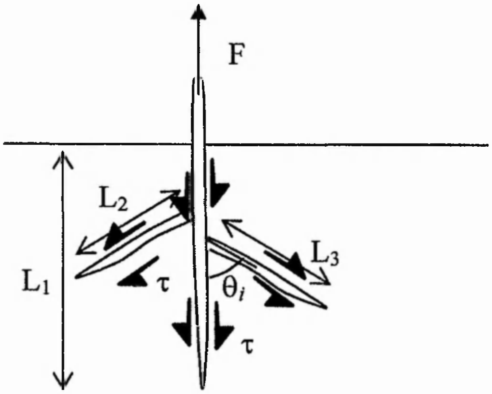


Figure 5.3. Forces resisting pull out on a laterally branched root system. L_i – length of individual roots; F – force to pull out the root system; τ – shear force, θ_i – branch angle (after Hamza *et al.*, 2006).

Stokes *et al.* (1996) developed the following pull out model for all types of root branching patterns and single axis roots:

$$F = a + bV + cH + dD_lH \qquad [5.6]$$

where F = force to pull out the root system; *a* = constant parameter (dimension force); *b* and *c* = scaling parameters (dimension force/unit length); *d* = scaling parameter (dimension force/unit area); D_l = length of the main axis; V = total vertical component of root length i.e. the length of the main axis (D_l) plus the vertical projection of the second order lateral (L_2 sinθ), $V = D_l + L_2 \sin\theta$; H = total horizontal component of root length, i.e. the length of the first order lateral (L_1) plus the horizontal projection of the second order lateral (L_2 cosθ), $H = L_1 + L_2 \cos\theta$; θ = angle between the first and second order laterals.

Stokes *et al.*'s (1996) model was based on the assumptions that a depth (vertical) component and horizontal component act independently and additively, with an additional variable which takes into account the depth of the lateral roots acting on a 'slice' of soil. The 'slice' has height D_l, the width is dependent on the length of the laterals ($L_l + L_2 \cos\theta$) and its weight is proportional to the total area of the slice, D_lH. The variables have appropriate scaling parameters and constants.

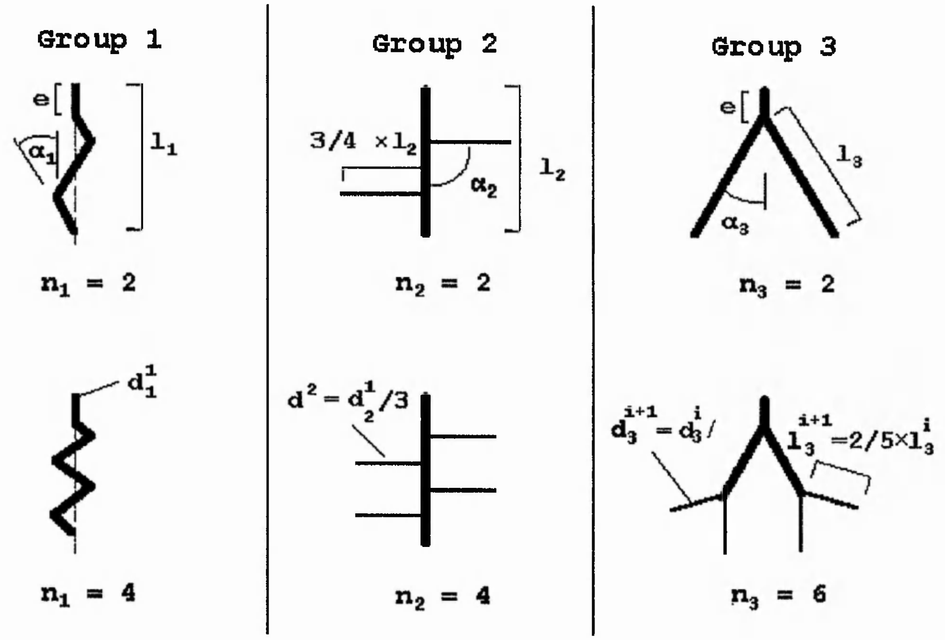


Figure 5.4. Three groups of root patterns used for numerical modelling analysis. Group 1 consisted of non-branching structures, Group 2 of 'herringbone-like' root systems and Group 3 of dichotomous-like root systems. n_i represents the number of secondary segments, l_i represents the distance used to calculate the length of the secondary segment, α_i represents the angle between a segment and the vertical axis. The ratio between the diameter of a root d_o and its daughter d_{o+1} remained constant (Dupuy *et al.*, 2004).

Numerical modelling of the uprooting resistance of different root branching patterns has been carried out (Dupuy *et al.*, 2004). By modelling the root systems (Figure 5.4) in this way, Dupuy *et al.* (2004) found that the number of roots and the diameter of the roots were the major components affecting uprooting resistance while the combination of topology and biomass could be used to explain the variation of tensile resistance. Image analysis of pull out tests on seedlings of pea and maize carried out to investigate the plant-soil mechanical interactions show strains in the roots that have not previously been observed (Hamza *et al.*, 2006).

Dupuy *et al.* (2004) and Hamza *et al.* (2006) found that taproot systems with no laterals have the lowest pull-out capacity (Group 1 in Figure 5.4), whereas root systems with lateral branches require larger forces to be pulled out of the ground.

The uprooting plant and model tests carried out by Ennos *et al.* (1993), Stokes *et al.* (1996) and Hamza *et al.* (2006) were all performed under controlled laboratory conditions. In nature, roots and soil exist in a heterogeneous environment which is considerably influenced by climate and environmental conditions, therefore it is expected that some aspects of uprooting will differ considerably from the root analogues and numerically modelled tests.

5.3 The relationship of root morphology to root reinforcement

Analysis of the root pull out resistance tests (see Section 4.5.1.2), revealed that the shape of the failure curve and the amount of resistance to pull out can be related to the morphology of the root and its architecture. This relationship was also observed by Ennos (1990), Riestenberg (1994), Zhou *et al.* (1998) and Norris (2005).

Zhou *et al.* (1998) in a series of pulling tests on roots of *Pinus yunnanensis* found that straight roots were easier to extract from soil than root segments of the same length which were twisted or irregular, while Ennos (1990) showed that short roots are more likely to pull whole out of the ground and maintain a residual shear force while long roots break, as in Figure 5.1. From pull out experiments on woody roots during this research, it was noticed that this model was not always true with longer roots actually pulling fully out of the ground and maintaining a residual force (Figure 5.5), and the shorter roots breaking and having minimal residual shear. Schmidt *et al.* (2001) also observed this phenomena on landslides in Oregon recording that 'larger diameter roots tend to slip through the soil matrix without breaking'. Ennos' (1990) model is therefore probably only applicable to seedlings or non woody roots and not woody branching root systems.

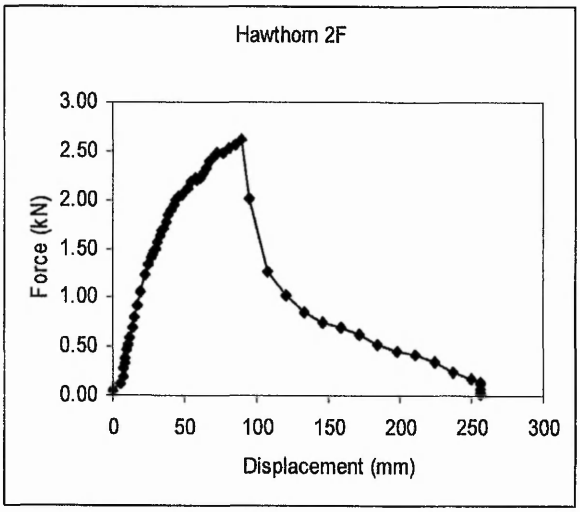


Figure 5.5. Graph of pull out failure of a single hawthorn root showing residual force (resistance) after peak failure. (H2F, length 967 mm, root diameter 24.5 mm at clamp)

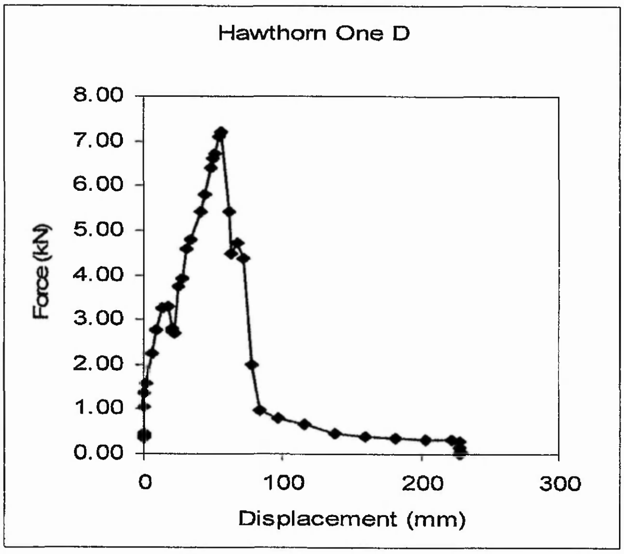


Figure 5.6. Graph to show pull out failure of a branched hawthorn root with lateral roots breaking before the root completely failed. (H1D, length 1380 mm, root diameter at clamp 31.2 mm)

Figures 5.5 and 5.6 show the variation in the form of the pull out failure curves with single and branched root systems. The failure of lateral roots from a multibranched root are observed by significant drops in force in Figure 5.6. The morphology of the hawthorn roots can be correlated to the failure curves (Figure 5.7), where three different types of failure (Type A, B and C) can be recognised (Norris, 2005). In Type A failures, e.g., Root H2C, the applied force (pull-out resistance) initially rises linearly with displacement to a peak force at displacements of 50 – 100 mm. The initial peak is then followed by a rapid reduction of force until there is no resistance and the root completely pulls out of the ground. In Type B failures e.g., Root H3E, the initial peak is followed by a continued high resistance (force) leading to a second peak failure. In Type C failure, e.g., Root H3N, pull-out resistance increases progressively as a series of stepped peaks to a final maximum peak. The stepped peaks corresponding to the failure of lateral root branches.

Type A failure generally relates to roots of a long length (> 0.7 m) with no or few branches. Type B failures tend to relate to roots that are highly branched or forked. Forked roots diverge into two major branches, at angles of approximately 45°. Type C failures relate to roots of a multibranched nature with significant lateral root branches failing before the main root. The three types of failure curves can be summarised in Figure 5.8.

The three types of failure modes of the hawthorn roots can be related to different root-soil relationships. The roots which have no branches tend to fail in tension and pull straight out of the ground with minimal resistance (Type A; Figure 5.8). The root reaches its maximum pull-out resistance then fails suddenly at a weak point along its length. Weak points may be at a node or branch. The gradual tapering of roots (decrease in root diameter along its length) in the ground means that as the root is pulled out, the root is moving through cavity space larger than its diameter so subsequently has no further bond or interaction with the surrounding soil.

Roots that have multiple branches or forked branches (Type B), typically have a tensile failure but also tend to fail in stages as each branch breaks within the soil. These types of roots either break with increasing applied tensile force in steps or

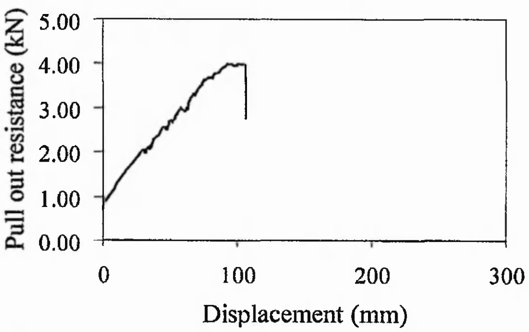
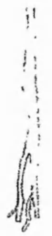
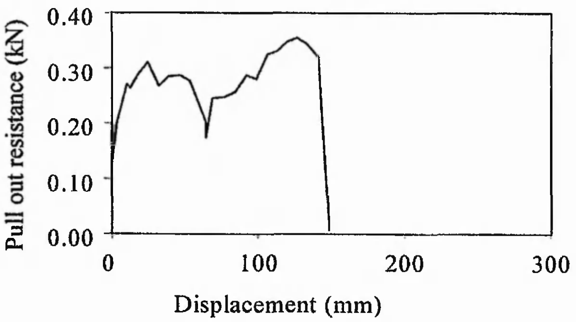
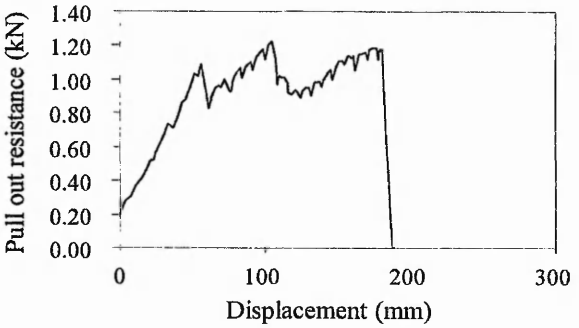
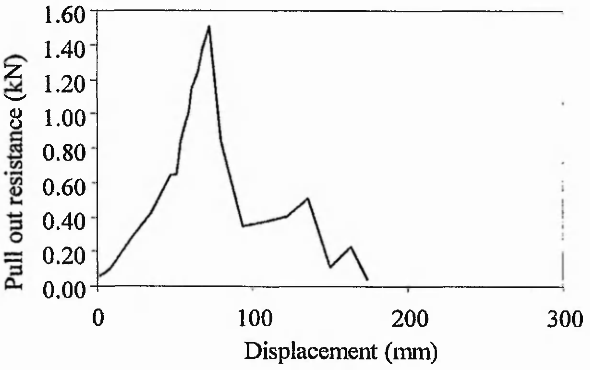
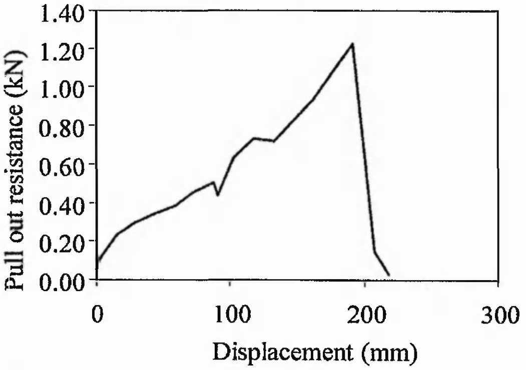
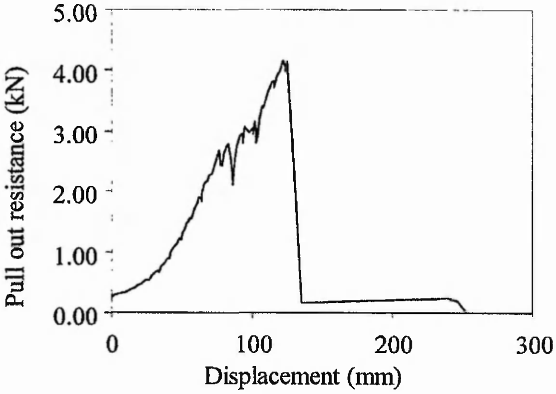
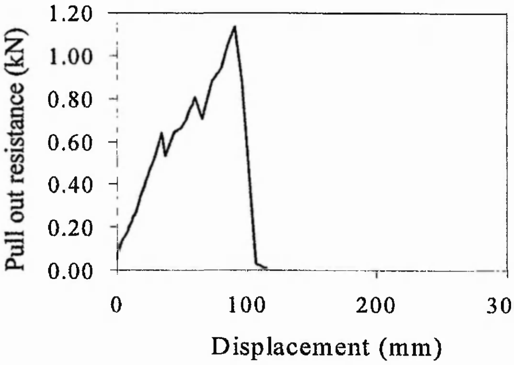
Failure curve	Root morphology	Failure Type
	Root ID: H2C d = 26.7 mm ℓ_T = 1610 mm	Type A.
	Root ID: H3E d = 7.4 mm ℓ_T = 745 mm	Type B.
	Root ID: H5D d = 26.8 mm ℓ_T = 762 mm	Type B.
	Root ID: H3L d = 15 mm ℓ_T = 362 mm	Type B.

Figure 5.7. Examples of types of root failure and associated root morphologies of pull out tests on hawthorn roots.

Failure curve	Root morphology	Failure Type
	 Root ID: H3N d = 11.2 mm ℓ_T = 885 mm	Type C.
	 Root ID: H5C d = 28.2 mm ℓ_T = 1167 mm	Type C.
	 Root ID: H1C d = 19.6 mm ℓ_T = 245 mm	Type C.

d = root diameter (at top of drawing), ℓ_T = total root length.

Figure 5.7. Examples of types of root failure and associated root morphologies of pull out tests on hawthorn roots. Key: d = root diameter (at top of drawing), ℓ_T = total root length.

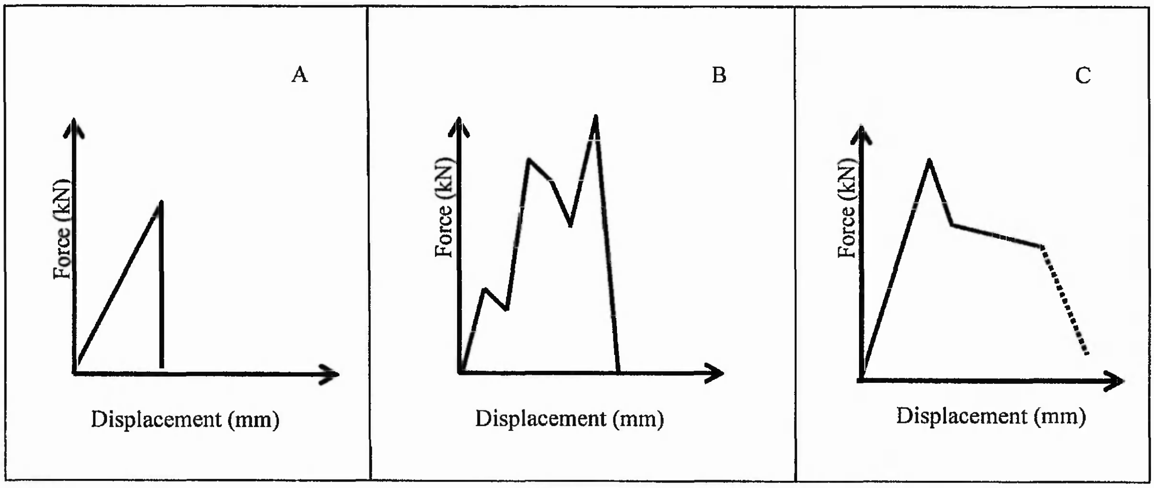


Figure 5.8. Force-displacement relationships as observed during root pull out tests of hawthorn. Peak force varies from 0.5 – 15 kN and displacements are recorded up to 800 mm. A. Single root has a rapid increase in pull out resistance then fails suddenly in tension and has no further bond with the surrounding soil. B. A forked or multi-branched root fails in stages maintaining pull out resistance until ultimate failure. C. A root with lateral branches reaches its maximum pull out resistance on straightening and fails at its weakest point, however in this case, it does not fail suddenly and pull straight out of the ground, it adheres and interacts with the soil producing a residual strength (modified from Norris and Greenwood, 2003b).

initially reach their maximum peak resistance then maintain a high resistance, which gradually reduces as the root branches fail after considerable strain. In some tests, significant adhesion between a section of the root and the soil can be measured before the root finally slips out of the soil mass (Clark, 2002). Forked roots resist failure as the increased root diameter at the point of the fork is larger than the root diameter above the fork, therefore more force is required to pull the root out of the soil. The clay soil was often uplifted and displaced during pull-out testing of forked roots, these observations agree with Mickovski and Ennos (2003) during the pull out testing of cone shaped models (see Section 5.4.1).

Multiple branched root failure (Type C; Figure 5.8) in the form of stepped peaks corresponded to roots of greater diameters breaking sequentially. The root gradually releases its bonds with the soil until the final tensile failure. In some cases, when the root is of a sinusoidal nature and has many small diameter rootlets along its length, the root reaches its maximum pull-out resistance on straightening and fails at its weakest point e.g., node or branch point. However in this case, it does not fail suddenly or pull straight out of the ground, it adheres and interacts with the soil producing a residual strength. If the pulling was stopped at this point, the root would provide additional strength to the soil. Since, the root is pulled completely out of the ground, there is no further interaction with the soil (Norris and Greenwood, 2003b; Greenwood *et al.*, 2004).

These modes of failures (Types A, B and C) are based on the shape of the failure curve and root morphology. In some cases, the shape of the failure curve may not be that distinct and relating branch failure points to drops in resistance is not straightforward, as proven by the non-significant relationship between number of branches and pull-out failure stress.

Riestenberg (1994) also devised three categories of failure curves relating to root morphology for pull out resistance tests on roots of maple and ash trees (Figure 5.9). Some similarities exist between the two classifications (Table 5.1), the main difference being that the length of the hawthorn roots did not influence the type of failure whereas the length of the maple and ash roots depicted either a type I or II failure.

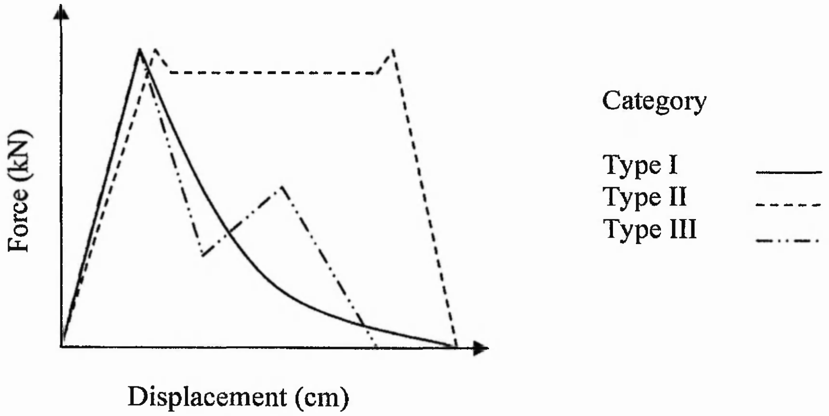


Figure 5.9. Schematic plot to show the relationship between the three categories of root morphology and their force-displacement curves (after Riestenberg, 1994). Type I roots were long, straight segments with few to moderate numbers of branches, Type II roots were short and highly branched, and Type III roots forked into two major branches.

Table 5.1. Comparison between Riestenberg's (1994) and Norris' (2005) category of root morphology and failure curve.

Type	Riestenberg (1994)	Norris (2005)
I or A	Long, straight segmented roots with few to moderate numbers of branches	Generally long lengths of root with no or few branches
II or B	Short and highly branched (feathery-type branching)	Multi-branched or forked roots with stepped failure (not feathery)
III or C	Forked roots	Multi-branched root failure with residual strength

5.4 Factors controlling the uprooting of roots and plants

The mechanics of uprooting was explained in Section 5.2 and although in itself a simple operation, many factors may have a greater or lesser effect on the resistance of the plant or root to pull out. The factors such as shape, length, number of branches, diameter, soil type and moisture content are discussed below, relating practical experience with published literature.

5.4.1 Shape and diameter

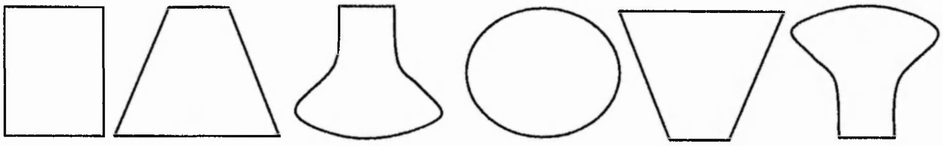


Figure 5.10. Model bulb shapes used in uprooting resistance tests, from left to right: cylinder, cone, onion-shaped bulb, sphere, inverted cone and inverted onion-shaped bulb. Each model had a maximum diameter of 33 mm (after Mickovski and Ennos, 2003).

Mickovski and Ennos (2003) modelled the uprooting of different shaped bulbs by making plasticine moulds (Figure 5.10) and embedding them in sand and agricultural soil to depths of 50, 70 and 100 mm. They found that the most resistant shaped model bulb to uprooting was the cone, followed by the 'onion'-shaped bulb and the cylinder. The least resistant was the inverted 'onion'-shaped bulb. The resistance of all model bulbs to uprooting increased when depth of embedment increased. The inverted cone model bulb showed the greatest increase in uprooting resistance with depth whereas the cylindrical model bulb was least affected by the change in embedment depth. An increase in bulb diameter showed an increase in the amount of uprooting force, as would be predicted.

The conical shaped bulb proved to be most resistant to uprooting since its maximum diameter is located at the furthest point from the soil surface, therefore there is greater pressure around the base of the cone and a greater area of soil above the cone to shear (Mickovski and Ennos, 2003).

5.4.2 Length

Root length was shown by Riestenberg (1994) and Stokes *et al.* (1996) to affect uprooting resistance. In pull out tests of hawthorn, oak and rowan roots, a non-significant relationship exists between root length and pull out resistance (Figure 4.16), although there is a general trend for longer lengths of root to have a greater pull out resistance than short root lengths.

In certain cases, as predicted by the single root model (see Section 5.2.1), there exists a critical length of root needed for the maximum tensile resistance to take effect.

5.4.3 Number of branches

Dupuy *et al.* (2004) numerically modelled non-branching and branching root systems. These authors found that single non-branching roots have less effective resistance than branching root systems. Norris (2005) found the mean pull-out resistances for the three failure types of roots, as described in Section 5.3, to be greater for single roots than multiple branched roots. Norris (2005) described the difference in observations due to the fixed arrangement of the root system branches in Dupuy *et al.*'s (2004) models which do not represent the type of morphologies and variation in root diameters as depicted by the hawthorn roots. Additionally, these observations were based on the recovered roots only, for instance what appeared to be a single root on uprooting may actually have been a forked or multi-branched root as the root during pull out may have failed at this branch (weak) point, thus leaving its daughter branches in the ground.

5.4.4 Depth

Stokes *et al.* (1996) and Mickovski and Ennos (2003) showed from experiments with models that uprooting resistance increases with embedment depth.

5.4.5 Soil type, moisture content and strength

Soil moisture content is known to have an effect on uprooting resistance (Ennos, 1990). Uprooting tests of leek seedlings in wet and dry soil showed that roots were more resistant to uprooting in dry soil than wet soil (Ennos, 1990). Failure by slipping would be much easier in wet soil rather than dry soil as high moisture content of the soil would reduce soil strength thereby reducing the roots resistance and hence slide through the soil.

The shearing resistance of a soil affects the amount of uprooting resistance. The bulb models, of Mickovski and Ennos (2003), uprooted in sand produced small soil failure bodies and local shear failures on the surface. The weight of these failure bodies only marginally increased uprooting resistance. In their experiments using agricultural soil, the uprooting force caused a curved shearing surface to occur above the model, with the shearing resistance of the soil only contributing slightly to the uprooting resistance.

5.4.6 Positions of root and soil breakage

Coutts (1983a) developed a simple theoretical model for determining the position of failure of a root. This model assumed three root arrangements. The first arrangement shows an unbranched (cylindrical) root of uniform diameter buried in soil over an indefinite length, which is under an applied tensile load from end A (Figure 5.11a). The tensile force will stretch the root. Root-soil resistance is proportional to the distance AB (length of root) and at some point along the root the root-soil resistance

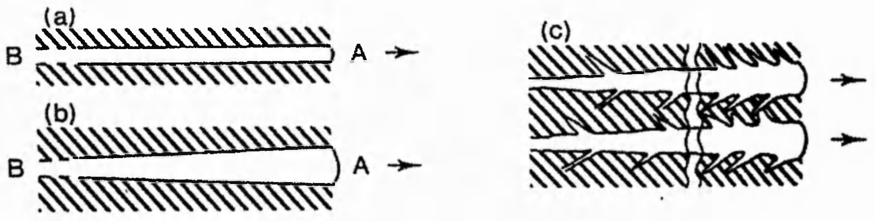


Figure 5.11. Root and soil behaviour when force is applied to (a) unbranched cylindrical roots, (b) unbranched tapered roots and (c) branched tapered roots (Coutts, 1983a).

equals the applied load. No strain will occur beyond that point. Maximum strain and therefore failure will occur where there is no root-soil resistance, i.e. at A.

In the second arrangement (Figure 5.11b), the root tapers from the point where the load is applied and the distribution of strain is determined by the root-soil resistance and the root cross sectional area. Under an applied load, strain increases with distance from A as the root decreases in diameter but subsequently decreases again as root-soil resistance increases with distance from A. There is a point of maximum strain between A and B where the root will break.

The third arrangement assumed a large amount of branched roots are present (Figure 5.11c). Root-soil resistance will exceed the tensile strength of the soil. The applied load causes the root-soil mass in this reinforced region to behave as a unit. When the amount of root material diminishes to give a root-soil resistance less than the soil strength, strain will first cause fracture of the soil, because of its low elasticity. After the soil has fractured the force may be considered to act on the roots so that roots will break distal to the soil fracture and project from the broken soil surface.

5.4.7 Obstructions

Roots grow in a very heterogeneous environment and as such come into contact with many obstructions, for instance stones, pipes and roots of other plants, for example, one hawthorn root from Site 2 (Root H5E) could not be uprooted as it was bound by

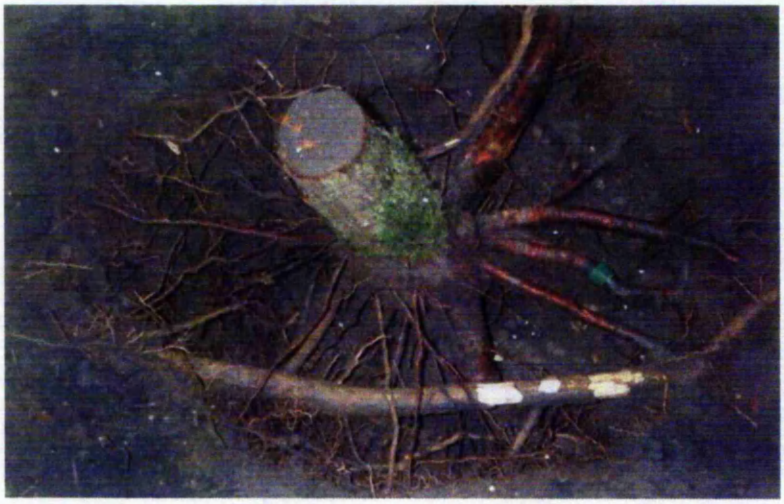


Figure 5.12. Hawthorn root system interacting with roots (white bark) of a nearby ash tree (Site 2: M11 H5).

a root from a nearby ash tree (Figure 5.12). These obstructions may serve as anchors to the plant as the root interacts or grows around the obstruction, resulting in a barrier to uprooting and stabilisation against gale force winds. Shtein (1996) studied the interaction of vertically growing roots with a rigid obstacle, showing that the root tip on encountering the obstacle curves, the growth rate of the root decreases and due to the change in direction of movement differential growth of the root occurs. Differential growth leads to higher concentrations of cellulose or lignin in different parts of the root thus altering the strength of the root (Stokes and Mattheck, 1996; Genet *et al.*, 2005).

5.4.8 Root-soil bond

The nature of the root-soil bond is probably one of the most unknown factors in plant physiology and bioengineering. The bark is the only part of the root that is in contact with the soil. The root-soil interface may be surrounded by mycorrhizas (fungal associations) which may serve to enhance or destroy the root-soil bond. During pull out tests of the oak roots, many of the oak roots lost their bark during pull-out, thus indicating a greater adhesion between the bark and the soil than between the bark and the stele (inner root core). Roots of hawthorn on the other hand, had intact bark with smeared clay on the surface. The presence of surface features on the bark, i.e. ridges may promote resistance to uprooting.

5.5 Tensile strength of roots

The results of the tensile stress tests of hawthorn and elder roots revealed a negative relationship between decreasing tensile stress and increasing root diameter. This relationship is consistent with that observed by other authors e.g. Nilaweera and Nutalaya, 1999; Genet *et al.*, 2005. The tensile strength of a root is the maximum tensile stress at failure.

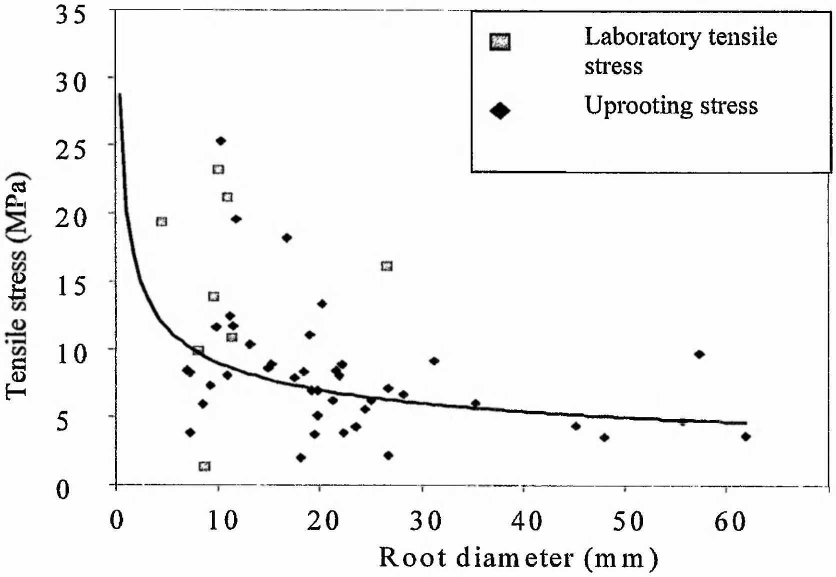


Figure 5.13. Comparison between the laboratory determined tensile stress and the uprooting tensile stress of hawthorn roots.

5.5.1 Relationship between pull out stress and laboratory tensile strength

A comparison of the tensile strength and pull out stress of hawthorn roots showed that the average failure stress was significantly greater for laboratory test specimens (15.5 MPa) than *in situ* roots (8.1 MPa). The laboratory test results do however fit the pattern observed by the pull out test roots (Figure 5.13). The variation in results may be explained by the following: in the pull out test, the applied force acting on the root acts over a much greater root area (multiple branches, longer lengths) than the short ~150 mm length of root used in the tensile strength test. The failure condition in the pull out test is likely to be initiated at weak points within the root system, i.e. branching points, nodes or damaged areas, as opposed to the forced failure within the restricted length of the tensile test specimen. The pull out failure stress is always going to be lower than the actual tensile strength of the roots. Experience in the field confirms this as the pull-out stress was within 50-70% of the tensile strength (Norris, 2005).

5.6 Factors controlling root strength

5.6.1 Species variation / mechanical role of a root

Root strength varies enormously not only between inter-and intra-species but also within the same root system, depending on the environment and mechanical role of the root. The forces acting on that root will cause a change in the root wood strength; e.g. leeward roots are more resistant to breaking than windward roots. The increase in strength has been attributed to a greater lignin content in these roots (Stokes *et al.*, 1998; Genet *et al.*, 2005). Root strength may even increase at certain points along a root in order to resist rupture as that root repeatedly bends during natural 'rocking' by the wind (Stokes and Mattheck, 1996; Stokes, 1999).

For alder and pine trees growing on slopes, tensile strength has been found to be greater in uphill roots than in downhill and horizontal lateral roots (Table 5.2, Schiechtl, 1980). Chiatante *et al.* (2003a) investigated the wood content of lateral roots of *Spartium junceum*, they found that the up slope lateral roots had a higher percentage of sclerenchyma fibres with respect to downslope lateral roots. These sclerenchyma fibres were not apparently lignified as they did not stain with a lignin stain. These fibres may account for the increase in the tensile strength of upslope roots although in reality there is probably very little difference between up and down slope roots. Norris (2005) showed that there is very little variation in tensile root strength between uphill (8.1 MPa) and downhill (8.2 MPa) hawthorn roots.

Fluctuations in tensile strength may be related to variation of lignin/cellulose ratio which is under seasonal and or abiotic factors such as mechanical stress (Hathaway and Penny, 1975; Plomìon *et al.*, 2001; Genet *et al.*, 2005). In tension wood the overall lignin content is lower, the cellulose content is higher and the microfibril angle is lower than that of corresponding normal wood.

Table 5.2. Variation in tensile strength of uphill and downhill roots (Schiechtl, 1980).

Plant Species	Tensile Strength (MPa)			No. of samples
	Minimum	Maximum	Mean	
Grey Alder (*Alnus incana*)				
Uphill	10.6	55.5	32.8	28
Downhill	6.9	56.2	28.3	10
Japanese Alder (*Alnus japonica*)				
Uphill	12.5	90.5	42.0	24
Downhill	17.2	73.8	40.1	25
Japanese Red Pine (*Pinus densiflora*)				
Uphill	30.9	71.2	47.6	6
Downhill	12.7	33.8	24.8	9
Horizontal	8.9	41.6	28.4	5

5.6.2 Root elasticity/stiffness

Root elasticity or stiffness is related to the moisture content of the root. Elder roots, with high root moisture contents (up to 400%) also had high Young's Modulus values (up to 1861 MPa) and were less woody in their structure. Hawthorn roots with moisture contents between 50-175% had low Young's modulus values (up to 205 MPa). When compared to the elasticity of common materials (Table 5.3), both elder and hawthorn roots have similar elastic properties as rubber.

Table 5.3. Elasticity of some common materials (modified from The Engineering Tool Box, 2005).

Material	Young's modulus, Elasticity (GPa*)
Rubber	0.01-0.1
Nylon	2-4
Oak wood	11
Iron and Steel	190-210
Douglas-fir	13
Hawthorn roots	Range of mean values 0.057 – 0.075
Elder roots	Mean value 0.18

1 GPa = 1 x 10^9 Pa.

5.6.3 Root diameter

Root diameter can influence tensile strength per unit of cross sectional area (Turmanina, 1965; Hathaway and Penny, 1975; Burroughs and Thomas, 1977; Waldron and Dakessian, 1981). The cortex or bark contributes little towards root strength (Coutts, 1983a; Norris and Greenwood, 2003b). Tensile strength decreases with increasing root (diameter) size due to differences in root structure, with smaller/younger roots possessing more cellulose than thicker/older roots, cellulose being more resistant than lignin in tension (Turmanina, 1965; Commandeur and Pyles, 1991; Genet *et al.*, 2005).

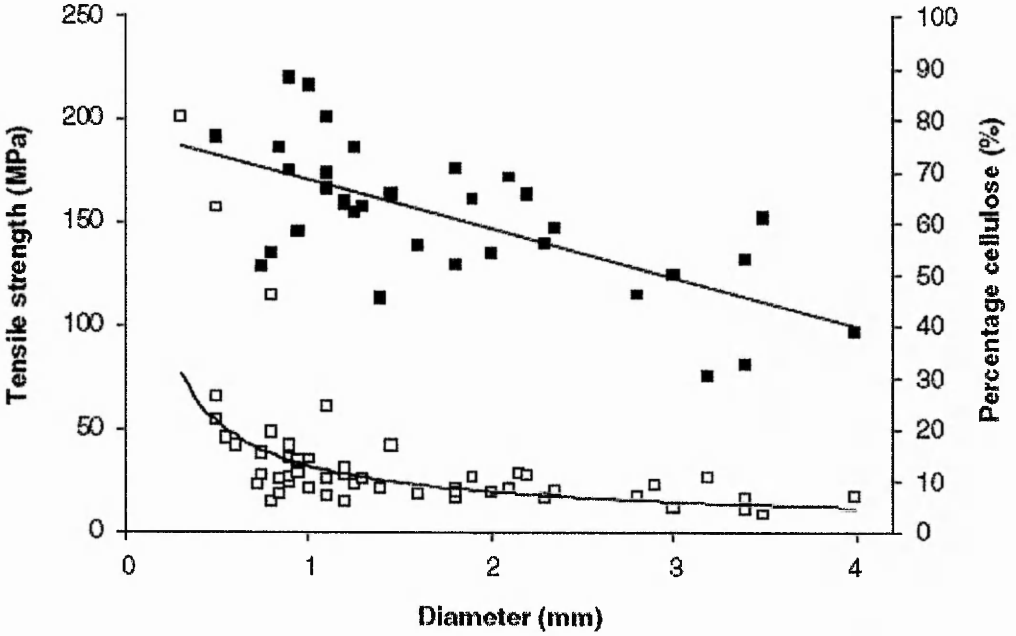


Figure 5.14. Tensile strength (white squares) and cellulose content (black squares) decreased significantly with increasing root diameter in roots of Sweet chestnut (Genet *et al.*, 2005).

Contrary to the increase in tensile strength with decreasing root size, compression and bending strength decrease with decreasing root size. This is more pronounced in species with heart and taproot systems compared to lateral roots from trees with plate root systems (Stokes and Mattheck, 1996; Stokes and Guitard, 1997).

5.6.4 Mode of planting

Plants may be grown either direct from seeding on site, by transplanting seedlings originally sown in containers, or planting of bare-root seedlings and transplanting of cuttings (bare-root or in containers). The mode of planting influences the mechanical stability and up rooting resistance of the plant and hence the root strength. It is considered that naturally regenerated and direct sown seedlings are the most mechanically stable and the more difficult to uproot (Halter and Chanway, 1993; Lindström and Rune, 1999) due to a well-developed and undisturbed root system. Container grown seedlings often have a limited root system, with lateral roots spiralling around the container (Lindström and Rune, 1999). Lindström and Rune (1999) showed that naturally regenerated Scots pine had roots more resistant in tension than those of planted pines, therefore to ensure both tree and slope stability naturally regenerated pines would be more beneficial.

5.6.5 Soil environment

The nature of the soil environment can influence the strength of roots, for example roots of maize (*Zea mays*) growing in a weak soil were stiffer than those growing in strong soil (Goodman and Ennos, 1999).

5.6.6 Seasonal variation

The seasonal climate change has an effect on the strength of roots throughout the year. Roots have a greater tensile strength during the winter months than in summer, due to the decrease in water content (Turmanina, 1965; Hathaway and Penny, 1975).

5.7 Summary

The mechanics of uprooting single and complex root systems have been described and are related to root architecture. A new classification scheme for relating failure mechanisms to root architecture was proposed and published (Norris, 2005). The factors that control the behaviour and up rooting strength of plants and roots are explained. The laboratory tensile strength data is compared with the pull out resistance data showing that the pull out resistance under-estimates the full tensile strength of the root. The large-scale variation in root tensile strength is attributed to the anatomical differences in the structure of the root, in particular the cellulose and lignin content.

Chapter 6: Effects of Removing Vegetation on Slope Stability

6.1 Introduction

Timber harvesting, clear cutting or large-scale removal of vegetation can potentially affect hillslope stability by reducing root reinforcement within the shallow substrate by root-wood deterioration (e.g. Watson *et al.*, 1999) and to a lesser extent temporarily increasing water input and soil moisture because of reduced evapotranspiration (Bethlahmy, 1962). On steep and potentially unstable slopes, a portion of the shear strength of the surface mantle of soil may be provided by the root structure. Sidle *et al.* (1985) considered that root systems contribute to the soil strength by providing an apparent cohesion with negligible influence on the frictional component of strength. Overall slope stability can be significantly increased by root reinforcement of the soil.

Increases in the frequency of small landslides have been associated with gradual decay of small tree roots following timber harvests in conifer forests (Burroughs and Thomas, 1977; Ziemer and Swanston, 1977; Wu and Swanston, 1980; Ziemer, 1981; Sidle and Swanston, 1982; O'Loughlin and Ziemer, 1982) and vegetation removal on railway embankments (e.g., Payne, 2003). Studies have shown that the majority of the original reinforcement is lost in 4–15 years following harvest (Ziemer, 1981; Ziemer and Swanston, 1977, O'Loughlin and Watson, 1979). The timing of landsliding may not always be coincident with maximum root deterioration because of the low frequency of occurrence of required storm thresholds (Sidle *et al.*, 1985). Failure does not normally occur immediately after felling but typically takes a few years to occur as the stability gradually decreases as soil moisture deficits are lost, and roots decay and lose strength (Hoskins and Rice, 1992).

Many shallow slope failures occur during the early spring when the vegetation is only just beginning to start its regrowth and ground water levels are at their maximum. Root die-back is also at a maximum at this time (Hoskins and Rice, 1992). The amount of root reinforcement is thus affected by the deterioration in root strength (decay) after clear felling (Watson *et al.*, 1999).

6.2 Case Study: decay of hawthorn roots

The link between vegetation removal and shallow slope failures on the railway infrastructure is a much disputed one (Payne, 2003), therefore at Site 3 (Great Central Railway) to provide some indication of the immediate change in root strength of roots from trees that had previously been cleared, four hawthorn shrubs were cut down in September 2003 and the tensile strength of the roots subsequently tested at 0, 1, 3 and 6 month intervals.

6.2.1 Methodology

Four hawthorn shrubs were selected and the height, spread, slope orientation and position recorded (see Section 4.5.2.3 for details). The four shrubs were then cut down using a pair of 'heavy duty loppers' and the stem diameter at ground level recorded. The stumps of the shrubs were clearly labelled to aid subsequent identification. One shrub was selected for testing immediately and the roots were excavated by hand using a trowel and spade. The procedure for recording root system architecture was followed as given in Section 3.1.1.6. All roots were sealed in plastic bags to maintain natural moisture content.

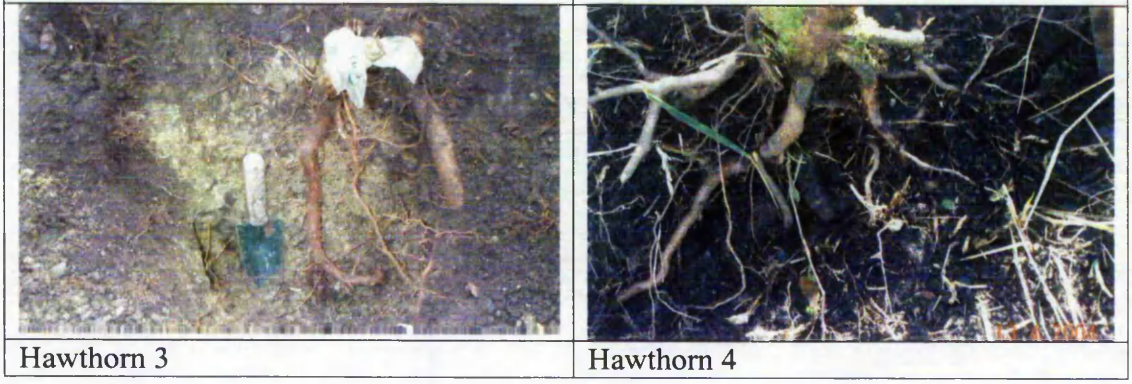
In the laboratory, all roots were washed to remove any soil. Each lateral root was sketched, and its diameter at its ends measured and length and number of branches recorded. Each lateral root was subsequently cut into ~150 mm lengths for testing in the Tensometer. Again, the diameter and length of the cut lengths of root were measured and recorded. Each cut length of root was kept in a sealed plastic bag until it could be tested. All roots were tested within 4–5 days of excavation.

Each root was placed in the jaws of the Tensometer machine (Figure 3.9). Roots over 12 mm in diameter were trimmed, using a Stanley knife, to enable them to fit into the jaws of the machine. Each root was strained at a rate of 2 mm per minute, and force recorded by either the 2 kN or 20 kN load cell depending on the diameter of the root. The test procedure as described in Sections 3.1.2.2 and 3.1.2.3 was followed. This same procedure was carried out for the three further root systems at 1, 3 and 6 monthly intervals.

6.2.2 The hawthorn shrub root systems

The root systems of the four hawthorn shrubs are pictured in Figure 6.1. Each root system had a different architecture (Figure 6.1), although the physical characteristics of the four trees were very similar (Table 6.1). Unfortunately, full recovery of the root was impossible due to the hard ground conditions preventing digging with the hand spade especially for the shrub at 0 months. Other factors which prevented full recovery were the depths of the root system, at depths greater than 0.5 m the roots were embedded in hard, blocky silt-clay which couldn't be excavated by hand; and as the railway embankment is on an operational steam railway, there was a concern with creating large areas of unstable ground which may subsequently fail.

Hawthorn 1 Hawthorn 2



Hawthorn 3 Hawthorn 4

Figure 6.1. Root architecture of hawthorn shrubs.

Table 6.1. Characteristics and root architecture of hawthorn trees.

Time since removal (months)	Tree Identification	Plant height (m)	Stem diameter at ground level (mm)	Architecture
0	RudH1	1.7	37.3	Tap root system, branched at depth
1	RudH2	1.55	14.9	Bifurcating tap root, branches upslope and downslope.
3	RudH3	1.2	35.1	Tap root system, branched at depth
6	RudH4	1.07	40.3	Asymmetric distribution of roots around the stem

6.2.3 Change in root strength with time

The amount of root recovery of the first hawthorn shrub at time 0 was unfortunate in that it provided very little meaningful data in which to provide a mean tensile strength for roots of freshly cut trees. The data for time 0 given in Figure 6.3a is therefore taken from the roots at Site 2 as an indication of the tensile strength of fresh hawthorn roots. Good recovery of the hawthorn root systems at time intervals 1, 3 and 6 months resulted in successful tensile tests of these roots.

Figure 6.2 shows the variation in root tensile strength for all four shrubs. There is a wide spread of tensile strength data with different root diameters. As can be seen from Figure 6.3a, mean tensile strength decreased during the initial months following cutting, from 16.8 MPa to 11.0 MPa, but then increased again at the six month interval (to 14 MPa). Root moisture content shows a general decreasing trend with time (Figure 6.3b), the widespread variation of root moisture contents at times 3 months and 6 months reflects the wide variation in tensile strength of the hawthorn roots.

The root decay of the four shrubs within the first six months of cutting seemed to have very little effect on the tensile strength of the roots. The apparent decrease in tensile strength is probably related to natural dieback during the winter season and

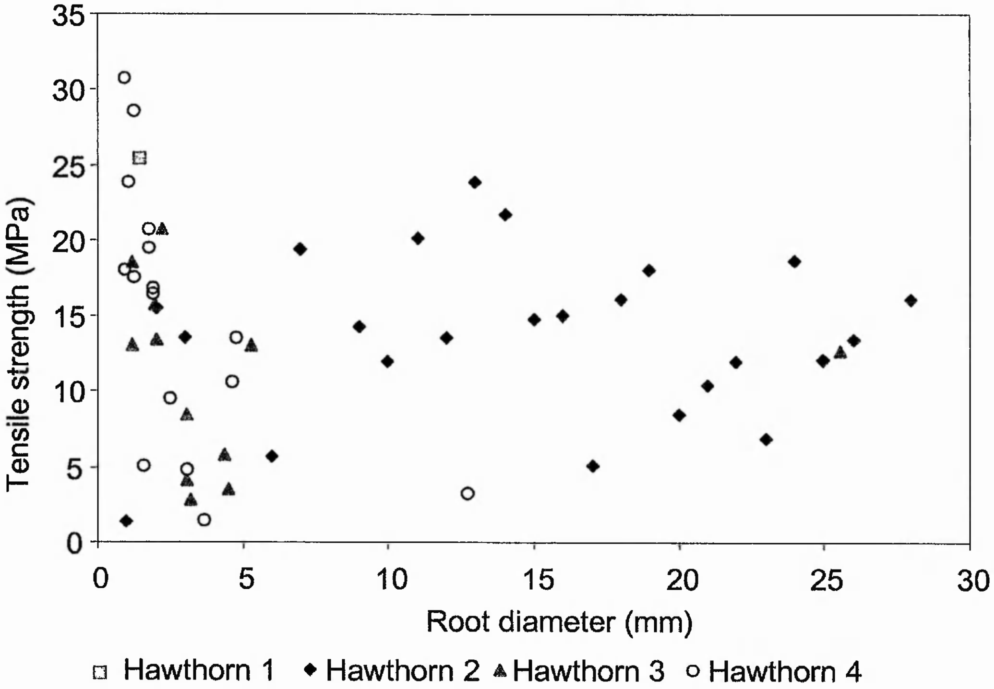


Figure 6.2. Variation in hawthorn root tensile strength following vegetation removal. Hawthorn 1 - 0 months; Hawthorn 2 - 1 month; Hawthorn 3 - 3 months; Hawthorn 4 - 6 months.

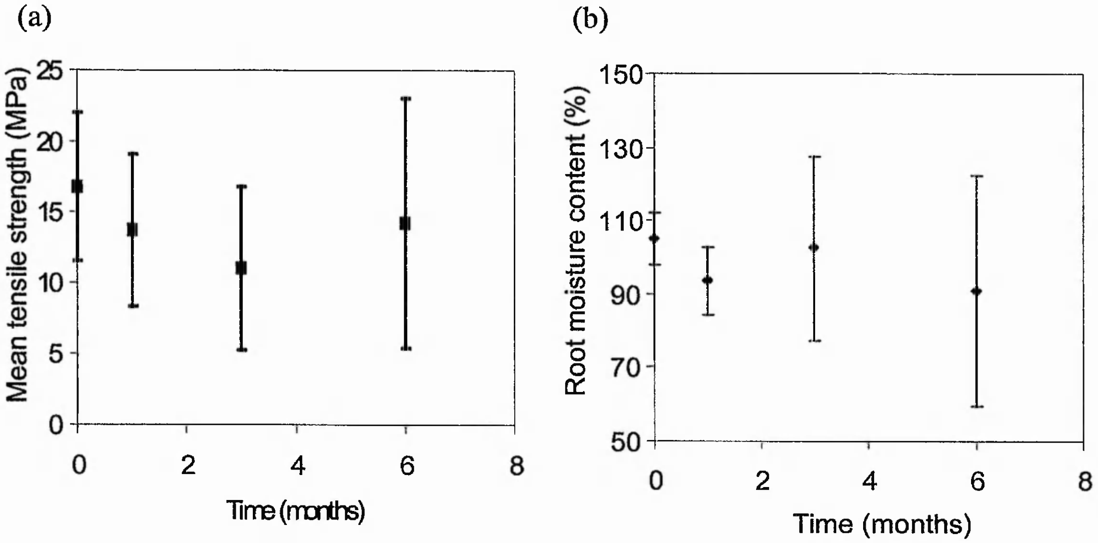


Figure 6.3. Graphs of change in (a) tensile strength and (b) moisture content of hawthorn roots following vegetation removal. Error bars represent standard deviation.

then regeneration during the Spring. This is coincident with the roots being tested in September, October, January and April. The relatively young, healthy shrubs that were tested would probably not have suffered to a great extent from being cut and would probably have sent out new shoots in the Spring. This was observed on Site 2 where roots that had been left in the ground after testing in 2003 had begun to regenerate the following Spring (Figure 6.4).

For management purposes, the selective removal of a relatively small number of shrubs will have very little effect on slope stability especially if the species is hawthorn which seems to regenerate after cutting. The large-scale clearance of vegetation is however another issue and requires further investigation on a site with good access and in an environment where if a landslide should occur it would not upset the transport infrastructure, so that root decay can be monitored over a longer time scale. A wider range of species could also be investigated so that recommendations could be made about which species to plant and which species not to plant on embankments and cuttings.

Figure 6.4. Regeneration of hawthorn shoots from cut roots.

6.3 Long term effects of vegetation removal on root strength

The clear felling of trees can have a dramatic effect on the root reinforcement, anchoring and buttressing roles of vegetation. The rate of decay of Radiata pine roots in New Zealand, a temperate climate, has been found by O'Loughlin and Watson (1979) to decline exponentially after felling (Table 6.2). The time to half strength was only 14 months. In western USA, Ziemer (1981) reported that about 30% of roots less than 17 mm in diameter (i.e. those contributing most to soil reinforcement) in a mixed conifer forest had totally decayed after 7 years. Burroughs and Thomas (1977) found that 75% of Douglas-fir roots 10 mm or smaller were lost within 2 years of felling on the west coast of North America and that the root tensile strength of these roots declined from ~26.5 – ~2.3 kPa within 30 months of felling. O'Loughlin (1974) reported that the tensile strength of Douglas-fir roots decreased by more than one-half within three years of timber removal in southern British Columbia and western red cedar roots required five years to lose one-half of their tensile strength. Ziemer and Swanston (1977) recorded a significant loss of strength in small diameter roots occuring rapidly in the first two years after timber logging on the Prince of Wales Island, Alaska, while the largest roots had lost considerable strength after 10 years.

Table 6.2. Residual strength of *Pinus radiata* roots after felling (O'Loughlin and Watson, 1979).

Time	Minimum		Maximum	
	Tensile strength (MPa)	Diameter (mm)	Tensile strength (MPa)	Diameter (mm)
Living trees	7.6	0.13	37.5	1.4
3 months since felling	2.9	0.2	33.3	1.1
9 months	2.9	0.2	43.3	1.5
14 months	2.7	0.2	30.9	1.5
29 months	0.3	0.3	14.3	1.8

The rates of decline in root strength and reduction of root biomass determine the speed at which a clear felled slope will deteriorate (Coppin and Richards, 1990). These rates are similar for many species. Roots with a high initial strength retain some strength for several years after felling, whilst those with low initial strength lose nearly all their reinforcing capacity in a short time (Coppin and Richards, 1990).

Slopes can recover from clearfelling as vegetation regrows. The rate of recovery depends on the type of regeneration and management of the vegetation. O'Loughlin and Ziemer (1982) produced a comparative chart of relative reinforcement of soils by roots following tree removal and subsequent regrowth of roots (Figure 6.5). The loss of root reinforcement of soil due to roots decaying with time is compensated for by increasing reinforcement by regrowing roots, the total reinforcement reaching a maximum after 10 years.

For long term stability, it is essential that after clearing, a new ground cover is introduced to depress the water level and provide some root anchorage (Brown and Sheu, 1975).

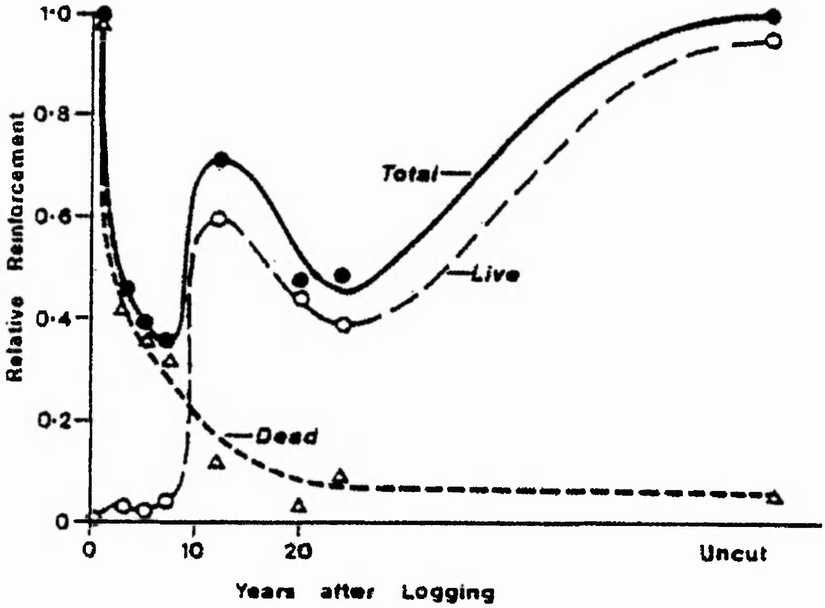


Figure 6.5. Relative reinforcement of soils by live and dead roots (O'Loughlin and Ziemer, 1982).

6.4 Summary

The change in root strength during root decay following vegetation removal was studied over a six month period. Over this period, very little change in root strength was observed although this is probably related to the age of the shrubs tested and the relatively few tests carried out. The removal of the above ground vegetation, however, exposes the soil slope to higher rates of precipitation which may potentially lead to slope failure. In the long term, for example after 20 years, the amount of root reinforcement becomes negligible and the stability of the slope will be reduced to the original shear strength of the soil. The change in Factor of Safety and stability of Site 3 is modelled in Chapter 9.

Chapter 7: Mechanics of Root Reinforcement

7.1 Introduction

Roots provide a reinforcing effect to soil through their tensile resistance and frictional or adhesional properties. Whether the reinforcing effect of roots is significant to slope stability depends primarily on the depth of potential slip surfaces within the slope. In the last 30 years, studies of root-soil reinforcement have included laboratory shear tests of soils with roots (Waldron, 1977; Kirsten, 2001), soils reinforced by fibres that simulate roots (Gray and Ohashi, 1983; Jewell and Wroth, 1987; Wu *et al.*, 1988a; Shewbridge and Sitar 1989, 1990, 1996) and *in situ* tests on soil blocks with roots (Endo and Tsuruta, 1969; O'Loughlin, 1974; Ziemer, 1981; Barker, 1987; Abe and Iwamoto, 1986; Wu *et al.*, 1988a; Nilaweera, 1994; Tobias, 1995; Wu and Watson, 1998; Norris and Greenwood, 2000b). These studies have lead to the development of analytical models for the contribution of roots to soil strength (Waldron, 1977; Waldron and Dakessian, 1981; Gray and Ohashi, 1983; Wu *et al.*, 1988a) and in the evaluation of root forces on slope failures (O'Loughlin, 1974; Wu *et al.*, 1979; Riestenberg and Sovonick-Dunsford, 1983; Riestenberg, 1994; Schmidt *et al.*, 2001).

The root reinforcement models (perpendicular, inclined, soil-root) and mechanisms of root failure on a slope are now introduced. The field data from the three study areas (Chapter 4) are applied to the perpendicular root reinforcement model to enable quantification of the increase in soil strength due to the roots. Values of root reinforcement or root cohesion are derived from the *in situ* shear tests results (Section 4.5.1.1) and compared with the values obtained from the root reinforcement models.

7.2 Root reinforcement models

The nature of root (or fibres)-soil interactions and the contribution of roots to soil shear strength have been modelled using simple force equilibrium models (Wu, 1976; Waldron, 1977; Wu *et al.*, 1979; Waldron and Dakessian, 1981), statistical models (Wu *et al.*, 1988b, c) deformation based models (Shewbridge and Sitar, 1989, 1990, 1996) and more complex finite element based models (Wu, 2006). The perpendicular root reinforcement model based on simple force equilibrium is widely accepted and recognised as the general model for root reinforcement (Gray and Leiser, 1982; Greenway, 1987; Coppin and Richards, 1990; Gray and Sotir, 1996), and as such the principles of the model are further described. All the models, show an increase in the shear strength of the soil through root reinforcement.

7.2.1 Perpendicular root reinforcement model

The perpendicular root reinforcement model was originally proposed by Wu (1976) with a virtually identical model developed and proposed independently by Waldron (1977).

The basis for the perpendicular root model is that roots increase the shear strength of soil by transferring the shear stresses that develop in the soil matrix into tensile resistance in the roots via interface friction along the embedded length of the root. The perpendicular root reinforcement model assumes a flexible elastic root which extends perpendicularly across a shear zone (Figure 7.1). When shearing occurs, the root is deformed, resulting in root elongation. The root elongates providing there is sufficient interface friction and confining stress to lock the root in place, and prevent pull out or slipping. The root must be sufficiently long and frictional, constrained at its ends and/or subjected to high confining stresses to increase the interface friction (Gray and Barker, 2004).

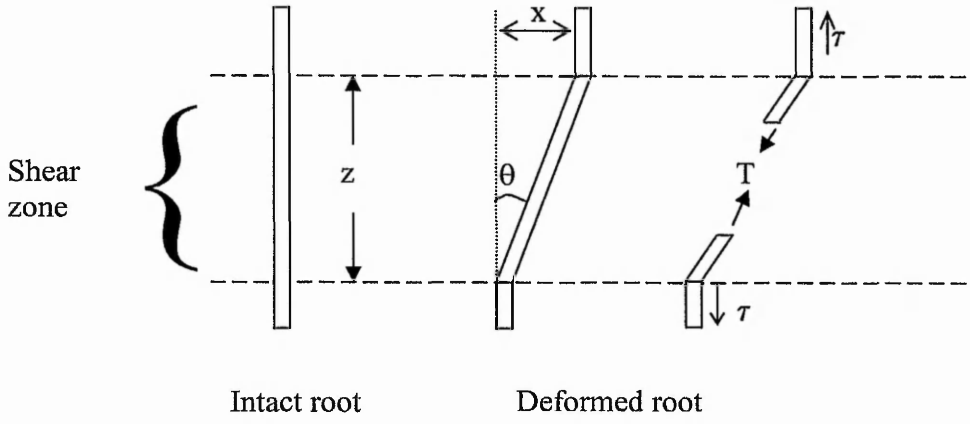


Figure 7.1. Schematic diagram of perpendicular root reinforcement model. Key: T – root tensile strength; θ – angle of shear distortion; τ – skin friction along the root; x – horizontal deflection of the root; z – thickness of the shear zone.

In the perpendicular root model, it is assumed that all roots are oriented at right angles to the slip plane, that the tensile strength of all roots is fully mobilised (i.e. the roots break in tension) and that the roots do not alter the soil friction angle (ϕ) (Gray and Leiser, 1982). The increase in shear strength due to the roots (Δs), as predicted by the perpendicular root model is

$$\Delta s = t_R (\sin\theta + \cos\theta \tan\phi) \quad [7.1]$$

where t_R is the mobilised tensile stress of roots per unit area of soil, θ is the angle of shear distortion in the shear zone and ϕ is the angle of internal friction of the soil.

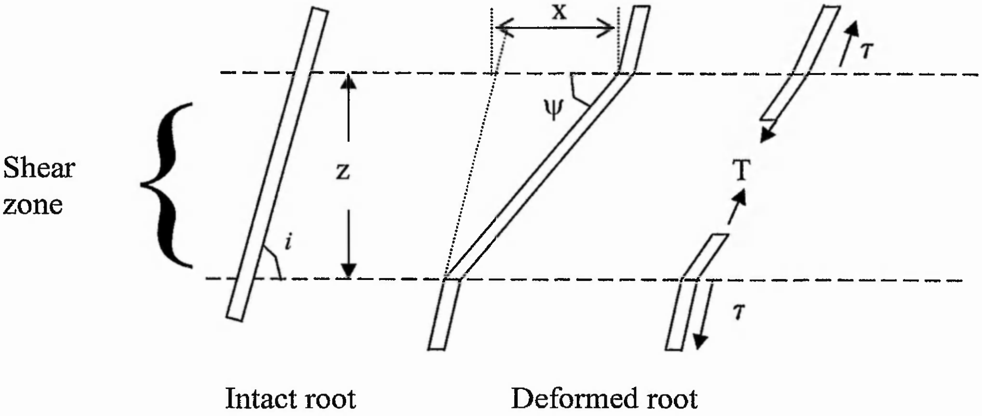


Figure 7.2. The inclined root reinforcement model (after Gray and Leiser, 1982). Key: z is the thickness of the shear zone, *i* is the initial angle of inclination of root, x is the distance the deformed root has moved; ψ is the angle of shear distortion, T is the tensile strength of the root; τ is the root-soil bond stress.

7.2.2 Inclined root model

Gray and Leiser (1982) considered the case of a root inclined with respect to the slip plane (Figure 7.2). The inclined root model shows that a shear distortion ratio, m, can be calculated:

$$m = x/z \quad [7.2]$$

where x is the distance the deformed root has moved and z is the thickness of the shear zone, such that the angle of shear distortion, ψ, becomes

$$\psi = \tan^{-1} [\ 1/\ m + (\tan i)^{-1}\ ] \qquad [7.3]$$

where i = initial angle of inclination of root.

The shear strength increase with respect to the inclined root is now:

$$\Delta s = t_R\,[\sin(90 - \psi) + \cos(90 - \psi) \tan\phi]. \qquad [7.4]$$

From equation [7.4], it is apparent that roots with an orientation of $\theta > 90°$ tend to go into compression rather than tension, which negates their reinforcing effect (Greenway, 1987).

7.2.3 Soil-root model

The soil-root model, proposed by Waldron (1977), treated roots as flexible, elastic reinforcing elements. The soil-root model is based on the Mohr-Coulomb equation in which shearing resistance S is developed by cohesive and frictional forces (Waldron, 1977, Waldron and Dakessian, 1981):

$$S = c + \sigma_N \tan \phi \qquad [7.5]$$

where σ_N is the normal stress on the shear plane, ϕ is the soil friction angle and c is cohesion. For rooted soil, Waldron (1977) and Waldron and Dakessian (1981) assumed that:

1. roots extend vertically across a horizontal shearing zone of thickness z, with z remaining constant during shear;
2. roots of different diameter classes, d_i, are flexible and linearly elastic with Young's modulus E;
3. the soil friction angle ϕ is unaffected by the roots;
4. the tensile strain in the roots was not large so that the stressed length approximates to the unstressed root length;
5. the soil loads the root in tension by tangential stress τ at the soil-root interface, this root-soil bond stress has a maximum value of τ_b at slippage;
6. all longitudinal displacements of the soil relative to the root mobilise the maximum tangential stress τ_b.

If the soil friction angle is unaffected by the roots, the Mohr-Coulomb equation for rooted soil, becomes:

$$S = c + \Delta s + \sigma_N \tan\phi \qquad [7.6]$$

where Δs is the increase in shear resistance due to the roots.

Waldron (1977) showed that for roots of all one diameter the shear resistance was:

$$\Delta s = A_r/A\ T_N (\sin\theta + \cos\theta \tan\phi) \qquad [7.7]$$

where A_r is the total root cross section at the shear plane; A is the total soil shearing cross section, θ is the angle of inclination from the vertical of roots produced by horizontal shear displacement of the root permeated soil; and T_N is the maximum tensile stress developed in the roots at any given shear displacement.

7.2.4 Mechanisms of root failure

Roots in the models, as described in Sections 7.2.1-3, respond to loading by either stretching, slipping through the soil or breaking. Waldron and Dakessian (1981) extended the soil-root model to take into account the range of root diameters and to account for the three failure mechanisms. Wu *et al.* (1979) extended the perpendicular root reinforcement for roots breaking, and thus derived the same equation as Waldron and Dakessian (1981).

During shearing of a root reinforced soil, the roots can either break, stretch or slip depending on their length, amount of root elongation and constraint. The tensile resistance t_R mobilised in each of these three scenarios varies, thus resulting in three new equations that represent the increase in shear strength due to the roots (Δs).

7.2.4.1 Shear strength increase during tensile root breaks

The increase in shear strength from the full mobilisation of the tensile root stress when roots break (t_{RB}) is determined from the mean tensile strength of the roots (T_R) and the fraction of soil cross-section occupied by the roots or Root Area Ratio (A_R/A):

$$t_{RB} = T_R (A_R/A) \qquad [7.8]$$

where A_R is the total cross-sectional area of all roots in a given cross-section of soil and A is the soil cross-section considered.

Root tensile strength varies considerably with root diameter, therefore the mean tensile strength of roots (T_R) can be determined by

$$T_R = \frac{\Sigma T_i n_i a_i}{\Sigma n_i a_i} \qquad [7.9]$$

where T_i = tensile strength of roots in class size i; n_i = number of roots in class size i; and a_i = mean cross-sectional area of roots in class size i (Waldron and Dakessian, 1981).

Substituting Equation [7.8] into [7.1] the predicted shear strength increase (Δs) can be found from

$$\Delta s = T_R\,(A_R/A)\,(\sin\theta + \cos\theta\,\tan\phi) \qquad [7.10]$$

Equation [7.10] shows that the shear strength increase due to roots can be predicted from the mean tensile strength of roots, the root area ratio and a factor that depends on the shear distortion angle and the angle of internal friction of the soil. The range of θ and ϕ in ($\sin\theta + \cos\theta \tan\phi$) is $40° < \theta < 90°$, and $25° < \phi < 40°$ (Greenway, 1987). Wu *et al.* (1979) simplified the ($\sin\theta + \cos\theta \tan\phi$) part of equation [7.10] to a mean value of 1.2, so that equation [7.10] now becomes

$$\Delta s = 1.2\,T_R\,(A_R/A). \qquad [7.11]$$

For roots to break, the predicted shear strength increase depends entirely on the mean tensile strength of the roots and the root area ratio. In the root reinforcement model it is assumed that the roots are well anchored and do not pull out of the soil when tensioned. If a simple uniform distribution of bond stress between soil and root is assumed, the minimum root length, L_{min}, required to prevent pull out is given by

$$L_{min} = \frac{T_R d}{4\tau_b} \qquad [7.12]$$

where T_R is the root tensile strength; d is the root diameter; and τ_b is the limiting bond stress between root and soil (Gray and Barker, 2004).

7.2.4.2 Shear strength increase during root stretching

Root stretching occurs when there is insufficient root elongation and constraint to mobilise the root tensile or breaking strength. The mobilised tensile strength of stretched roots (t_{RS}) is determined by the amount of root elongation and the root tensile modulus E_R (Gray and Barker, 2004). The mobilised tensile stress (t_{RS}) per unit area of soil is now:

$$(t_{RS}) = (4z\,\tau_b\,E_R/d)^{1/2}\,(\sec\theta - 1)^{1/2}(A_R/A) \qquad [7.13]$$

where z is the thickness of the shear zone; τ_b is the root-soil bond stress; E_R is the tensile modulus of the root; d is the root diameter; and θ is the angle of shear distortion (Waldron and Dakessian, 1981).

The root-soil bond stress can be estimated from the confining stress acting on the roots and the coefficient of friction. For vertical roots, bond stress varies with depth, and is given by the equation:

$$\tau_b = z\,\gamma\,(1 - \sin\phi)\,f\tan\phi \qquad [7.14]$$

where z is the depth below the ground surface; γ is the soil density; ϕ is the angle of internal friction and f is the coefficient of friction between the root and soil (varies between 0.7-0.9 for wood and soil) (Gray and Barker, 2004).

The increase in shear strength from mobilisation of root tensile resistance from stretching is thus:

$$\Delta s = (4z\,\tau_b\,E_R/d)^{1/2}\,(\sec\theta - 1)^{1/2}\,(A_R/A)\,(\sin\theta + \cos\theta\tan\phi) \qquad [7.15]$$

Equation 7.15 can be rewritten as:

$$\Delta s = k\,\beta\,(A_R/A)\,(\sin\theta + \cos\theta\tan\phi) \qquad [7.16]$$

where $k = (4z\,\tau_b\,E_R/d)^{1/2}$ and $\beta = (\sec\theta - 1)^{1/2}$.

7.2.4.3 Shear strength increase during slipping of roots

Short, unconstrained roots tend to slip or pull out during root-soil shearing. These roots however still contribute to the soil reinforcement (Waldron and Dakessian, 1981; Gray and Barker, 2004). At the point of slippage, the maximum tension in the root (T_N) can be expressed by

$$T_N = 2\, \tau_b\, L/d \qquad [7.17]$$

where τ_b is the root-soil bond stress; L is the root length and d is the root diameter (Waldron and Dakessian, 1981).

The shear strength increase from slipping roots is given by

$$\Delta s = [\pi\, \tau_b\, n\, L\, d\, /2\, A]\, (\sin\theta + \cos\theta\, \tan\phi) \qquad [7.18]$$

where n is the number of roots slipping of one class size. If there are multiple roots of different class sizes, then equation [7.18] becomes (Waldron and Dakessian, 1981):

$$\Delta s = [\pi\, \tau_b\, /2\, A]\, (\sin\theta + \cos\theta\, \tan\phi)\, \Sigma\, n_i L_i d_i. \qquad [7.19]$$

7.2.5 Model summary

The simplest root reinforcement model assumes the roots to be perpendicular to the slip plane. The inclined root model demonstrates that a perpendicular orientation ($\theta = 90°$) is not optimum with respect to reinforcement but that it may be a reasonably representative compromise between more and less optimum orientations. An inclination angle of $40° < \theta < 70°$ was shown to be more appropriate for a range of common soil friction angles ($25° < \phi < 40°$) (Wu *et al.*, 1979). However, Gray and Ohashi (1983) showed from laboratory tests on sand-fibre mixtures and Maher and Gray (1990) from statistical analysis of sands with randomly distributed fibres that perpendicular orientations of reinforcing fibres provide comparable reinforcement to randomly oriented fibres. The perpendicular root model is therefore the most practical method to use as it provides an estimate of all possible root orientations and is based on the full mobilisation of root strength (Coppin and Richards, 1990; Gray and Barker, 2004).

7.3 Calculating the increase in shear resistance by roots (Δs)

The increase in the shear resistance of the soil by the plants root system (Δs) or root cohesion (c'_v) (see Section 7.4) can be determined by using the theoretical models previously described and experimentally by carrying out *in situ* shear box tests (Chapter

3). The increase in shear resistance due to the roots (Δs) are now derived by using both methods for the three study areas.

7.3.1 Derivation of Δs from the perpendicular root reinforcement model

The perpendicular root reinforcement model can be used to determine the increase in shear strength (Δs) due to the roots for the three study areas as described in Chapter 4. By inputting the actual parameters derived from the field and laboratory tests (from Chapter 4), as summarised in Table 7.1, into equation [7.10] the increase in shear strength due to the roots was determined for (i) roots at angles perpendicular to the shear plane and (ii) roots at angles of 45° to the shear plane. These angles were chosen as representative root inclinations which are applicable to both the root reinforcement model and in the slope stability analysis models (Chapter 9).

Table 7.1. Parameters used to determine the increase in shear strength by roots for Sites 1, 2 and 3.

Parameter	Site 1		Site 2		Site 3	
Friction angle ϕ	20°		20°		43°	
Tensile strength of roots* T_R	Rowan roots 10 MPa		Hawthorn roots 8 MPa		Elder roots 28 MPa	
Root Area Ratio*	0.16%		0.17%		0.0669%	
Angle of inclination of roots with shear plane θ	45°	90°	45°	90°	45°	90°
Increase in shear strength, Δs (kN/m^2)	15.4	16.0	13.1	13.6	25.6	18.7

* Values as described in Chapter 4.

The variation in angle of inclination of the roots with the shear plane shows similar increases in shear strength values for both the 45° and 90° angles for Sites 1 and 2. This relationship was confirmed by the authors of the models and the simplification of equation [7.10] to equation [7.11]. For Site 1, the theoretical values of Δs compare favourably with the measured value of 15.8 kN/m^2 from the mean of the four *in situ* shear tests. For Site 3, there is significant variation in the values of the shear strength for the two angles. This variation is most likely due to the friction angle of the soil (ϕ = 43°)

affecting the results. The friction angle used is outside the range (25° < ϕ < 40°) reported by Wu *et al.* (1979).

7.3.2 Derivation of Δs from the *in situ* shear tests

The increase in shear strength due to root reinforcement (Δs) can be determined by using the principles illustrated in Figure 7.3. It is generally assumed that the soil friction angle (ϕ') remains the same for both rooted and non-rooted soil (Coppin and Richards, 1990), therefore Δs is equivalent to c'_v. (Note that: Kirsten (2001) found from laboratory shear box tests on rooted and non-rooted soil that ϕ' varies with varying root biomass). The amount of root reinforcement (c'_v) can thus be calculated by subtracting the shearing resistance of the non-rooted soil from the shearing resistance of the rooted soil.

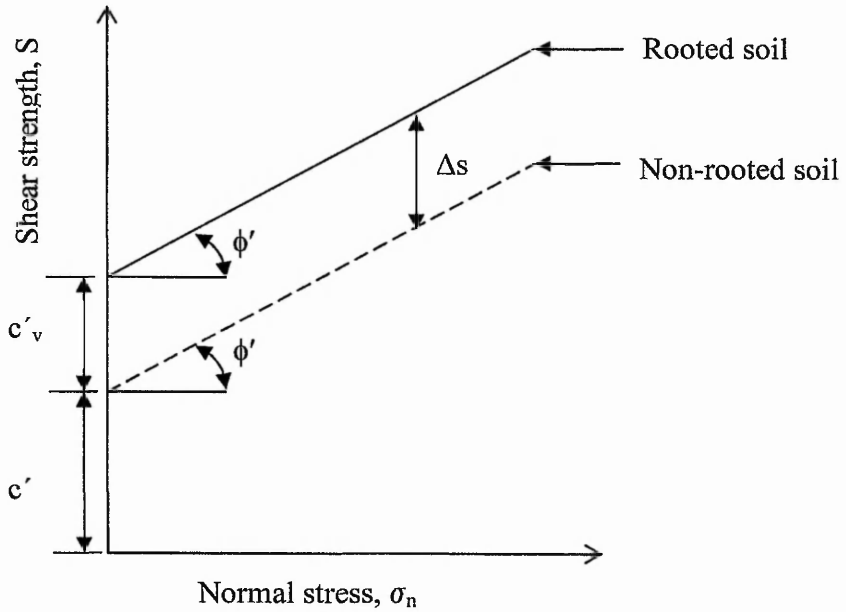


Figure 7.3. Effect of root reinforcement on the shear strength of soil. Key: ϕ' – effective internal friction angle; c' – effective cohesion; c'_v – increase in effective cohesion due to root reinforcement; Δs – increase in soil shear strength due to root reinforcement.

Table 7.2. Values of root cohesion c'_v derived from *in situ* shear tests for Sites 1 and 2.

	Site 1				Site 2	
	SB1	SB2	SB3	SB4	M11A	M11B
Residual shear strength (kN/m^2)	3.0	3.5	2.5	5.6	15.0	15.0
Peak shear strength (kN/m^2)	25.0	13.0	13.0	25.0	77.0	17.0
Root cohesion c'_v (kN/m^2)	21.0	9.5	10.5	19.4	62.0	2.0

For the study areas given in Chapter 4, values of c'_v were derived from the residual shear strength of the soil as found from the in situ shear tests and the peak shear stress of each test. The residual strength was assumed to be equivalent to the shear strength of non-rooted London Clay soil. The value of c'_v was therefore the difference between the two shear stresses (Table 7.2). As all of the tests on Site 1 were affected by the heterogeneous soil conditions (i.e., the presence of gravel), the root cohesion values for these tests are probably overestimated. The peak shear stress value for the test with the oak root system is also likely to be overestimated, as its validity would need to be confirmed by further tests. Root cohesion values for the London Clay soil on Sites 1 and 2 have thus been assigned as ranging between 2 – 10 kN/m^2. These values are of the same order as those found by other researchers (Table 7.3).

If the c'_v values determined by the *in situ* shear test method (Table 7.2) are compared with the values calculated by the root reinforcement models (Table 7.1) then some similarities are observed between them. However it is apparent that the values obtained by the *in situ* shear method underestimate those obtained by the root reinforcement model.

7.4 Root cohesion

The amount of increase in soil shear strength by roots has been termed an enhanced cohesion or root cohesion, c'_v. Root reinforcement or root cohesion promotes slope stability in shallow soils (Schmidt *et al.*, 2001). The values of c'_v given in Table 7.3 are based on direct *in situ* shear tests, back analysis or from root density and vertical root model equations. The values of c'_v vary from -0.6 – 40 kN/m^2 depending on the type of soil and vegetation. The negative values indicate that the non rooted soil had a greater shear strength than the rooted soil. These values can be reliably used as input parameters in slope stability analysis calculations of vegetated sites (see Chapter 9).

Table 7.3. Typical values for increases in soil reinforcement (c'_V) due to roots.

Source	Vegetation, soil type and location	Root cohesion c'_v (kN/m^2)
Grass and Shrubs		
Wu[3] (1984a)	Sphagnum moss (*Sphagnum cymbifolium* L.), Alaska, USA	3.5 – 7.0
Barker in Hewlett *et al.*[2] (1987)	Boulder clay fill (dam embankment) under grass in concrete block reinforced cellular spillways, Jackhouse Reservoir, UK	3.0 – 5.0
Buchanan & Savigny[1] (1990)	Grasses, sedges, shrubs, sword fern, glacial till soils, Washington, USA	1.6 – 2.1
Gray[5] (1995)	Reed fiber (*Phragmites communis* Trin.) in uniform sands, laboratory	40.7
Tobias[2] (1995)	*Alopecurus geniculatus* L., forage meadow, Zurich, Switzerland	9.0
Tobias[2] (1995)	*Agrostis stolonifera* L., forage meadow, Zurich, Switzerland	4.8 – 5.2
Tobias[2] (1995)	Mixed pioneer grasses (*Festuca pratensis* Huds., *Festuca rubra* L., *Poa pratensis* L.), alpine, Reschenpass, Switzerland	13.4
Tobias[2] (1995)	*Poa pratensis* L. (monoculture), Switzerland	7.5
Tobias[2] (1995)	Mixed grasses (*Lolium multiflorum* Lam., *Agrostis stolonifera* L., *Poa annua* L.), forage meadow, Zurich, Switzerland	-0.6 – 2.9
Cazzuffi *et al.*[5] (2006)	Elygrass (*Elytrigia elongata L.*), Eragrass (*Eragrostis curvala* Nees), Pangrass (*Panicum virgatum L.*), Vetiver (*Vetiveria zizanioides* L.), clayey-sandy soil of Plio-Pleistocene age, Altomonto, S. Italy	10.0, 2.0, 4.0, 15.0
Norris[2] (2005, Chapter 4)	Mixed grass on London Clay embankment, M25, England	~10.0
Van Beek *et al.*[2] (2005)	Natural understory vegetation (*Ulex parviflorus* Pourr., *Crataegus monogyna* Jacq., *Brachypodium* var.) on hill slopes, Almudaina, Spain	0.5 – 6.3
Van Beek *et al.*[2] (2005)	*Vetiveria zizanoides* L., terraced hill slope, Almudaina, Spain	7.5
Deciduous trees		
Endo & Tsuruta[2] (1969)	Silt loam soils under alder (*Alnus* P. Mill.), nursery, Japan	2.0 – 12.0
O'Loughlin & Ziemer[2] (1982)	Beech (*Fagus* L.), forest-soil, New Zealand	6.6
Riestenberg & Sovonick-Dunford[4] (1983)	Bouldery, silty clay colluvium under sugar maple (*Acer saccharum* Marsh) forest, Ohio, USA	5.7
Schmidt *et al.*[3] (2001)	Industrial deciduous forest, colluvial soil (sandy loam), Oregon	6.8 – 23.2
Conifers		
Swanston[1] (1970)	Mountain till soils under hemlock (*Tsuga mertensiana* Bong. Carr.) and spruce (*Picea sitchensis* (Bong.) Carr.), Alaska, USA	3.4 – 4.4
O'Loughlin[1] (1974)	Mountain till soils under conifers (*Pseudotsuga menziesii* (Mirb.) Franco), British Columbia, Canada	1.0 – 3.0
Ziemer & Swanston[3,5] (1977)	Sitka spruce (*Picea sitchensis* (Bong.) Carr.) - western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Alaska, USA	3.5 – 6.0
Burroughs & Thomas[4] (1977)	Mountain and hill soils under coastal Douglas-fir and Rocky Mountain Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) West Oregon and Idaho, USA	3.0 – 17.5
Wu *et al.*[3] (1979)	Mountain till soils under cedar (*Thuja plicata* Donn ex D. Don), hemlock (*Tsuga mertensiana* Bong. Carr.) and spruce (*Picea sitchensis* (Bong.) Carr.), Alaska, USA	5.9
Ziemer[2] (1981)	Lodgepole pine (*Pinus contorta* Dougl. & Loud.), coastal sands, California, USA	3.0 – 21.0
Waldron & Dakessian[4] (1981)	Pine seedlings grown in small containers of clay loam.	5.0
Gray & Megahan[3] (1981)	Sandy loam soils under Ponderosa pine, Douglas fir and Engelmann spruce, Idaho, USA	~ 10.3
O'Loughlin *et al.*[2] (1982)	Shallow stony loam till soils under mixed evergreen forests, New Zealand	3.3
Waldron *et al.*[2] (1983)	Yellow pine (54 months), laboratory	3.7 – 6.4
Wu[3] (1984b)	Hemlock, sitka spruce and yellow cedar, Alaska, USA	5.6 – 12.6
Abe & Iwamoto[2] (1986)	*Cryptomeria japonica* D. Don (sugi) on loamy sand (Kanto loam), Ibaraki Prefecture, Japan	1.0 – 5.0
Buchanan & Savigny[1] (1990)	Hemlock, Douglas fir, cedar, glacial till soils, Washington, USA	2.6 – 3.0
Gray[5] (1995)	*Pinus contorta* Dougl. & Loud. on coastal sand	2.3
Schmidt *et al.*[3] (2001)	Natural coniferous forest, colluvial soil (sandy loam), Oregon	25.6 – 94.3
Van Beek *et al.*[2] (2005)	*Pinus halepensis* Mill., hill slopes, Almudaina, Spain	-0.4 – 18.2

Key: 1. Back analysis. 2. *In situ* direct shear tests. 3. Root density information and vertical root model equations. 4. Back analysis amd root density information. 5. Laboratory shear tests.

7.5 Summary

In this chapter, three models of root reinforcement and the mechanisms by which roots fail were described. The perpendicular root reinforcement model is recommended as the most practical model as it provides an estimate of all possible root orientation and is based on the full mobilisation of the root strength. The perpendicular root reinforcement model was applied to the data obtained for the three study areas and values of root cohesion were obtained. When compared with the values of root cohesion obtained from the *in situ* shear tests, it was found that the modelled results overestimated the experimental results.

Table 7.3 provides up-to-date information of root cohesion values for different soils and vegetation species from numerous sources. The information given in this table can be used as input parameters for modelling slope stability analysis by limit equilibrium methods. An example of this is given in Chapter 9 using the root cohesion data obtained during this study.

Chapter 8: Root Architecture

8.1 Introduction

Root architecture is a key element of the stability of soil slopes as the distribution and form of the root system is fundamental to promoting stabilisation. This chapter introduces the available methods of classifying root architecture thus providing guidance to engineers on how to describe a root system. It also considers the factors that lead to the variation of root architecture on slopes, and those factors that are essential for slope stability.

8.2 Root system architecture and morphology

In geotechnical engineering, the nature of root systems has never seriously been considered, even less so their architecture or morphology. There is now a need for engineers to understand where roots are growing in the ground so that the tensile strengths and root cohesion properties of the root system can be accurately used in slope stability analyses. In plant sciences, the architecture of root systems have been described and classified, albeit with classification schemes which seem rather complex for the needs of the geotechnical engineer. The following is a brief review of the more commonly used classification systems and how they can be adapted for use in engineering.

8.2.1 Root architecture classification

The architecture of a root system can be defined by its three-dimensional network of roots resulting from the processes of growth and branching of individual root axes (Thaler and Pagès, 1998). Root system architecture can be broken down into two components: shape and structure (Pagès, 2002). Shape refers to the root system geometry or to the spatial distribution of the roots. Root distribution often presents non uniform but clumped patterns. Structure refers to the differentiation of components within the root system and to their mutual relationships; differences in their ontogenetic characteristics which are organised along the axes and differences between the connected roots. Connection relationships define the topology of the branching system (Fitter, 1982, 2002; Fitter and Ennos, 1989). Topology refers to the linkage arrangements of the roots anatomical structure.

The components of the root system are defined as the roots or root apices (tips) belonging to different developmental branching orders (order 1 directly connected to the shoot system and order *i* being to the next root along the branch giving rise to *i* + 1 branching). The branching orders are usually termed 1st, 2nd, 3rd, 4th orders.

The overall form of root systems are dependent on three distinct architectural features (Fitter, 1987). They are:

i) the balance of primary and adventitious roots. Adventitious root systems are common in monocotyledons, these species lack the single dominant axis achieved by primary root systems.
ii) degree of branching. Both primary and adventitious root systems may be unbranched or heavily branched.
iii) plasticity of branching. Lateral branches proliferate in fertile (nutrient and moisture-rich) soil zones but avoid sites of hypoxia or toxic levels of minerals (Manske and Vlek, 2002).

Other architectural classifications of root systems have been attempted (e.g. Cannon, 1949; Weaver, 1958; Krasilnikov, 1968) but due to the variable nature of root systems these classification systems were not tremendously successful (Fitter, 1987). More recent classification systems have been developed using computer simulations (Nielsen, 1995; Danjon *et al.*, 1999; Pagès, 2002) and herringbone shaped models (Fitter and Ennos, 1989). In the herringbone shaped model, the architecture of a rooted tree is determined by five components: topology, link length, branching angles, radial angles and link radii. These components all vary in form. All topologies lie along a spectrum from a herringbone pattern comprising a single axis with lateral daughters (Figure 8.1a) to a dichotomous pattern in which every link has two daughters (Figure 8.1b). The topological root classification system of Fitter and Ennos (1989) (Figure 8.2) shows a logical progression from a simple two axes system to a more complex herringbone shaped root system.

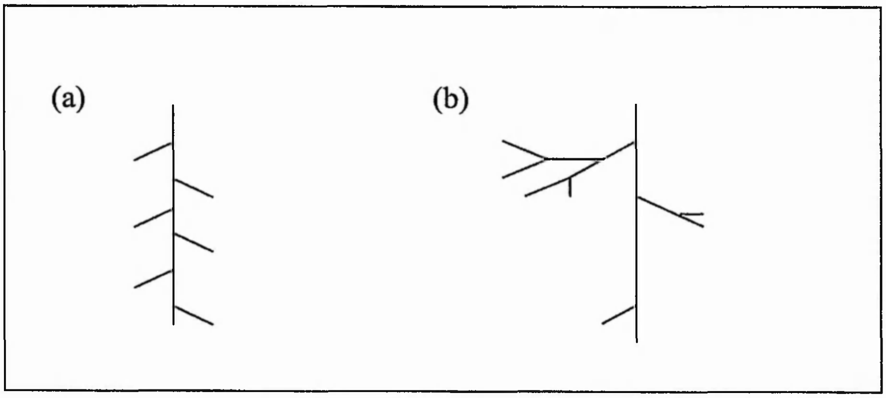


Figure 8.1. Idealised root systems illustrating the range of architectural characteristics (a) herringbone pattern (b) dichotomous system (Fitter and Ennos, 1989).

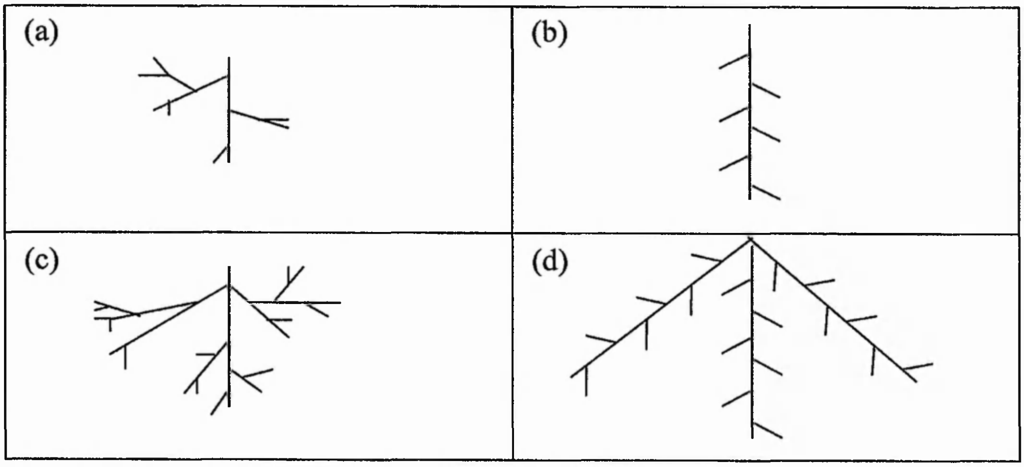
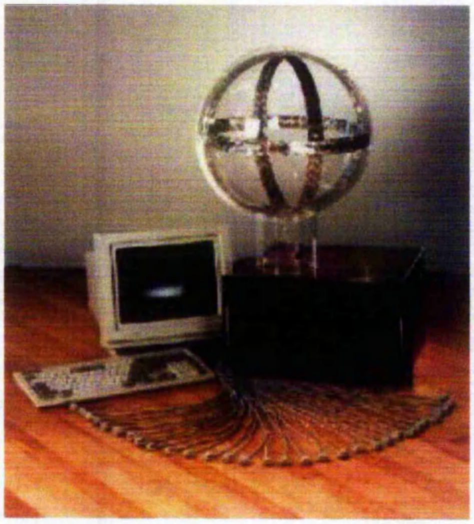


Figure 8.2. Development of a root system from a simple classification system using two axes to herringbone shaped root systems. Examples of these types of root systems would be (a) annuals, (b) tap rooted species, (c) trees and (d) grasses (Fitter and Ennos, 1989).

In forest research, with the advancement of computer technology, root system architecture has been three dimensionally digitised and mapped using a Polhemus Fasttrack Magnetic Marker (Polhemus, 2005) (Figure 8.3). The digitiser can be used for both in-situ and excavated root systems. This method provides a complete numerical representation of the structural root system and an accurate description of the spatial distribution of root volume as a function of radial distance and depth. The 3D root system can be combined with 3D mapping of soil layers to relate structural roots to soil conditions. AMAPmod software (CIRAD, France) is used for root system analyses, providing the user with tools for encoding, exploring and modelling plant roots. The 3D digitising system requires complete excavation of the root system prior to digitising and is also time consuming to digitally record all the roots within the whole root system.


(a)

(b)

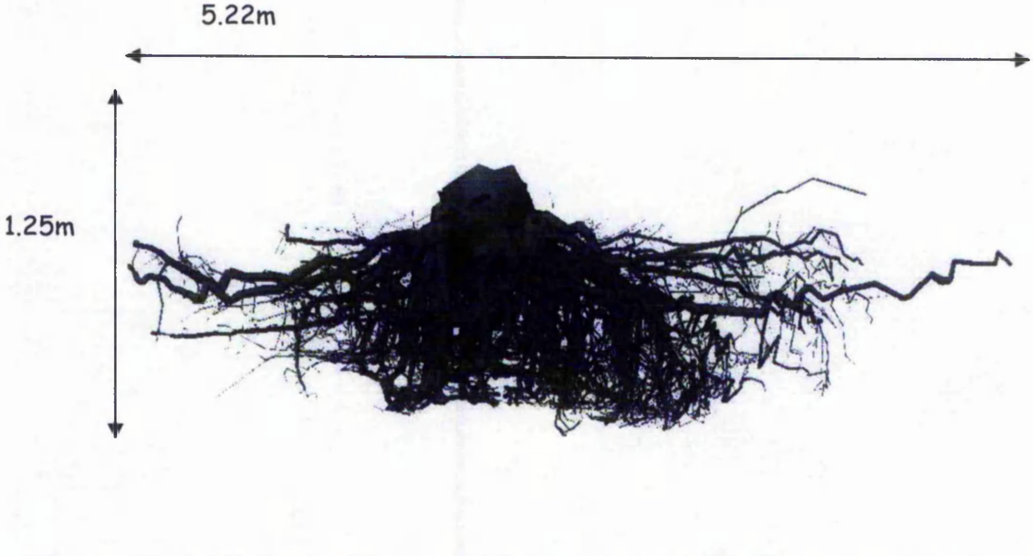


Figure 8.3. (a) Polhemus Fasttrack digitiser (www.polhemus.com). (b) Visual image of a digitised Maritime pine tree root system (Danjon *et al.*, 1999).

The computer simulation of the root system provides a detailed and complete picture of the root system. This level of detail is actually too complex for the needs of the engineer for carrying out rapid slope stability analyses. It may however be used in sophisticated finite element slope stability models where 3D root systems could be modelled.

The topological architecture classification is also too complex and not necessary for engineers to understand or classify the architecture of a tree root system. A simple system of recording the main taproot and the woody lateral roots of greater than medium-sized diameters is all that is required for engineering purposes, as these roots are integral for interacting with potential slip planes and can be used to calculate slope stability (Chapter 9). Engineers can thus use the branching order system to describe the stabilising roots in a root system, i.e., the taproot, if present, is the 1st order root, then subsequent lateral roots that branch from the taproot would be 2nd order roots and daughter roots of the 2nd order laterals would be classed as 3rd order roots. If no taproot was present, then the major lateral roots would be classed as 1st order roots, with subsequent branching classed as 2nd orders, *etc.* Orders below 3 would be too small in diameter to influence slope stability by root reinforcement.

8.2.2 Variation of root architecture with vegetation type

For the geotechnical engineer, a general picture of the shape, structure, extent and orientation of the roots is vital for determining the plants which can or cannot provide the necessary stabilisation of a slope. Coppin and Richards (1990) illustrates the variation in root architecture with type of vegetation (Figure 8.4). Figure 8.4 indicates that the shrubs and trees with deep tap-roots and deep branched roots are the type of vegetation most suitable for stabilising the 1-1.5 m deep slip surfaces. Shallow rooting (plate type) systems such as Sitka spruce, would therefore not be suitable for stabilising potential slips at depth below 1 m.

In trees, three different forms of root architecture have been recognised (Kőstler *et al.*, 1968; Stokes and Mattheck, 1996). They are plate, heart and tap root systems (Figure 2.6). Plate root systems have large lateral roots and vertical sinker roots,

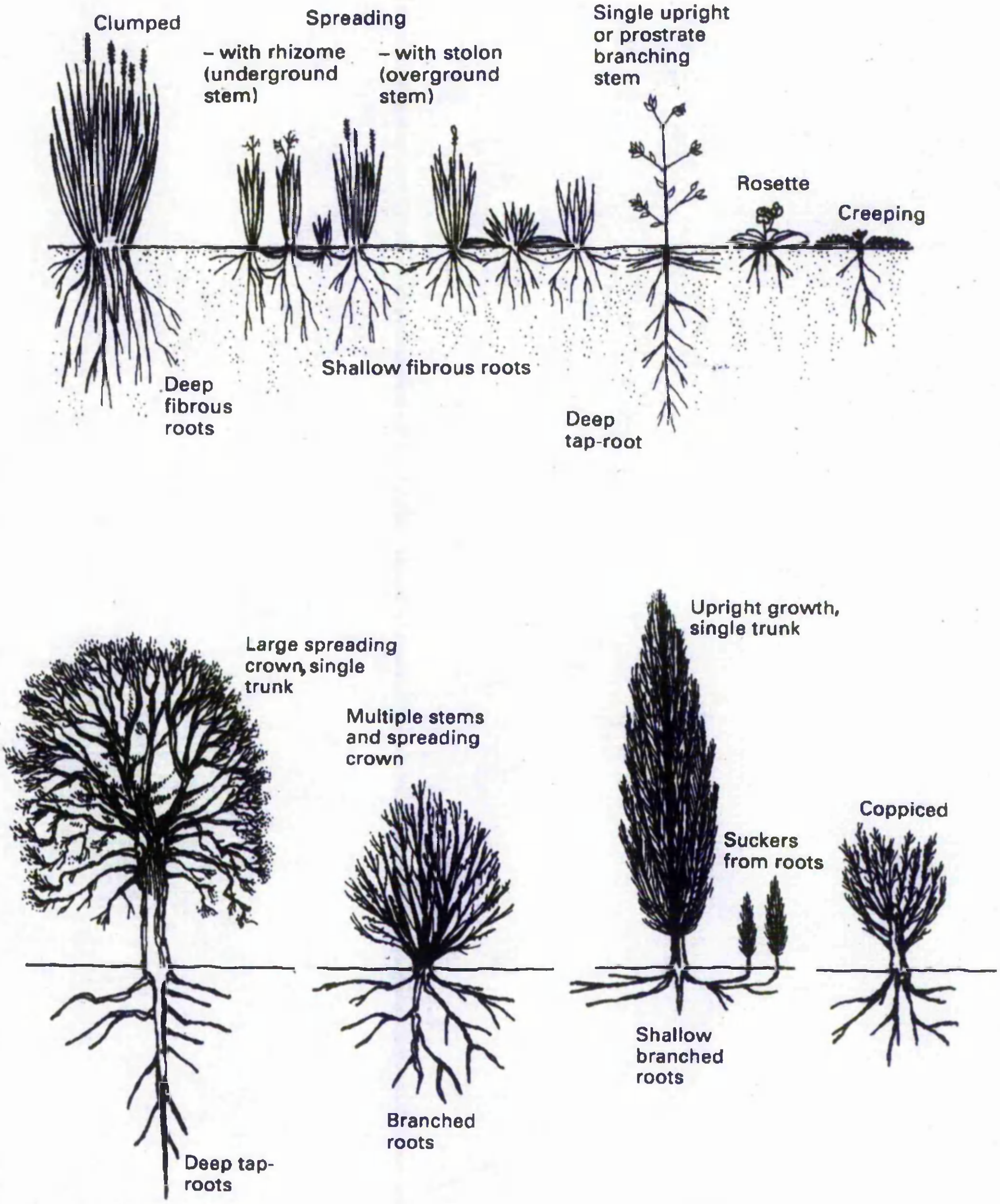


Figure 8.4. Variation in root architecture of grasses and herbs (top) and shrubs and trees (bottom) (Coppin and Richards, 1990).

heart systems possess many horizontal, oblique and vertical roots and tap root systems have one large central root and smaller lateral roots. Some species may be classified as having a mixture of all three root system types (Stokes, 2002). As roots of the same species intertwine and come into contact with each other, they gradually develop as a net of grafted roots e.g. oak (Lyford, 1980), plane trees (Edelin and Atger, 1994) and Norway spruce (Kűlla and Lŏhmus, 1999). Grafting results in increased tree stability and greater root reinforcement.

8.2.3 Morphology of individual roots

Individual roots within a root system may be further classified into subgroups depending on their morphology and function. Extensive roots are those which grow to large depths and spread diameters, while intensive roots are short, fine roots, localised within an area and often attached to larger structural roots. The term 'adventitious' refers to those roots which grow at the soil surface and whose specific function is the procuring of water and nutrients for the plant.

For the purposes of this research, a much simpler description of the morphology of individual extensive roots within the whole root system was required, since the whole root system was broken down into individual roots especially for the root pull out resistance tests. Terms to describe root morphology were not apparent in the literature, therefore descriptive words were assigned to describe the morphology of the roots in terms of their length, diameter, shape and surface features (Table 8.1).

Table 8.1. Terminology used to describe the morphology of roots.

Length	Diameter	Shape	Surface features	Woodiness
long short very long	$\left.\begin{array}{l}\text{fine}\\\text{small}\end{array}\right\}$ thin $\left.\begin{array}{l}\text{medium}\\\text{large}\\\text{very large}\end{array}\right\}$ thick	bended branched contorted curved feathery fibrous forked sinuous straight tapered tortuous	knotted ridged smooth	non-woody rubbery woody

8.2.4 Symmetry of root systems

The stability and soil reinforcing capacity of trees on horizontal and sloping sites is strongly influenced by the symmetry of the structural system of woody roots. Three types of root system asymmetry exist:

- Type 1, whereby individual roots can vary in diameter, which can result in an asymmetric system, even if the arrangement of roots is regular (Figure 8.5a) (Coutts *et al.*, 1999)
- Type 2, whereby the roots are not uniformly arranged, even though they may all be the same size (Figure 8.5b) (Coutts *et al.*, 1999)
- Type 3, asymmetry in slope condition, with irregular arrangement and variation of diameter (Figure 8.5c) (Di Iorio, pers. comm.).

When root systems are symmetrical the stability of the tree is usually enhanced. However, trees on slopes tend to have highly asymmetrical systems, depending on species type. An asymmetrical root system with numerous or thicker roots along the axis of stress develops when trees are subjected to mechanical stress, for instance, wind loading, or growth on slopes (Norris *et al.*, in prep.).

8.3 Variation of tree root architecture

The root architecture of trees can be recognised by different types of root systems, however, there are a number of factors that may lead to variation in root architecture, in particular the change with slope angle and with soil type. The maximum extent and depth of root systems is also affected by these factors. Engineers should be aware of the marked variations in root systems both intra and inter species.

8.3.1 Slope angle

Slope angle has been shown to affect both the distribution of roots around the stem and the change in type of root system (Chiatante *et al.*, 2003b; Di Iorio *et al.*, 2005; Norris, see Section 4.5.4.2).

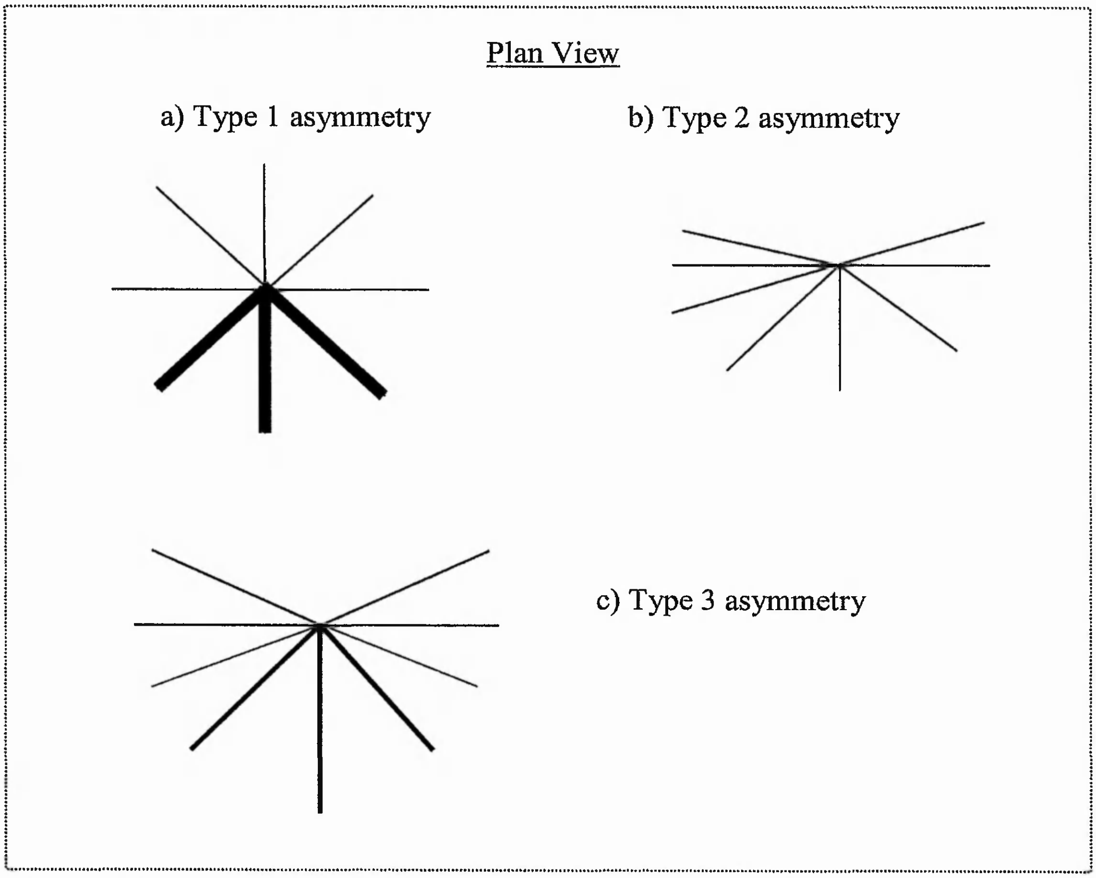


Figure 8.5. Root systems exhibit different types of asymmetry: a) in Type 1, individual roots can vary in diameter, even if the arrangement of roots is regular; b) Type 2, the roots are not uniformly arranged, even though they may all be the same size (Coutts *et al.*, 1999) and Type 3 on a slope, the arrangement of roots is irregular and roots vary in diameter. All tree root systems exhibit a combination of these asymmetries (Norris *et al.*, in prep.).

Chiatante *et al.* (2003a) showed that slopes affect the root systems of broom (*Spartium junceum*) and manna ash (*Fraxinus ornus*). For root systems of broom, Chiatante *et al.* (2003a) observed that on slopes, an asymmetrical distribution of lateral roots around the tap root contrasted sharply with a symmetrical distribution of plants growing on a horizontal plane (Figure 8.6). The 90 degree bend of the stem from the tap root as observed in the elder shrubs growing on slopes (Figure 8.7a) was also apparent in broom plants growing on slopes (Figure 8.7b).

Chiatante *et al.* (2003b, c) reports that roots of broom (*Spartium junceum*) growing on slopes have two preferential orientations – upslope and downslope, with a higher

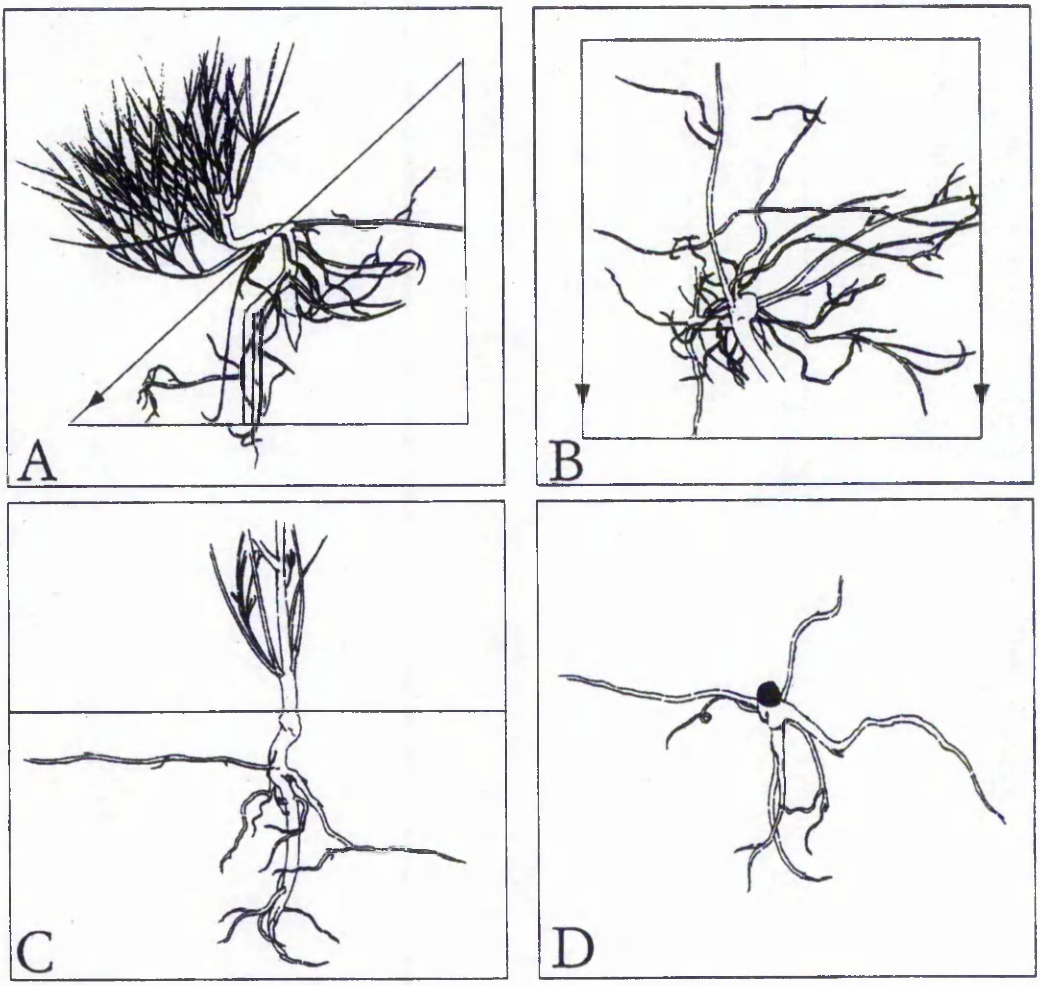


Figure 8.6. Schematic diagram of root distribution in broom (*Spartium junceum*) under slope conditions – asymmetric distribution (A - lateral view, B - plan view) and horizontal plane conditions – symmetric distribution (C - vertical view, D - plan view). Arrows indicate slope direction (Chiatante *et al.*, 2003a).

Figure 8.7. Examples of the change in growth angle of the stem-root junction of shrubs on slopes. (a) Elder [Rud19] (*Sambucus nigra*). (b) Broom (*Spartium junceum*) (Chiatante *et al.*, 2003a).

degree of root branching in seedlings of the same species (Chiatante *et al.*, 2003c). Figure 4.35 shows that this is not the case for elder shrubs. Norris (2005, and Figure 4.32) also showed that roots of hawthorn preferentially were at 90° to the upslope direction. The preferential root growth directions are probably site specific and serve to improve root anchorage in response to mechanical stress, e.g. prevailing wind direction and slope angle (Chiatante *et al.*, 2003c).

8.3.2 Soil conditions

Root system morphology is complex and exhibits high variation, depending on species, soil type and site conditions (Coutts, 1983a). Soil and site conditions which can affect root morphology include:

- Availability of air and nutrients in soil;
- Soil moisture content and permeability;
- Location and variation of the groundwater table;
- Extent to which soil is compacted;
- Presence of certain compounds in the soil (e.g. toxic substances, salinity);
- Soil thickness; and
- Presence of stones and other objects

When not limited by soil or ground water conditions, herbaceous, shrub and woody species have intrinsic root system morphological characters.

In both broadleaved (Lyford, 1980) and coniferous (Preisig *et al.*, 1979; Gruber, 1994) tree species, the architecture of the root system, depending on the soil conditions can be modified from the tap rooted type to plate root type with sinker and superficial root systems.

When influenced by local soil conditions, e.g. the presence of a hard pan or a seasonal water table, rooting depth may be inhibited, and sinker or tap roots may be asphyxiated or unable to penetrate the hard pan (Nicoll and Ray, 1996; Cucchi *et al.*, 2004). These root systems will thus have the appearance of a plate root system. The

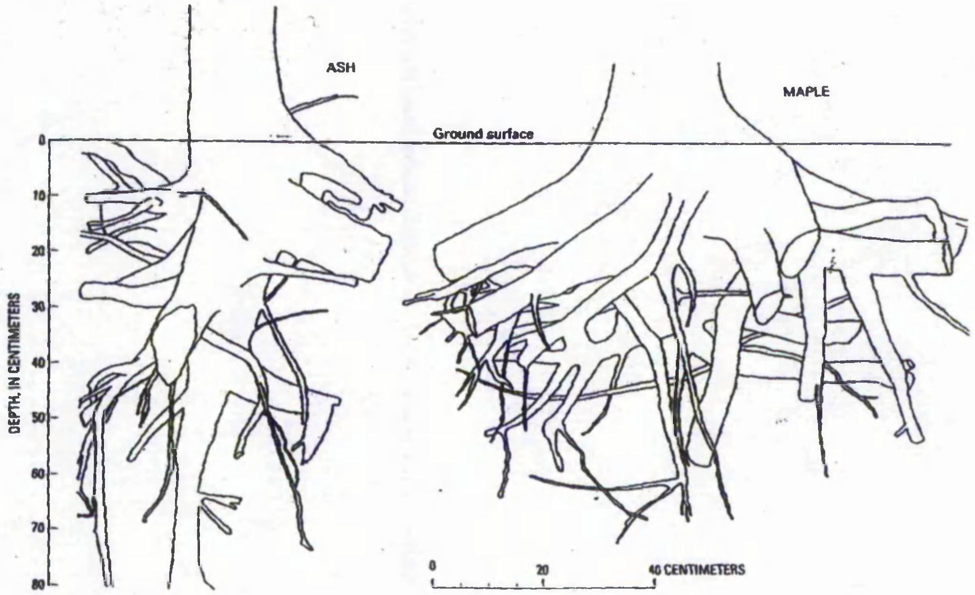


Figure 8.8. A comparison between the tap root system of white ash and the plate root system of the sugar maple (Riestenberg, 1994).

hawthorn root systems on Site 2, exhibited a limited rooting depth of 0.5 m, most likely caused by the stiff clay conditions.

The variation in root morphology of sugar maple and white ash with variation in thickness of soil on gently sloping and steep hillslopes was studied by Riestenberg and Sovonick-Dunford (1993) and Riestenberg (1994). Root morphology of the sugar maple revealed a plate type root system with highly branched tapering roots that were concentrated within the uppermost soil horizons (0.4 m depth) whereas the white ash had a much deeper tap root system (to 0.9 m) and also a set of lateral roots that were parallel to the ground surface (Figure 8.8). There was very little variation in the root morphology between the gently sloping and steep hillslope conditions (Figure 8.9).

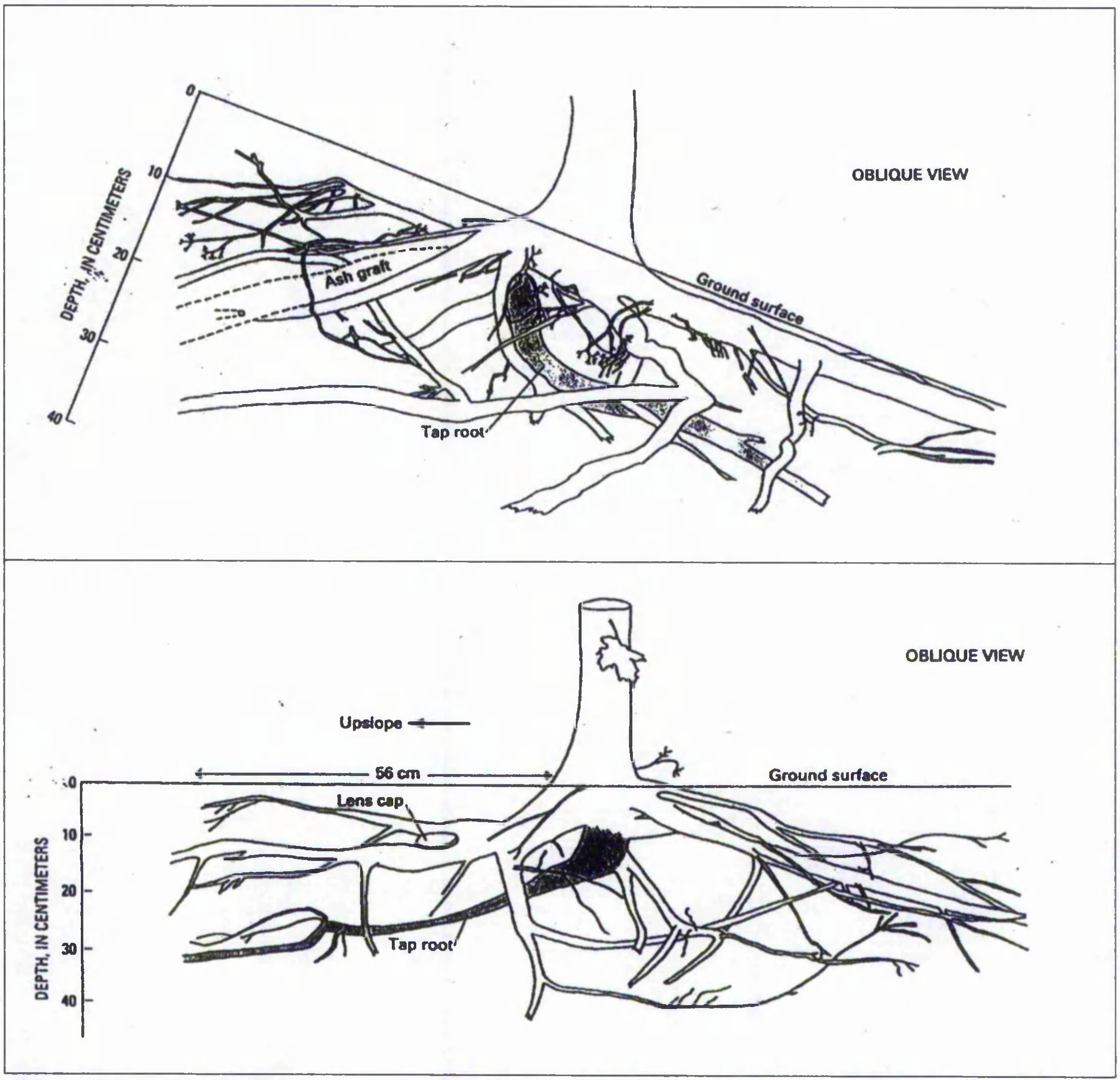


Figure 8.9. Variation in root morphology with slope angle and soil type. Top: sugar maple grown on a steep hillslope underlain by a thin mantle of colluvium. Bottom: sugar maple grown on gently sloping terrain underlain by deep colluvium (Riestenberg, 1994).

8.3.3 Age

Root morphology changes with age of the plant (Lyford, 1980; Watson, 1990). Pine (*Pinus radiata*) root systems (Figure 8.10) showed an increase in the lateral extent of the roots from 3 m at 8 years to 9.5 m at 25 years, the depth of the root system increased from 2 to 3 m over the same period (Watson and O'Loughlin, 1990). In young oak trees, the tap root system is important but in older oak trees the tap root becomes overshadowed by 5–10 large woody horizontal laterals originating near the ground surface (Lyford, 1980).

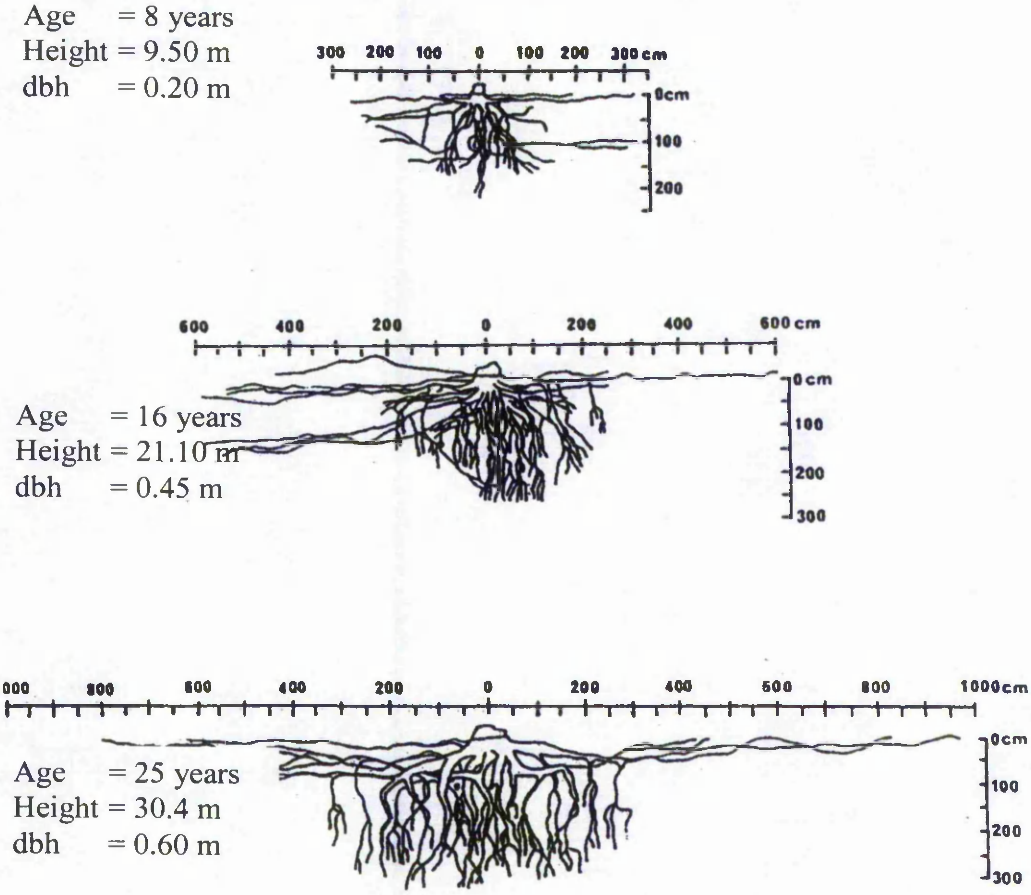


Figure 8.10. Variation in root morphology with age of tree for 8, 16 and 25 year old pine (*Pinus radiata*) trees (modified from Watson and O'Loughlin, 1990).

8.3.4 Maximum extent of tree roots

The maximum extent of tree roots, both radially and with depth, depends on the nature and characteristics of the soil substrate, for example, poorly aerated and dense soils create barriers to root penetration and thus reduce the number, the maximum size and the longevity of roots (Stone and Kalisz, 1991). Stone and Kalisz (1991) collated information, mainly of American origin, on the maximum depth and radial extent of roots in a range of soil types for 211 species of forest trees, horticultural trees and shrubs to demonstrate the great vertical and horizontal extent of tree roots in favourable conditions. Table 8.2 provides information on shrubs and trees that can be found growing on embankments and cut slopes in the United Kingdom.

Table 8.2. Maximum rooting depth and radii of selected trees (compiled from Cutler and Richardson (1981) and Stone and Kalisz, 1991).

Tree species	Age (years) or height (m)	Soil type	Maximum Depth (m)	Maximum Radius (m)	Reference
Ash (*Fraxinus* sp.)	Mature	clayey loam, sandy loam	1.8	13.1	Bunger and Thomson (1938)
Beech	20 m	-	-	15.0	Cutler and Richardson (1981)
Beech (*Nothofagus fusca*)	Mature	silty loam, pumice	> 2.0	-	Stone and Kalisz (1991)
Birch (*Betula* sp.)	20-60 years	-	>3.6	-	Röhrig (1966)
Birch	12-14 m	-	-	10	Cutler and Richardson (1981)
Common alder (*Alnus glutinosa*)	75 years	-	3.8	-	Köstler *et al.* (1968)
Common ash	23 m	-	-	21.0	Cutler and Richardson (1981)
Elder (*Sambucus nigra*)	2 m	silt-clay	0.5	0.8	Norris (see Chapter 4)
Elm	20-25	-	-	25.0	Cutler and Richardson (1981)
Hawthorn	10 m	-	-	11.5	Cutler and Richardson (1981)
Hawthorn (*Crataegus monogyna*)	80 years, 6-7 m	clay	0.5	2.5	Norris (see Chapter 4)
Hornbeam (*Carpinus betulus*)	70-80 years	clay	1.4	-	Köstler *et al.* (1968)
Lime (*Tilia* sp.)	16-24 m	clay	-	20.0	Cutler and Richardson (1981)
Maple/sycamore	17-24 m	-	-	20.0	Cutler and Richardson (1981)
Oak (*Quercus* sp.)	-	-	5.0	-	Cermak *et al.* (1980)
Oak	16-23 m	-	-	30.0	Cutler and Richardson (1981)
Oak (*Quercus robur*)	11-13 years	-	9.0	-	Köstler *et al.* (1968)
Plane	25-30	-	-	15.0	Cutler and Richardson (1981)
Poplar (*Populus deltoides*)	8 years	clay	1.2	7.0	Francis (1985)
Poplar	25 m	-	-	30.0	Cutler and Richardson (1981)
Sycamore maple (*Acer pseudoplatanus*)	Mature	sandy loam	1.4	9.0	Köstler *et al.* (1968)
Silver maple (*Acer saccharinum*)	35 years	clay	1.3	14.9	Yeager (1935)
Silver maple (*Acer saccharinum*)	31 years	silty loam	3.3	6.4	Sprackling and Read (1979)
Sycamore (*Platanus* sp.)	25-30 m	clay	-	15.0	Cutler and Richardson (1981)
Whitebeam/rowan	8-12 m	-	-	11.0	Cutler and Richardson (1981)
Willow (*Salix* sp.)	-	-	>3.6	-	Cannon (1960)
Willow	15 m	-	-	40.0	Cutler and Richardson (1981)
Mixed maple and beech (*Acer saccharum* and *Fagus grandifolia*)	Mature woodland	sandy loam over clay	>2.7	-	Harlan and White (1968)

It is important to know the extent of a root system so that firstly buildings and property can be protected from structural damage caused by the removal of soil moisture by the roots. Cutler and Richardson (1981), the Building Research Establishment (BRE, 1996) and the National House Building Council (NHBC, 1997) have all produced recommended guidelines for the safe distance between trees and buildings. Secondly, knowing the extent and depth of a particular root system and the type of soil these maximum conditions occur in, can assist the engineer in selecting suitable plants that can be effectively used to stabilise shallow landslides. The data given in Table 8.2 can also be used in slope stability models, to model the long term stability of a slope throughout the growth period of the vegetation.

8.4 Summary

The variation of root architecture with different types of vegetation has been addressed and the wide variation of root architecture exhibited by plants on slopes discussed. It is hoped by illustrating the root architectures of a number of different plant species, that engineers can appreciate that root architecture changes between flat and sloping conditions, with soil type and with age. The reference table of maximum radial and depth extent of tree roots for different soil types can be used for (a) selecting suitable plant species for slope stabilisation and (b) for modelling different types of vegetation on different slopes.

Chapter 9: Slope Stability Analysis

9.1 Introduction

Shallow slope instability is a common problem on earthworks (embankments and cut slopes) particularly in overconsolidated clay soils in England. The excavation and placement processes during earthworks result in a reduction in overburden stresses and the stiff overconsolidated clays are consequently susceptible to swelling and softening as they gain access to water. Zones of instability form typically at depths of 0.75 to 1.5 m below the slope surface (Perry, 1989; Greenwood *et al.*, 1985; Perry *et al.*, 2003 a, b). It is recognised that vegetation can assist in the stabilisation of these types of shallow slope failures (Coppin and Richards, 1990; *etc.*).

The practice of analysing slope stability by mathematical methods is well established, and there are a number of recognised methods for calculating the Factor of Safety for a particular slope based on the Method of Slices (Duncan and Wright, 2005). However, the practice of including the reinforcing effects of vegetation is still debatable with new methods being proposed in the literature (e.g. Ekanayake and Phillips, 1999; Greenwood *et al.*, 2004). The methods of analysis are briefly reviewed within the scope of their applicability to vegetation reinforcement. The factors, which should be taken into account when considering vegetation, are discussed. The variations in the methods of analysis are compared using an Excel spreadsheet developed by Greenwood (2006) called SLIP4EX. This program was further used to model the three study areas as reported in Chapter 4.

9.2 Slope stability analysis by limit equilibrium methods

The stability of slopes may be analysed by limit equilibrium methods e.g. the Simplified Bishop procedure (Bishop, 1955), the Swedish Method (Fellenius, 1936) and the Simple or General Method (Greenwood, 1986, 1989, 1990; Morrison and Greenwood, 1989). This type of analysis requires information about the strength of the soil but not its stress-strain behaviour. Slope movements are usually analysed by finite-element methods e.g. Plaxis (Brinkgreve, 2002). For these methods, characteristic stress-strain behaviour is required (these methods are not discussed further here).

In limit equilibrium techniques, the stability of a possible slip surface is assessed by comparing the gravitational disturbing forces with the available shearing resistance (shear strength) of the ground along the slip surface. For stability, disturbing forces acting along all potential slip planes must be less than the resisting forces that can be mobilised along them. The disturbing forces are due to the self weight of the material lying above the failure surface and to any external loads. Resisting forces are generated by the strength of the soil and by soil reinforcement (for instance, roots of vegetation). For stability to be maintained the available shear strength must exceed the disturbing forces.

The Factor of Safety, F against failure is expressed by

$$F = \frac{\text{shear resistance}}{\text{shear force required for equilibrium}} = \frac{\text{Restoring force}}{\text{Disturbing force}} \qquad [9.1]$$

The Factor of Safety is based on the sum of restoring and disturbing forces along the particular slip surface and is generally expressed in terms of moment equilibrium. The Factor of Safety, F, will be 1 or greater for a stable slope.

The Factor of Safety for a slope is normally derived by the method of slices. This method uses the friction block acting on an inclined plane as the basis for stability analysis. A block or slice of soil of unit width, above a potential slip surface, has the same friction principles applied to control stability but now there is the added effect of soil cohesion and water pressure which will govern the effective stresses.

To determine the Factor of Safety by the method of slices a circular slip surface is assumed and the soil mass above the slip surface is divided into a number of vertical slices as shown in Figure 9.1. The slope is divided into slices for analysis purposes only. It is assumed that all slices rotate around the centre of the circle O as a whole body. This implies that forces must act between the slices, termed interslice forces (Figure 9.2). The Factor of Safety value must be determined for the surface that is likely to fail, i.e. the critical slip surface. It is necessary to perform calculations for a considerable number of possible slip surfaces in order to determine the location of the critical slip surface.

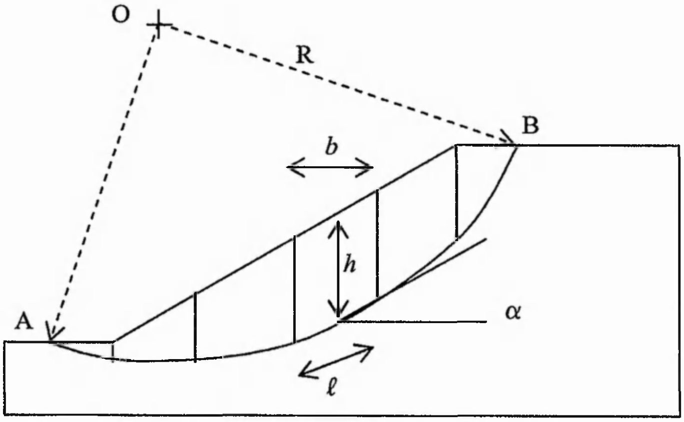


Figure 9.1. Determining the Factor of Safety by the method of slices. A circular slip surface of radius R has centre O and intersection points at the ground surface of A and B. The soil mass above the slip surface is divided into a number of vertical slices of width *b* and varying height *h*. The base of each slice is assumed to approximate to a straight line inclined at an angle α to the horizontal and with a length ℓ.

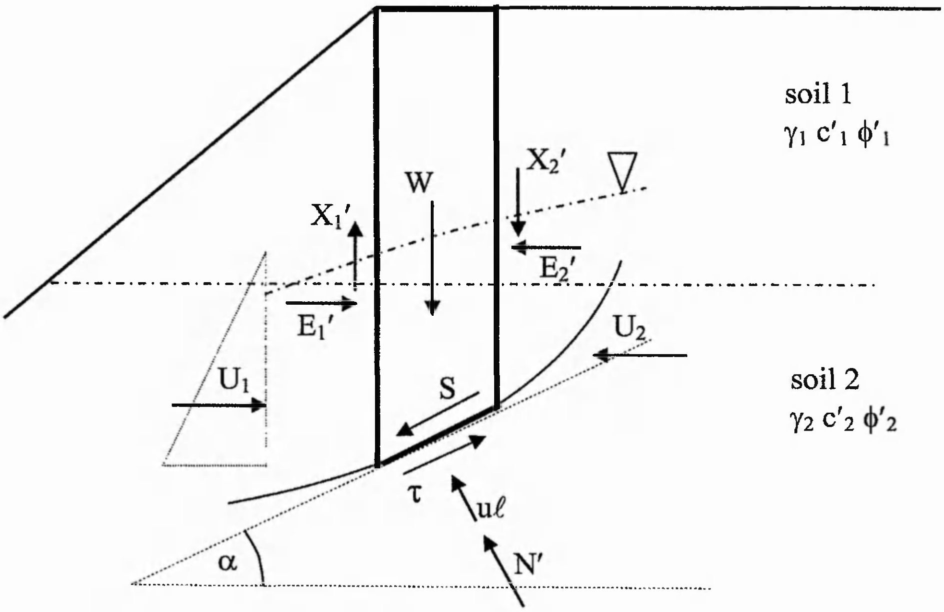


Figure 9.2. Forces acting on a slice (Greenwood, 2006). Notation - The total weight of the slice, $W = \gamma bh$ where γ is the bulk unit weight of the soil, *b* is the width of the slice and *h* is the average height of the slice above the slip surface. The weight of each slice induces a shear force parallel to its base $S = W\sin\alpha$. The effective normal force on the base, $N' = \sigma'\ell$. (The effective normal force is obtained from total normal force, $N = \sigma_n\ell$ and subtracting the water force $U = u\ell$ where u is the pore water pressure.) The shear force $\tau\ell$. The interslice forces are shown as effective interslice forces (E_1', E_2', X_1', X_2') together with water forces U_1 and U_2 whereas traditional analysis assumes total normal forces E_1 and E_2 and tangential shear forces X_1 and X_2.

The forces acting on each slice are illustrated in Figure 9.2. For the single slice, the Factor of Safety is given by (from Figure 9.2)

$$F = \frac{\tau\ell}{W \sin\alpha} \qquad [9.2]$$

By applying the Mohr-Coulomb strength relationship, i.e. $\tau = c' + \sigma_n'\tan\phi'$ where τ = available shear stress, c' = effective cohesion, σ_n' = effective normal stress on the shear plane and ϕ' = effective angle of friction at the slip surface. The Factor of Safety can now be written as

$$F = \frac{c'\ell + N'\tan\phi'}{W \sin\alpha} \qquad [9.3]$$

where $N' = \sigma_n'\ell$.

The effects of the single slice are added to the adjacent slices to give the overall Factor of Safety for the slip surface:

$$F = \frac{\Sigma(c'\ell + N'\tan\phi')}{\Sigma W \sin\alpha} \qquad [9.4]$$

In equation [9.4], N′ is obtained by the resolution of forces such that $N' = W\cos\alpha - u\ell + (X_2 - X_1)\cos\alpha - (E_2 - E_1)\sin\alpha$. Therefore substituting for N′, equation [9.4] becomes

$$F = \frac{\sum\left(c'\ell + (W\cos\alpha - u\ell)\tan\phi' + \left[(X_2 - X_1)\cos\alpha - (E_2 - E_1)\sin\alpha\right]\tan\phi'\right)}{\sum W \sin\propto} \qquad [9.5]$$

However, to solve equation [9.5] assumptions must be made regarding the interslice forces. Fellenius (1936), Bishop (1955), Janbu (1973) and Greenwood (1989) have solved equation [9.5] by making appropriate interslice force assumptions. The familiar stability analysis equations are thus given in Table 9.1 with the appropriate interslice force assumptions.

Table 9.1. Solutions and assumptions to the Factor of Safety equation.

Method	Equation	Assumptions
Swedish (*Fellenius*, 1936)	$F = \dfrac{\sum\left[c'\ell + \left(W\cos\propto - u\ell\right)\tan\phi'\right]}{\sum W\sin\propto}$	Water surface is parallel to the slip surface i.e. $(X_2 - X_1)\cos\alpha - (E_2 - E_1)\sin\alpha = 0$.
Bishop (1955)	$F = \dfrac{\sum\left[\dfrac{\left(c'b + (W - ub)\tan\phi'\right)\sec\alpha}{(1 + (1/F_m)\tan\phi'\tan\alpha)}\right]}{\sum W\sin\propto}$ where F_m is expressed in terms of moment equilibrium.	Tangential interslice forces are equal and opposite ($X_1 = X_2$) and the normal interslice forces are not equal ($E1 \neq E2$). NB. The value of F occurs on both sides of the expression, therefore an estimated value for F must be chosen on the right hand side to obtain a value of F on the left hand side. By successive iteration convergence on the true value of F is obtained.
Janbu (1973)	$F_f = \dfrac{\sum\left[\dfrac{\left(c'b + (W - ub)\tan\phi'\right)\sec\alpha}{(1 + (1/F_f)\tan\phi'\tan\alpha)\cos\alpha}\right]}{\sum W\tan\propto} \quad x\ f_0$	Identical to Bishop except that the equation is expressed in terms of horizontal force equilibrium and a compensation multiplying factor is introduced (typically $f_o = 1.05$).
Greenwood General (1989)	$F = \dfrac{\sum\left[c'\ell + \left(W\cos\propto - u\ell - \left(U_2 - U_1\right)\sin\propto\right)\tan\phi'\right]}{\sum W\sin\propto}$	The resultant of the effective interslice forces is parallel to the base of the slice, i.e. in the direction of movement – a logical assumption as failure progresses, i.e. $(X'_2 - X'_1)\cos\alpha - (E'_2 - E'_1)\sin\alpha = 0$. Replaces total interslice forces with effective interslice forces and horizontal water forces.
Greenwood Simple (1985)	$F = \dfrac{\sum\left(c'b\sec\alpha + \left[(W - ub)(1 + K\tan^2\alpha)\cos\propto\right]\tan\phi'\right)}{\sum W\sin\propto}$ where K is the coefficient of earth pressure.	A consistent horizontal water surface across the slice i.e. $U_2 - U_1 = -ub\tan\alpha$. It is conservative to assume $K = 0$.

9.3 Stability analyses including the effects of vegetation

The slope stability analysis equations, as listed in Table 9.1, have been developed to take into account the effects of the vegetation. The effects of the vegetation on the stability of a slope are initially described and the stability analysis equations with 'vegetation' are illustrated.

The main influences of vegetation on the stability of a slope are shown in Figure 9.3. The parameters reflecting the effects of vegetation in stability analysis are: -

- an additional effective (root) cohesion, c'_v.
- an increase in weight of slice due to the vegetation, W_v.
- a tensile reinforcement force by the roots present on the base of each slice, T.
- wind force, D_W.

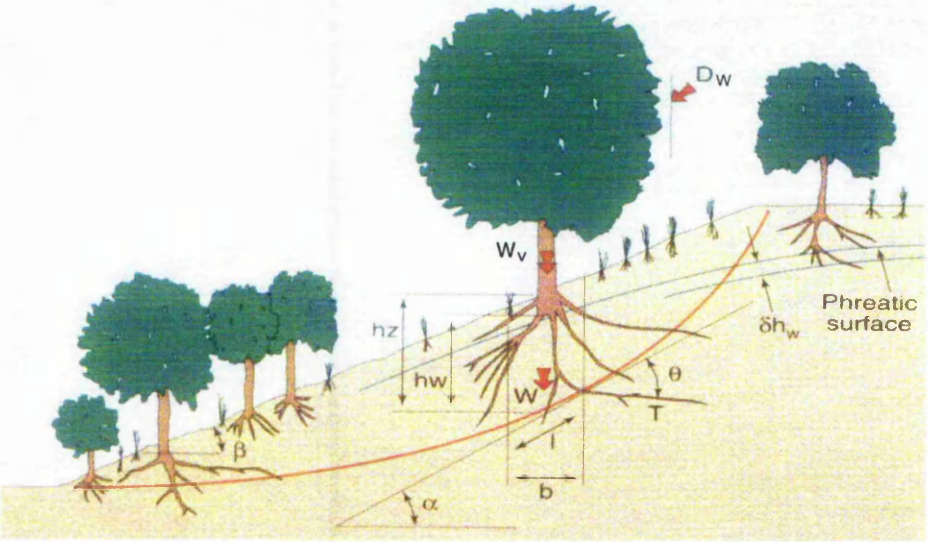


Figure 9.3. Forces acting on a vegetated slope (Greenwood *et al.*, 2004). Parameters: α – angle of slip surface; β – slope angle; D_w – wind force; b – width of slice; l – length of slice; h_z – height of slice above slip surface; h_w – height of phreatic surface above slip surface; δh_w – change in phreatic surface due to uptake of water by vegetation; W – total weight of soil slice; W_v – surcharge of vegetation; T – tensile force of roots acting on slip surface; θ – angle of roots to slip surface.

- possible changes in the undrained soil strength due to moisture removal by the vegetation, c'_s,
- suctions and changes in pore water pressure, u_v.

The parameters are fully described in Coppin and Richards (1990) and Greenwood *et al.* (2004). Greenwood *et al.* (2004) discusses the concepts and different scenarios as well as describing methods of characterising each of these parameters. A brief summary of the parameters are given here:

An additional effective (root) cohesion, c'_v – the effect of root reinforcement on the shear strength of soil is well documented and a number of root reinforcement models can be used to determine values of c'_v (see Chapter 7). Alternatively, root-soil strength or root cohesion can be determined by *in situ* shear testing (see Chapter 3). The reliable benefit of an enhanced c′ value is limited to shallow depths, as root distribution is mainly concentrated within 1 m of the ground surface (Greenwood *et al.*, 2004).

An increase in weight of slice due to the vegetation, W_v, – this parameter is only relevant when a soil slope is densely vegetated with large and tall trees (dbh[*] of >0.3 m and height >20 m (Coppin and Richards, 1990) since the weight of grass, herbs and small shrubs is comparatively insignificant. Trees on slopes have both an adverse and beneficial effect; surcharge increases the downslope forces while the additional vertical load increases the magnitude of the upslope forces. Trees located at the toe of a potential slip could add 10% to the factor of safety, although if located at the top of a potential slip the factor of safety could be reduced by 10%. Each situation must be individually assessed for the mass of vegetation involved (Greenwood *et al.*, 2004).

A tensile reinforcement force by the roots present on the base of each slice, T – the tensile strengths of roots of various diameters from different species have been measured in the laboratory and range from 2 – 68 MPa (Table 9.2). In the field, to make use of the available tensile strength to enhance slope stability the root must have sufficient embedment and adhesion with the soil. The available force contribution from the roots may be measured by *in situ* pull out tests (see Chapter 3). The maximum breaking force or pull out resistance of the roots together with an assessment of the root size and distribution (root area ratio, see Chapter 4) is used to determine the appropriate tensile root reinforcement values for inclusion in the stability analysis (see Section 9.3.1.1).

Wind force, D_W – loading by wind is usually only significant when winds are stronger than 11 m/s (Coppin and Richards, 1990) causing trees with shallow root systems to uproot and destabilise the soil slope.

Changes in the undrained soil strength due to moisture removal by the vegetation, c'_s – trees remove moisture from the soil by evapotranspiration thus enhancing the strength of the soil. Evapotranspiration is controlled by seasonal variation and climatic changes, therefore high levels of evapotranspiration occur in the summer and low levels in the winter, when the vegetation is dormant. In the winter months, soil moisture levels may build up to field capacity (the amount of water remaining in a soil after the soil layer has been saturated and the free (drainable) water has been

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[*] dbh = standard measurement of trunk diameter taken at breast height (1.3 m). On slopes, dbh is measured from the upslope side of the tree.

Table 9.2. Tensile root strength of selected shrub and tree species.

Species	Mean tensile strength (MPa)	Author
Acacia (*Acacia confusa*)	11	Schiechtl (1980)
Alder (*Alnus firma* var. *multinervis*)	52	Schiechtl (1980)
Common alder (*Alnus glutinosa*)	7	Greenwood *et al.* (2001)
Grey alder (*Alnus incana*)	32	Schiechtl (1980)
Ash (*Fraxinus excelsior*)	26	Riedl (1937)
Common beech (*Fagus sylvatica*)	55	Stokes and Mattheck (1996)
Red beech (*Nothofagus fusca*)	36	Schiechtl (1980)
Black Locust (*Robinia pseudoacacia*)	68	Coppin and Richards (1990)
Elder (*Sambucus nigra*)	28	Norris (see Chapter 4)
Hawthorn *(Crataegus monogyna)*	14	Norris (see Chapter 4)
Huckleberry (*Vaccinium* spp.)	16	Schiechtl (1980)
Small leafed lime *(Tilia cordata*)	26	Schiechtl (1980)
Lime (*Tilia parvifolia*)	21	Riedl (1937)
English oak (*Quercus pedunculata*)	45	Riedl (1937)
English oak (*Quercus robur*)	32	Schiechtl (1980)
Red oak (*Quercus rubra*)	32	Turmanina (1965)
Oak (*Quercus* sp.)	7	Norris (2005)
European spruce (*Picea abies*)	28	Schiechtl (1980)
Sitka spruce (*Picea sitchensis*)	23	Coppin and Richards (1990)
	16	Schiechtl (1980)
	35	Coutts (1983b)
	40	Lewis (1985)
Scots pine (*Pinus sylvestris*) - paperpot	7	Lindström and Rune (1999)
- naturally regenerated	20	
Maritime pine (*Pinus pinaster*)	17, 28	Dupouy (1992); Stokes (unpub data)
Poplar (*Populus deltoides*)	37	Schiechtl (1980)
Black poplar (*Populus nigra*)	5 - 12	Coppin and Richards (1990)
Poplar (*Populus yunnanensis*)	41	Hathaway and Penny (1975)
Rowan (*Sorbus aucuparia*)	10	Norris (see Chapter 4)
Scotch broom *(Cytisus scoparius)*	32	Schiechtl (1980)
Silver birch (*Betula pendula*)	37	Schiechtl (1980)
Silver birch *(Betula verrucosa)*	38	Riedl (1937)
Silver fir (*Abies alba*)	31	Stokes (unpub data)
Sycamore *(Acer pseudoplatanus*)	2	Clark (2002)
Grey willow (*Salix cinerea*)	11	Coppin and Richards (1990)
Crack willow (*Salix fragilis*)	18	Schiechtl (1980)
Willow (*Salix helvetica*)	14	Schiechtl (1980)
Contorted willow (*Salix matsudana*)	36	Schiechtl (1980)
Purple willow (*Salix purpurea*)	36	Schiechtl (1980)

Care must be taken when using this table, as the methodology employed differs between authors. Root diameter is not given and is also an important factor when considering root strength (Stokes, 2002).

allowed to drain away after 24 hours) and thus lead to failure of a soil slope. Vegetation can, however, modify the soil moisture content far beyond the physical extent of the root systems, i.e. up to 6 m radius and 4 m depth (Coppin and Richards, 1990). Note that, while changes in soil moisture content influence the undrained shear strength (c_u), the effective stress parameters (c' and ϕ') as generally used in routine stability analysis are not directly influenced by the changing moisture content, although the water pressures (suctions) used in the analysis will change.

Suctions and changes in pore water pressure, u_v – changes in soil moisture content result in changes in pore water pressures and soil suctions in partially saturated and saturated soils.

There are two approaches to including the effects of vegetation in stability analysis. The first approach is to include the effects within the limit equilibrium stability analysis methods as championed by Greenwood (1989, 2006). The second approach known as the energy approach is based on the total energy capacity of the soil-root system during shearing (Ekanayake *et al.*, 1997; Ekanayake and Phillips, 1999a, b, 2002). The two approaches are described in Sections 9.3.1 and 9.3.2.

9.3.1 The limit equilibrium approach

The influences of vegetation on the Factor of Safety of a slope can be modelled by routine limit equilibrium stability analysis methods, e.g. the method of slices. The limit equilibrium methods are discussed in Section 9.2. Two methods of analysis (Greenwood and Swedish) are readily adapted for including the influences of vegetation. Figure 9.4 shows the additional forces due to the vegetation, reinforcement and hydrological changes in the General Equation of Greenwood (2006). Greenwood (2006) purports that the addition of these influences of vegetation in other stability analysis methods such as Bishop and Janbu is not straightforward due to the iterative process and imposition of the Factor of Safety on to each slice. The stability analysis equations with the additional influences of the vegetation are given in Table 9.3.

An EXCEL spreadsheet, SLIP4EX, was developed by Greenwood (2006) to compare the various routine methods of analysis for a given slip surface and to quantify the changes to the Factor of Safety due to the influences of the vegetation. This spreadsheet was used to model the influence of the vegetation for the three study areas (see Section 9.4).

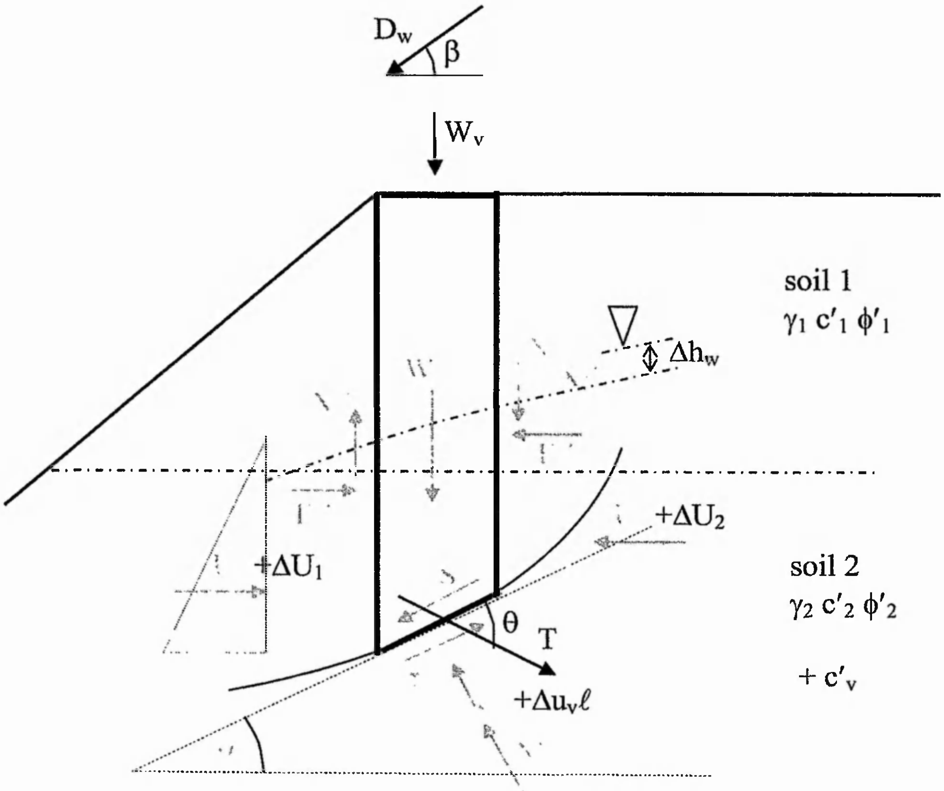


Figure 9.4. Additional forces due to vegetation, reinforcement and hydrological changes (Greenwood, 2006). Notation: c'_v – additional effective cohesion at base of slice due to vegetation, *etc.*; W_v – increase in weight of slice due to vegetation (or surcharge); T – tensile root or reinforcement force on slice; θ – angle between direction of T and base of slip surface; D_w – wind force (downslope); β – angle between wind direction and horizontal (often assume equal to slope angle); ΔU_1 – increase in water force on downslope side of slice; ΔU_2 – increase in water force on upslope side of slice; Δh_w – increase in average piezometric head at base of slice (due to vegetation); Δu_v – increase in average water pressure at the base of the slice.

Table 9.3. Stability analyses equations with vegetation parameters included.

Method	Equation	Assumptions
Greenwood General equation (Greenwood *et al.*, 2004)	$F = \frac{\sum[(c'+c'_v)\ell + ((W+W_v)\cos\propto -(u+\Delta u_v)\ell - ((U_2+\Delta U_{2v})-(U_1+\Delta U_{1v}))\sin\propto - D_w\sin(\alpha-\beta) + T\sin\theta)\tan\phi']}{\sum[(W+W_v)\sin\propto + D_w\cos(\alpha-\beta) - T\cos\theta]}$ where c′ = effective cohesion at base of slice, c'_v = enhanced cohesion due to roots, ℓ = length along base of slice, W = weight of soil, W_v = weight of vegetation, α = inclination of base of slice to horizontal, ϕ' = effective angle of friction at base of slice, u = water pressure on base of slice, Δu_v = change in water pressure due to vegetation, U_1 and U_2 = interslice water forces on left and right hand side of slice, ΔU_{1V} and ΔU_{2V} = change in interslice water forces due to vegetation, D_w = wind force, T = tensile force of roots, θ = angle of roots to slip surface.	Interslice water forces, U_1 and U_2, are assumed hydrostatic conditions below the phreatic surface or derived from a flow net for more complex hydraulic situations. Note: the tangential component of the root reinforcement force, $T\cos\theta$, is correctly deducted from the denominator as it is a negative disturbing force. In practice the term is often assumed to be a positive restoring force and is added to the numerator. This approach is statically correct in accordance with the force diagram. The differences in the calculated Factor of Safety by either approach are small with identical values calculated when F = 1 (Greenwood, 2006).
Swedish	$F = \frac{\sum\lvert(c'+c'_v)\ell + [(((W+W_v)\cos\propto -(u+\Delta u_v)\ell - D_W\sin(\alpha-\beta)+T\sin\theta))]\tan\phi'\rvert}{\sum[(W+W_v)\sin\propto - T\cos\theta + D_W\cos(\alpha-\beta)]}$ Notation as above.	

9.3.1.1 *Calculating T in Greenwood's General Equation*

In Greenwood's General equation, the tensile force contribution of the roots, T may be determined from the pull out resistance or breaking stress and the cross sectional area of the roots (root size and distribution) per unit area of soil (Norris and Greenwood, 2000b; Greenwood *et al.*, 2003; 2004; Greenwood, 2006).

The available root force acting on the base of each slice, T, is calculated by the equation:

$$T = T_{rd} \text{ x } \ell \qquad [9.8]$$

where T_{rd} is the available (design) root force per square metre of soil and ℓ is the length of the slip surface.

T_{rd} is based on the ratio of the measured (ultimate) pull out resistance (strength based on diameter at clamp), the mean root diameter and the number of roots per square metre across the slip plane (T_{ru}) to a partial Factor of Safety (F_r) to allow for uncertainty in root distribution and incompatibility of failure strain between the root and the soil (Greenwood *et al.*, 2003), i.e.

$$T_{rd} = \frac{T_{ru}}{F_r} = \frac{\text{ultimate root resistance (strength) x root area per square metre of soil}}{F_r} \qquad [9.9]$$

The uncertainty regarding root distribution in the ground and the resisting forces which are available in particular soil conditions require cautious selection of the value of F_r. Values of F_r of 8 or 10 (Norris and Greenwood, 2000b) have been assigned to reflect the uncertainties and to allow for the large strains, typically in the order of 20%, necessary to generate the ultimate root resistance to pull out (Greenwood *et al.*, 2004).

Greenwood (2006) assumes the angle θ between the root direction and the slip surface to be 45°. The assumption of $\theta = 45°$ is conservative because, as shearing occurs and the roots distort, the value of θ is likely to decrease thereby slightly increasing the available root resisting forces on the slip surface. Wu *et al.* (1979) showed from tests on inclined fibres that the effective angle varies between 40° and 70°. Greenwood *et al.* (2004) report that parametric studies on both geosynthetic and root reinforcement (Greenwood, 1990; Norris and Greenwood, 2003a, b) indicate that the calculated resistance due to the (root) reinforcement is not particularly sensitive to θ because as the enhanced normal component acting across the slip surface decreases, the tangential component increases and vice versa.

9.3.2 The Energy Approach

The energy approach was developed by Ekanayake *et al.* (1997), Ekanayake and Phillips (1999a, b, 2002), to take into account the contribution of roots to soil strength for specific New Zealand soils. In the stability analysis, the method incorporates the ability of tree roots to withstand strain during shear displacement. The characteristics of the shear stress–shear displacement curve obtained from an *in situ* direct shear test are used to find the total energy capacity of the soil-root system and the amount of energy exchanged up to the current displacement (Figure 9.5). The energy exchanged during the shearing process is directly related to the area between the stress-displacement curve and the x-axis. The total energy capacity of the soil-root system is the area under the soil with roots curve up to the shear displacement at peak shear stress.

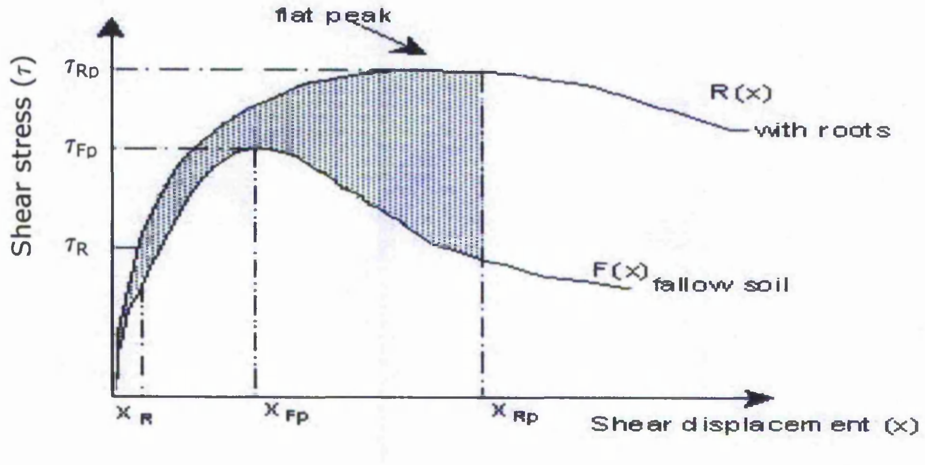


Figure 9.5. Ideal shear stress–displacement curves for fallow soil F(x) and soil with roots R(x). x_{Fp} is shear displacement at the peak stress (τ_{Fp}) for fallow soil, x_{Rp} is shear displacement of the peak stress (τ_{Rp}) for soil with roots (Ekanayake and Phillips, 1999b).

The Factor of Safety expressed in terms of energy is the ratio between the total energy capacity before failure and the energy consumed during the shearing process up to the current shear displacement x_{Rp}, i.e.

$$F = \frac{\int_0^{x_{Rp}} R(x)dx}{\int_0^{x_R} R(x)dx} \quad \text{where } x_{Rp} \text{ is maximum shear displacement.} \qquad [9.10]$$

The shear stress displacement curve can be approximated by an ellipse up to the peak shear stress, which enables the Factor of Safety to be evaluated in terms of shear displacement.

The energy approach is limited in its validity because the peak shear strength is resolved into two independent components: a soil strength component and root strength component. The soil-root cohesive strength properties are still a part of the soil-root interactions. Therefore, the root strength component may indirectly depend on the particular soil characteristics.

The energy approach stability analyses method estimates the Factor of Safety using the energy associated with the root-soil shearing process. The Factor of Safety is defined by the ratio of energy already spent up to the current shear displacement and the total energy capacity of the soil-root system. As the shear displacement is taken into account within the energy approach, it means that this method always overestimates the Factor of Safety when compared with that calculated by limit equilibrium methods. The validity of the energy approach has been questioned by Wu (2003) and as a result was not used in this thesis.

9.4 Effects of the vegetation as applied to the three study areas

The theoretical effects of the vegetation, i.e. the parameters listed in Section 9.3, are discussed with respect to the nature of the vegetation on the three study areas, and suitable values are suggested for modelling using the SLIP4EX program.

9.4.1 Root cohesion, c'_v

Root cohesion (c'_v) on highway embankments or cut-slopes such as those described in the three study areas, is in the order of 2-10 kN/m^2 (Figure 4.13, Section 7.3.2) for a mixed grass vegetation cover on London Clay soil. The amount of root cohesion provided by deep rooting shrubs and trees is only marginally greater than that of grasses (Table 7.2). The amount of root cohesion varies depending on the type of vegetation and within the same vegetation.

Grass with its dense network of roots acts at shallow depths (to 0.3 m) providing an increase in soil cohesion and preventing soil erosion, whilst deep rooting shrubs and trees have a wider range of root distribution with depth (to 1.5 m) therefore the root cohesion in this instance may be sufficient to enhance the soil cohesion.

The addition of the parameter c'_v in the analysis, therefore increases c' resulting in an increase in the Factor of Safety.

9.4.2 The mass of vegetation (surcharge), W_v

The mass of vegetation growing on a slope depends on the species, diameter, height and spacing of the trees. The total mass of a dense forest has been shown to exert a surcharge when considered to be uniformly distributed on a slope (Greenway, 1987). In reality, the weight of a tree is not distributed uniformly on the slope but is transmitted to the area within the root spread. Surcharge on a slope increases both the normal and downslope force components on potential slip surfaces. Surcharge has a net stabilising influence when the slope angle is less than angle of internal friction of the soil (Greenway, 1987; Coppin and Richards, 1990).

For the three study areas, the amount of surcharge applied in the models was calculated as follows: on Site 2, the hawthorn trees had an average biomass of 32.8 kg or 0.32 kN, average diameters (at breast height, dbh) of 0.08 m and an average height of 5.2 m (Norris, 2005). Comparing this data with say a 30 m tall tree having a dbh of 0.8 m and a weight of 100–150 kN (Coppin and Richards, 1990) the total mass of the vegetation on this site would in terms of stability analysis be insignificant in relation to the weight of the soil.

On Site 1, where there is a large area of grasses and small shrubs and an immature copse present, the surcharge applied to the slope would be insignificant, i.e. 0 kN. However Site 3, has some considerably mature vegetation, of tall (~20 m) ash and sycamore trees. The mass of these trees may therefore have a significant effect on stability. A mass of 100 kN was assumed for Site 3.

This parameter was disregarded in the analysis for Sites 1 and 2 but included for Site 3 (see Table 9.6).

9.4.3 Tensile root force contribution, T

The tensile strength contribution is probably the most significant parameter, which influences the results of the stability analyses. The equations [9.8 and 9.9] developed by Norris and Greenwood (2000b) and Greenwood *et al.* (2004) for the root tensile force contribution (T) were used to derive T values (Table 9.4) for the plant species used in the pull out resistance tests. The root force calculation is based on the pull out strength of the roots and the distribution of roots across a potential slip plane. It was assumed that T acts at an average of 45° to the slip plane (i.e. $\theta = 45^\circ$). An example of the root tensile force calculation for rowan roots on Site 1 is shown in Table 9.4 using the mean pull out strength as determined in Section 4.5.1.2.

Table 9.4. Root force calculation.

Number of roots per sq m	Typical root diameter m	Pull out strength kN/m^2	Ultimate root force T_{ru} kN/m^2	Applied Factor of Safety F_r (assumed)	Design root force T_{rd} kN/m^2	Root force on slice T kN
4	0.012	10000	4.52	8	0.57	0.81

9.4.4 Wind loading, D_W

Wind loading should be considered for the stability of individual trees but is of lesser significance for general slope stability where the wind forces involved represent a much smaller proportion of the potential disturbing forces and trees within a stand are sheltered to some extent by those at the edge (Coppin and Richards, 1990).

On Site 1, the copse of trees at the eastern end of the embankment may have a small wind loading effect, whilst the grassed area would not be affected by the wind. On Sites 2 and 3, which contain mature vegetation, wind loading may have a significant effect on the stability analysis, although this would obviously be dependent on the location of slope in relation to the prevailing wind direction.

To calculate the amount of wind loading on a forested slope, Hsi and Nath (1970) developed the following equation:

$$\mathrm{p} = 0.5\ \rho_{\mathrm{a}} V^2 \mathrm{C_D} \qquad [9.7]$$

where p = wind pressure, ρ_a = air density in kg/m^3, V = wind velocity in m/s and C_D = dimensionless drag coefficient. Greenway (1987) suggested that a 90 km/hour wind, at an air density of 1.22 kg/m^3 and a drag coefficient of 0.2 would have a wind loading of approximately 1 kPa at the edge of the forest.

9.4.5 Enhanced soil cohesion (c'_s) and pore water pressure (u_v)

In the routine assessment of the stability of slopes it is usually assumed that there is no soil suction. However, seasonal drying and wetting are likely to cause subsequent changes to the *in situ* suctions, especially during the summer months when suctions are high. Ridley *et al.* (2003) showed that cycles of suction such as those shown in Figure 9.6 can be detrimental to the serviceability of embankment structures.

Soil moisture content was monitored on Site 1 (as part of the ECOSLOPES project) by using theta probes (locations shown on Figure 4.9) for a period of three years. The probes measured soil moisture at depths of 0.1, 0.2, 0.3, 0.4, 0.6 and 1.0 m within the small copse area. The results of the monitoring showed that seasonality dominates the variation in soil moisture contents across the site. Lowering of the soil moisture content was apparent in the centre of the copse where the vegetation was at its densest (Anon, 2004; Norris *et al.*, 2004a).

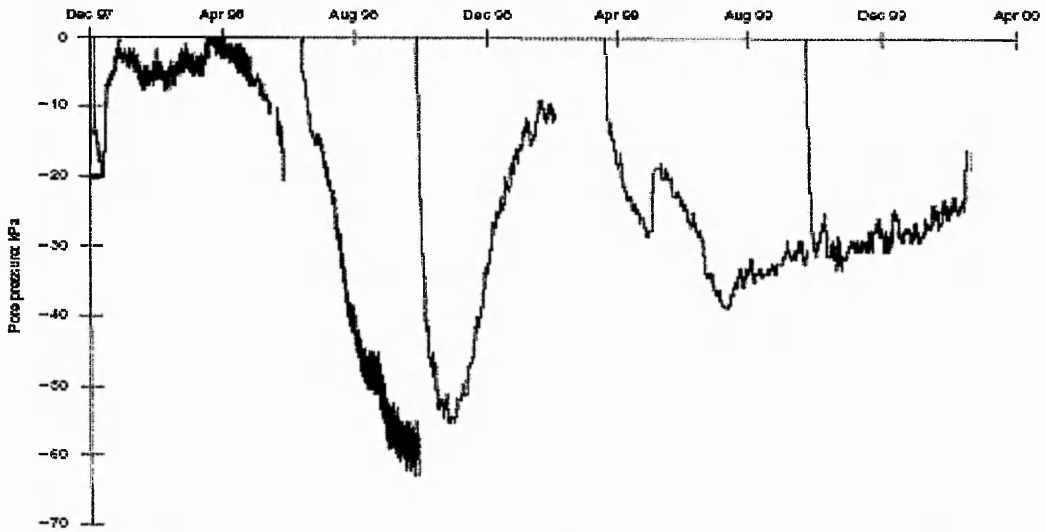


Figure 9.6. Example of pore pressure (suctions) measured at a depth of 2 m in an old railway embankment constructed of London Clay, with a surface vegetation of wild flowers and tall grasses (Ridley *et al.*, 2003).

Although, there is some debate about whether vegetation changes soil moisture content on embankments and cut-slopes, the effects are regularly observed in other situations, e.g., damage to buildings during drought conditions (Hunt *et al.*, 1991; Biddle, 1998). Therefore changes in pore water pressures and levels of the water table have been assumed and modelled for the three study areas. As the three study areas had different types of vegetation, the assumed values were different for each site (Table 9.6).

9.5 Modelling the effects of the vegetation using SLIP4EX

9.5.1 Analysis using SLIP4EX

The stability problem is drawn out to scale with the single slip surface defined as shown in Figure 9.7. All slice dimensions and the angles between the base of each slice and the horizontal, are scaled from the diagram. The soil property parameters for the particular problem can either be assumed, taken from laboratory tests or published sources. The data for each slice are manually input into the SLIP4EX spreadsheet (Sheet 1) program (Figure 9.8).

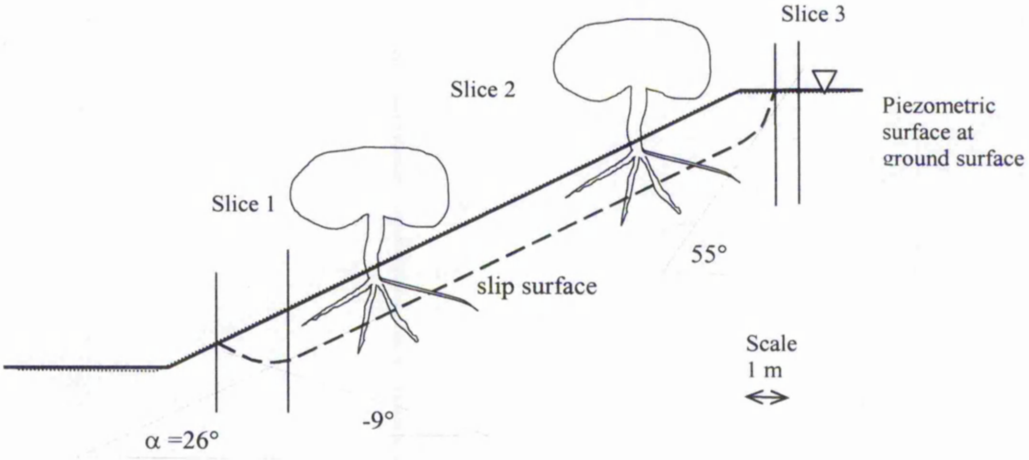
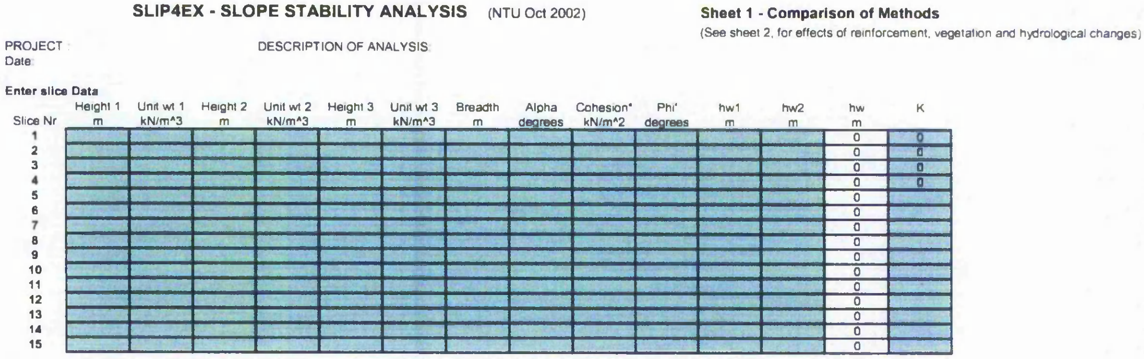


Figure 9.7. Scale drawing of an example slope and potential slip surface with example angles of slip surfaces (after Greenwood, 2006).



SLIP4EX - SLOPE STABILITY ANALYSIS (NTU Oct 2002)

Sheet 1 - Comparison of Methods

(See sheet 2, for effects of reinforcement, vegetation and hydrological changes)

PROJECT :
DESCRIPTION OF ANALYSIS:
Date:

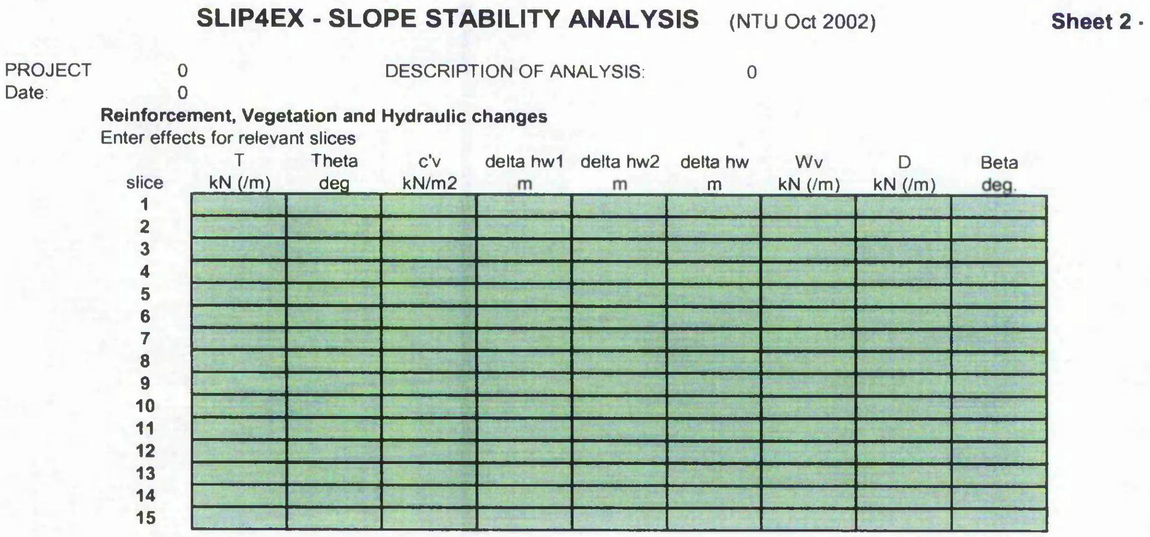
Enter slice Data

Slice Nr	Height 1 m	Unit wt 1 kN/m^3	Height 2 m	Unit wt 2 kN/m^3	Height 3 m	Unit wt 3 kN/m^3	Breadth m	Alpha degrees	Cohesion' kN/m^2	Phi' degrees	hw1 m	hw2 m	hw m	K
1													0	0
2													0	0
3													0	0
4													0	0
5													0	
6													0	
7													0	
8													0	
9													0	
10													0	
11													0	
12													0	
13													0	
14													0	
15													0	

Figure 9.8. Extract of SLIP4EX spreadsheet (Sheet 1) showing input parameters.

SLIP4EX calculates the forces acting on each slice of the analysis, the total forces acting on the slip surface and calculates the Factor of Safety of the slip surface using Greenwood, Janbu, Swedish and Bishop methods for the non-vegetated slope (as described in Section 9.2). There is the option within SLIP4EX to include the parameters relating to the effects of vegetation (Section 9.3). Again, appropriate parameters are assigned to each slice and manually input into the spreadsheet (Sheet 2, Figure 9.9). The changes in the Factor of Safety due to the effects of the vegetation are calculated using the modified Greenwood and Swedish equations as given in Table 9.3.

Further details of the SLIP4EX program can be found in Greenwood (2006).



SLIP4EX - SLOPE STABILITY ANALYSIS (NTU Oct 2002) **Sheet 2**

PROJECT 0 DESCRIPTION OF ANALYSIS: 0
Date: 0

Reinforcement, Vegetation and Hydraulic changes

Enter effects for relevant slices

slice	T kN (/m)	Theta deg	c'v kN/m2	delta hw1 m	delta hw2 m	delta hw m	Wv kN (/m)	D kN (/m)	Beta deg.
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

Figure 9.9. Extract of SLIP4EX spreadsheet (Sheet 2) showing the vegetation, hydrological and reinforcement parameters.

9.5.2 Parameters used in the SLIP4EX analysis

The soil parameters for each site, as given in Table 9.5, were used in the stability analysis models. The soil parameters used were derived from either published sources or soil characterisation data as given in Tables 4.1 and 4.2, Figure 4.8. The depth of the potential slip surface was assumed to be 1.5 m in all cases, this being representative of the majority of earthwork failures (Greenwood *et al*., 1985; Perry

Table 9.5. Soil and slope input parameters (assumed and derived) for SLIP4EX.

	Site 1	Site 2	Site 3
Soil type	London Clay (fill)	London Clay (Cut-slope)	Mercia Mudstone (fill)
Bulk unit weight, γ (kN/m^3)	19[1]	19[1]	21[2]
Cohesion, peak c_p' (kN/m^2)	13[3]	15[3]	8[3]
Friction angle, peak ϕ_p' (°)	20[4]	20[4]	43[3]
Slope angle (°)	26[3]	20[3]	25[3]

Notes:

1. Data from Skempton (1997), this value was used in preference to the data given in Tables 4.1 and 4.2.
2. From Chandler and Forster (2001).
3. Own data from Chapters 3 and 4.
4. From Skempton (1997).

Table 9.6. Vegetation input parameters in SLIP4EX.

Parameter	Site 1		Site 2	Site 3	
Case No.	A	B		A	B
Vegetation type	Grass	Mixed vegetation (immature)	Hawthorn	Mixed vegetation (shrubs and trees)	
Root tensile force, T (kN/(m)), based on 4 roots per sq m	0	0.57 – rowan 1.02 – mix of rowan, birch and hawthorn[1]	0.47[2]	1.24[3]	
Root direction, θ°	0	45	45	45	
Additional effective cohesion, c'_v (kN/m^2)	2	2	2	2	
Change in height of free water surface Δh_w (m)	0	0.2	0.2	0.5	
Mass of vegetation, W_v (kN/(m))	0		0	100	
Wind force, D_w (kN/(m))	0		0	0	1
Wind direction, β°	0		0	25	

Notes:

1. Based on pull out resistances of 10 MPa for rowan and 8 MPa for hawthorn (Chapter 4), and tensile strength of 37 MPa for birch (Schiechtl, 1980). Assumed average tensile strength of 18 MPa for the three species.
2. Based on pull out resistance of 8 MPa for hawthorn (Chapter 4).
3. Based on laboratory tensile strengths of 28 MPa for elder and 14 MPa for hawthorn (Chapter 4), and published tensile strength of ash of 26 MPa (Riedl, 1937). Assumed average tensile strength of 22 MPa for the three species.

et al., 2003a, b). Saturated conditions exist in all cases, i.e. phreatic surface is at the ground surface, since slopes fail mainly under these conditions. The vegetation input parameters included in the analysis are given in Table 9.6. The spreadsheets for each case study are included in Appendix 2.

9.5.3 Modelling using SLIP4EX

SLIP4EX was used to model (a) the vegetation parameters as determined by the field experiments for all three study sites and (b) the reduction in stability due to the loss of root strength by decay over time.

9.5.3.1 Modelling the vegetation parameters on the three study areas

The SLIP4EX spreadsheet produces comparative tables of Factors of Safety with and without the inclusion of the vegetation parameters for all limit equilibrium methods. The results of the modelling of the three study areas are given in Table 9.7 and Appendix 2, Figures B1–B5. It is apparent from Table 9.7 that all three slopes are currently stable (Factor of Safety > 1) for the input parameters given in Table 9.5. However, by using the experimental *in situ* and laboratory shear strength values the Factor of Safety values are too high. It is recognised that most embankments and cut slopes are only just stable with designed Factors of Safety of 1.2 – 1.4 (BS6031, 1981). Back analysis of failed slopes also reveals a much lower cohesion (c′) value than the experimental data, for example, Skempton (1997) showed that 60 mm shear box tests on brown London Clay give peak shear strength parameters of $c' = 14$ kN/m^2 and $\phi' = 20°$ whereas back analysis of a first time slide in London Clay gives parameters of $c' = 1$ kN/m^2 and $\phi' = 20°$. The models were therefore rerun with modified c′ values of $c' = 1$ kN/m^2 based on Skempton's (1997) back analysis (Table 9.8).

The revised Factors of Safety for the three study areas are shown in Table 9.9 and the corresponding spreadsheets are given in Appendix 2, Figures B6–B10. Note that, c'_v was increased to 5 kN/m^2 to demonstrate the added value of root cohesion. In the revised models, it is apparent that Sites 1 and 2 are both unstable without any type of vegetation being present on them and marginally stable with the presence of vegetation. These Factors of Safety are akin to actual conditions with

Table 9.7. Variation in Factor of Safety with and without vegetation parameters.

	Site 1 Case 1A - grass		Site 1 Case 1B - mixed vegetation		Site 2 – hawthorn trees		Site 3 Case 3A – mixed vegetation, no wind loading		Site 3 Case 3B – wind loading	
Analysis Method	No veg	Veg	No veg	Veg	No veg	Veg	No veg	Veg	No veg	Veg
Greenwood General	1.85	2.09	1.98	2.12	2.20	2.55	1.67	1.81	1.67	1.79
Greenwood Simple	1.91	2.14	2.03	2.11	2.27	2.62	1.86	1.99	1.86	1.98
Swedish	1.79	2.02	1.92	1.89	2.19	2.54	1.63	1.74	1.63	1.73

Key: Veg – vegetation.

Table 9.8. Modified soil input parameters for SLIP4EX.

	Site 1	Site 2	Site 3
Soil type	London Clay (fill)	London Clay (Cut-slope)	Mercia Mudstone (fill)
Bulk unit weight, γ (kN/m^3)	19^1	19^1	21^2
Cohesion, peak c_p' (kN/m^2)	1^1	1^1	2^4
Friction angle, peak ϕ_p' (°)	20^1	20^1	43^3
Slope angle (°)	26^3	20^3	25^3

Notes:
1. From Skempton (1997).
2. From Chandler and Forster (2001).
3. Own data from Chapters 3 and 4.
4. Assumed.

Table 9.9. Variation in Factor of Safety with and without vegetation parameters for modified soil conditions.

	Site 1 Case 1A - grass		Site 1 Case 1B - trees		Site 2		Site 3 Case 3A – no wind		Site 3 Case 3B - wind	
Analysis Method	No veg	Veg	No veg	Veg	No veg	Veg	No veg	Veg	No veg	Veg
Greenwood General	0.45	1.03	0.52	0.93	0.53	1.18	1.11	1.39	1.11	1.38
Greenwood Simple	0.50	1.09	0.57	0.92	0.60	1.26	1.30	1.57	1.30	1.56
Swedish	0.38	0.97	0.46	0.70	0.52	1.17	1.07	1.32	1.07	1.31

shallow slope failures occurring adjacent to both sites, see Figure 4.5 and Sections 4.1.2 and 4.2.2. Site 3 appears to be stable with or without vegetation.

The variation in Factor of Safety on Site 1 is due to the type of vegetation modelled in each case. In Case 1A, the grass although it has no tensile root force acting on the slip plane, it still provides root cohesion, and thus still increases the overall Factor of Safety when vegetation is taken into account. The enhanced root cohesion (of 5 kN/m^2) appears to significantly increase the Factor of Safety on both Sites 1 and 2.

For Site 3, the addition of wind loading forces in Case 3B marginally reduces the Factor of Safety for the slope. The stability gained by the root cohesion and tensile forces is clearly much more beneficial and far outweighs the minor loss in stability from the wind force.

9.5.3.2 Modelling loss of root strength with time

The effect of root decay or loss of strength after cutting down the vegetation was studied over a six month period on Site 3 (see Chapter 6). The values obtained for the change in tensile strength of the roots were modelled in SLIP4EX to determine the changes in stability through the loss of root strength.

Table 9.10. Initial vegetation parameters prior to vegetation removal.

Slice	Tensile strength MPa	No. roots per sq m	Angle root intersects slip plane θ°	Root diameter m	Root cohesion c'_v kN/m^2	Change in water level Δh_w m	Weight of vegetation Wv kN (/m)	Wind force D_w kN (/m)	Wind direction β°
1	16	4	45	0.012	2	0.35	100	0	0
2	16	4	45	0.012	2	0.7	100	0	0
3	16	4	45	0.012	2	0.35	100	0	0

The initial soil and slope input parameters were the same as that used in Table 9.8 for Site 3. The slope was modelled for changes in stability before the vegetation was removed and at intervals following removal. Initial vegetation parameters prior to vegetation removal are detailed in Table 9.10. The changes due to the decay of roots and removal of the above ground vegetation over a five year period are outlined in Table 9.11. The spreadsheets from the SLIP4EX program are figured in Appendix 3 (Figures C1-C7). Figure 9.10 shows graphically the change in Factor of Safety over the five year period. Generally there is a decrease in the Factor of Safety over the five year period, when at this time the Factors of Safety equal the Factors of Safety for the original non-vegetated slope. The most striking change is the significant drop in Factor of Safety immediately after the vegetation has been removed. As the only vegetation parameter that has changed is the mass of the vegetation, the rapid removal obviously creates unstable conditions in the short term. This is reminiscent of the newspaper article by Payne (2003) in January 2003, when trees had been cut down on a railway embankment just before the embankment failed after heavy rains. The loss of the trees removed the additional loading that they were adding to the slope and also the protection layer that trees provide during precipitation to the ground surface. The removal of the trees thus removed the potential for interception and infiltration by the plants foliage and active root system thereby decreasing the stability of the embankment.

Table 9.11. Changes to the vegetation parameters following vegetation removal.

Time from removal of vegetation	Changes to vegetation parameters
Immediately after removal of vegetation	Remove W_v from analysis, all other parameters stay the same.
One month	Reduced drawdown of Δh_w, tensile strength reduced to 14 MPa (Chapter 6)
Three months	Water level now returned to phreatic surface at ground level (assumed), the number of effective roots crossing the slip plane is reduced to 3 (assumed), tensile strength reduced to 11 MPa, no c'_v (assumed).
Six months	The number of effective roots crossing the slip plane is reduced to 1 (assumed), although tensile strength is increased to 14 MPa (as per results in Chapter 6)
One year	Tensile strength reduced to 9 MPa (assumed)
Five years	Tensile strength reduced to 2 MPa (assumed)

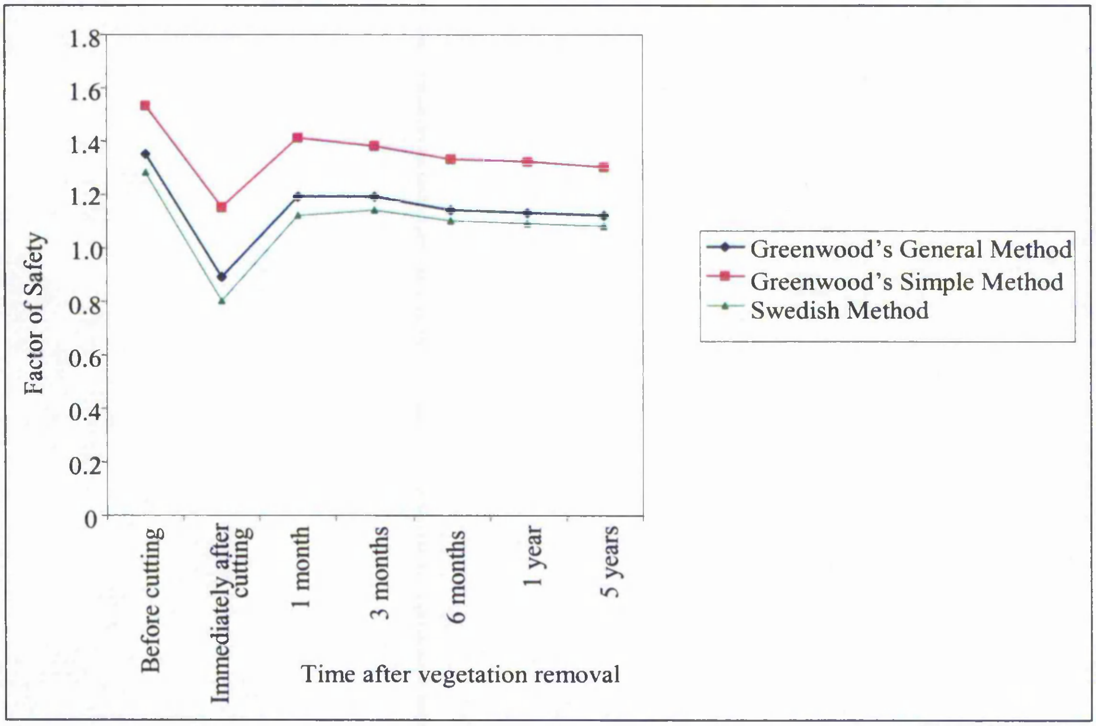


Figure 9.10. Changes in Factor of Safety and stability for Site 3 due to removal of vegetation. Note – stability of the soil slope without vegetation is 1.11 for Greenwood's General Method, 1.30 for Greenwood's Simple Method and 1.07 for the Swedish Method.

9.6 Summary

Methods of analysing the stability of a slope have been reviewed and methods identified for including the effects of vegetation. The Greenwood (General and Simple) and Swedish methods were found to be the most appropriate methods for including the effects of vegetation. The vegetation parameters which influence the analysis are: root cohesion, c'_v; weight of the vegetation, W_v; root tensile force, T; wind force, D_W; changes in the undrained soil strength due to moisture removal by the vegetation, c'_s and changes in pore water pressure, u_v.

The SLIP4EX program, designed by Greenwood (2006), allows modelling of both non-vegetated and vegetated slopes and also provides comparative limit equilibrium methods of analysis. SLIP4EX was used to model the stability of the three study areas and also to model the changes in stability due to removal of vegetation. The modelling showed that including vegetation parameters can significantly increase the Factor of Safety of a slope (up to 20%). The effect of removing vegetation has a significant impact in reducing stability in the immediate term but over the long term the stability reduced to the stability of the non-vegetated slope.

All sites have differing and variable ground conditions therefore each individual slope stability case must be carefully assessed and modelled on its own merits. The modelling carried out in this thesis should not be used and applied to other sites.

Cautionary note: Vegetation and roots must not be relied up on where life and property are at risk and other engineering solutions may be more acceptable and readily available. The author does not accept responsibility for any slope failure resulting from work carried out based on this research.

Chapter 10: Conclusions, Recommendations and Future Research

10.1 Conclusions and recommendations

The purpose of research embodied in this thesis was to investigate the role of vegetation in stabilising shallow slope failures by considering the mechanics of the roots and their corresponding parameters for use in slope stability analyses. The key mechanical properties of roots that assist in slope stabilisation are the tensile strength of the root, its resistance to uprooting and the reinforcing effects that the roots exert on the soil mass. In addition to the mechanical properties, the distribution, morphology and architecture of the plant's root system is important for ensuring that roots are of a certain length, diameter and abundance so that they intersect with potential slip planes and provide sufficient reinforcement to promote stability.

To assist geotechnical engineers and other non-plant specialist disciplines, the biological component parts of a root were first reviewed and then simplified into two components: the bark and the inner core. The structural aspects of roots were found to be important when carrying out root pull out resistance and tensile strength tests, due to the variation in strength of the bark and the core, and the presence of fluids between the bark and core resulting in separation of the two parts when pulled apart.

Since natural vegetation is not widely recognised as a suitable material for slope stability within the civil engineering community in the United Kingdom, there are relatively few standard procedures and practices for investigating the geotechnical characteristics of vegetation and for recording detailed measurements of roots prior to and after testing. A new procedure for measuring the geotechnical characteristics of the roots and vegetation prior to and after *in situ* testing was therefore devised and a suitable data sheet formulated.

Methods of measuring root characteristics, distributions and describing root morphology, were adapted from other scientific disciplines, for example, techniques such as the profile trench wall method for counting the number and area of roots at depth, and hand and mechanical excavation of root systems to determine length, direction, size and branching arrangements of roots were employed.

The *in situ* strength of roots and soil was successfully determined by carrying out *in situ* shear box and root pull out tests. A portable multi-purpose apparatus was designed and developed for measuring root-soil strength. The apparatus could either be used for measuring the resistance of roots during pull out or for measuring the shear strength of a rooted soil mass. The combined root-soil *in situ* shear test was a much more complex and difficult test to perform than the root pull out test. This was demonstrated by the relatively few tests that were carried out and the problems encountered and limitations of *in situ* shear testing. However, it is recommended that a small-sized shear box is used for testing fine root networks or for single individual roots of small diameter. A larger-sized box is thus recommended for substantial root systems and roots of medium-large diameters. The *in situ* shear box test does give values of root reinforcement or root cohesion c'_v for use in the slope stability analysis calculations. However, caution must be applied if c' values are determined by in situ shear testing as these values usually overestimate the actual c' values that are derived by back analysis of first time slides.

Root cohesion c'_v can also be determined from the perpendicular root reinforcement model, which incorporates the root area ratio values as determined from root distribution counts.

The root pull out resistance test was a relatively rapid and easy test to perform. The values of root resistances to pull out can be readily adapted and included in the calculations of slope stability with vegetation i.e., Greenwood's stability equation. This can be done by converting the pull out resistance to a root tensile force using the ultimate strength, root distributions and applying a partial safety factor.

The mechanics of uprooting can be modelled by considering the pull out of a single root or a complex root system. Both models consider that the tensile strength of the root must be fully mobilised during failure such that the frictional bond between the roots and the soil exceeds the tensile strength of the roots, otherwise the root will either slip (pull) out, stretch or break.

The mechanics of uprooting are clearly linked to the morphology of the roots. In the pull out tests of the hawthorn roots, three types of failure mechanisms were linked to variations in root morphology. Type A consisted of a single root failure with rapid rise in pull out resistance until failure; Type B consisted of a double peak failure of a forked or branched root and Type C consisted of a stepped failure with multiple branches failing successively. These types of pull out failures and their associated root morphologies had similarities with pull out tests conducted on maple and ash trees by Riestenberg (1994).

Tensile strengths of hawthorn and elder roots both show decreasing tensile strength with increasing root diameters; this finding is consistent with previous studies of root tensile strengths (Turmanina, 1965; Wu, 1976; Burroughs and Thomas, 1977; O'Loughlin and Watson, 1979; Gray and Sotir, 1996; Nilaweera and Nutulaya, 1999; Operstein and Frydman, 2000; Genet *et al.*, 2005). The large-scale variation in root tensile strength is attributed to the anatomical differences in the structure of the root, in particular the cellulose and lignin content.

When the pull out resistances of roots are compared with the laboratory derived tensile strengths, it is apparent that the pull out resistance underestimates the actual tensile strength of the root. Field observations showed that the pull out stress was within 50-70% of the tensile strength.

The framework established by Greenwood *et al.* (2004) for assessing the contribution of vegetation to slope stability was applied to this research. The vegetation parameters which influence the analysis of a slope are: root cohesion, c'_v; weight of the vegetation, W_v; root tensile force, T; wind force, D_w; changes in the undrained soil strength due to moisture removal by the vegetation, c'_s and changes in pore water pressure, u_v. For each of these parameters, values were assumed, estimated or derived from actual test results so that the stability of the three study areas could be modelled.

From the review of limit equilibrium and finite element methods for slope stability analysis, the Greenwood (General and Simple) and Swedish methods were found to be the most appropriate methods for analysing a vegetated reinforced slope. The SLIP4EX program successfully models both non-vegetated and vegetated slopes and also provides comparative limit equilibrium methods of analysis.

The SLIP4EX program was used to model the stability of the three study areas and also to model the changes in stability due to removal of vegetation. The modelling showed that including vegetation parameters can significantly increase the Factor of Safety of a slope by up to 25%, for example Factor of Safety increases from 1.07 to 1.32. The effect of removing vegetation has a significant impact in reducing stability in the immediate term (Factor of Safety reduces from 1.35 to 0.89) but over the long term the stability slowly reduces to the stability of the original non-vegetated slope.

Overall, the results of the research contained herein have shown that hawthorn and elder (used in isolation) would not be sufficient to stabilise a shallow landslip at 1-1.5 m depth since both species lacked sufficient rooting depth. Both species could potentially be used in conjunction with other more deep rooting species such as willows, as both species provide good surface root reinforcement. The modelling showed that when sufficient numbers of roots of a certain tensile force interact with the slip plane, then a shallow slope failure can be prevented and the Factor of Safety for that slope can be increased.

Vegetation should now be considered as a practical engineering material as it can be monitored and tested successfully. The contribution of the vegetation can be incorporated into routine site investigation (Greenwood *et al.*, 2006) and its suitability can be assessed using a slope decision support system (SDSS) prior to construction works (Norris and Greenwood, *in press*). New data sets have been compiled that give information on the tensile strengths, effective root cohesion and the depth and extent of root systems for a wide range of species including grasses, woody shrubs and trees that exist and are used for aesthetic purposes on embankments and cut slopes. These new data sets can be used as input data for modelling slope stability with vegetation.

10.2 Future research

Future research to further develop the knowledge regarding the interactions between roots and soil should be concentrated on testing more of the commonly found vegetation species to enhance the data set of information on root depth, architecture and root strength. The testing of more species would assist in the validation of the classification scheme of the links between root morphology and mode of failure as observed during the pull out tests.

For the pull out testing, it is recommended that different size clamps and strops be trialled and tested as a means of clamping on to roots, to enable a wider range of root diameters to be tested.

The case study investigating the immediate loss of root strength following vegetation removal showed that when a few small young trees are removed, there is very little effect on root strength. Therefore, to test the theory that clearing large amounts of vegetation from earthworks promotes land instability, a number of readily accessible earthworks require allocating as experimental test sites so that changes in root strength, moisture conditions, soil suctions and climate effects can be monitored over a longer time scale (up to 10 years).

The method of calculating root forces as described in the routine stability analysis (Section 9.3.1.1), currently requires the use of high partial Factors of Safety (say $F_r = 8$ or more) to allow for the uncertainties and variability in the assumed or observed root distribution with depth, the availability of adequate root-soil adhesion throughout the seasons of the year and the large strains generated to achieve the ultimate pull out forces. Further research into the location of roots at certain depths and the variability of root networks with seasonal change could lower the required partial Safety Factor.

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Appendices

Appendix 1: Root pull out graphs of rowan, oak and hawthorn.

Appendix 2: SLIP4EX spreadsheets showing variation in stability of the three study areas

Appendix 3: SLIP4EX spreadsheets showing changes in Factor of Safety following removal of vegetation

Appendix 4: Published papers.

Appendix 1: Root pull out graphs

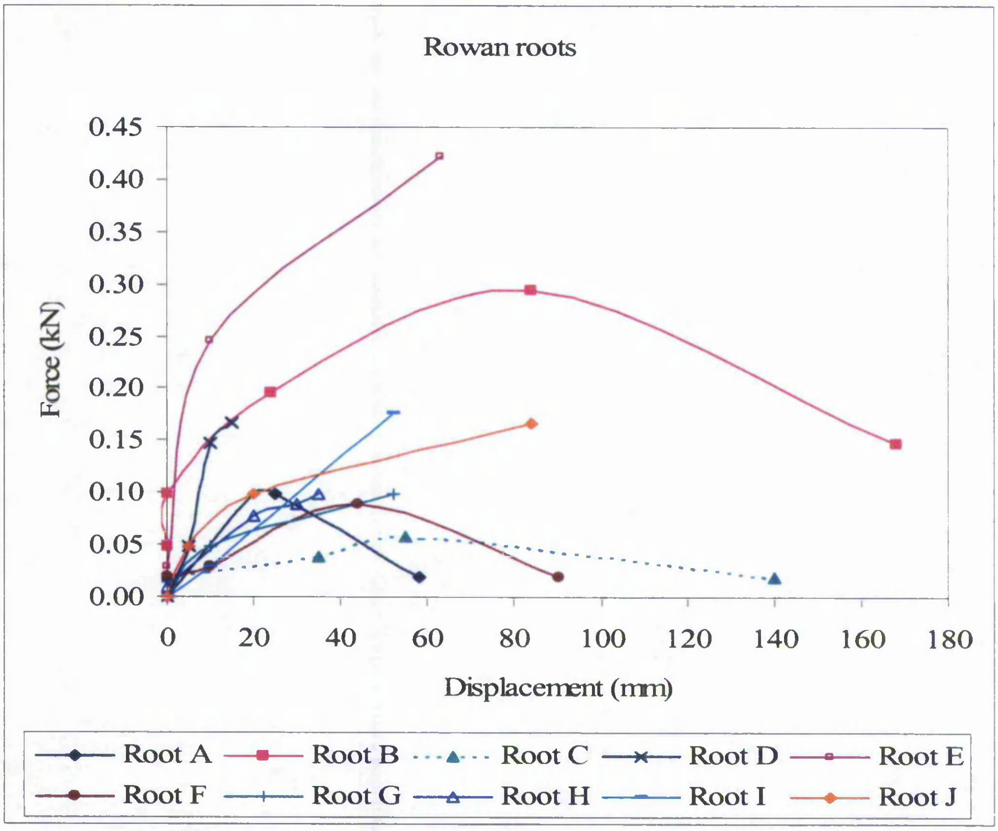


Figure A1. Root pull out graphs of Rowan roots.

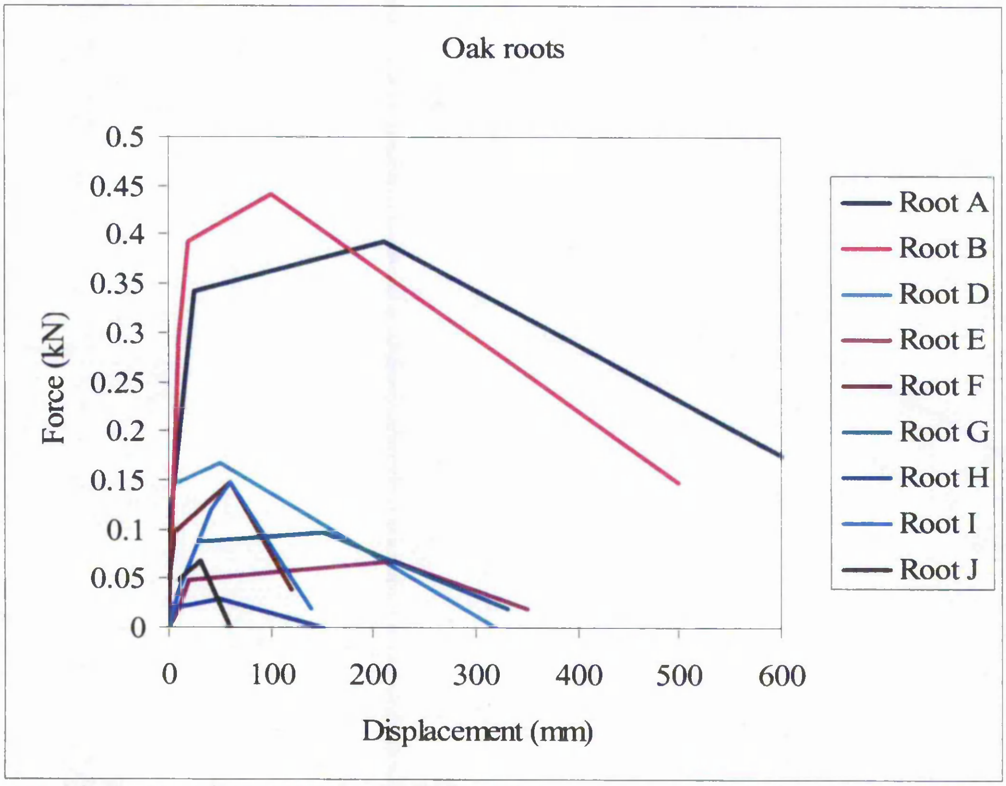


Figure A2. Root pull out graphs of Oak roots.

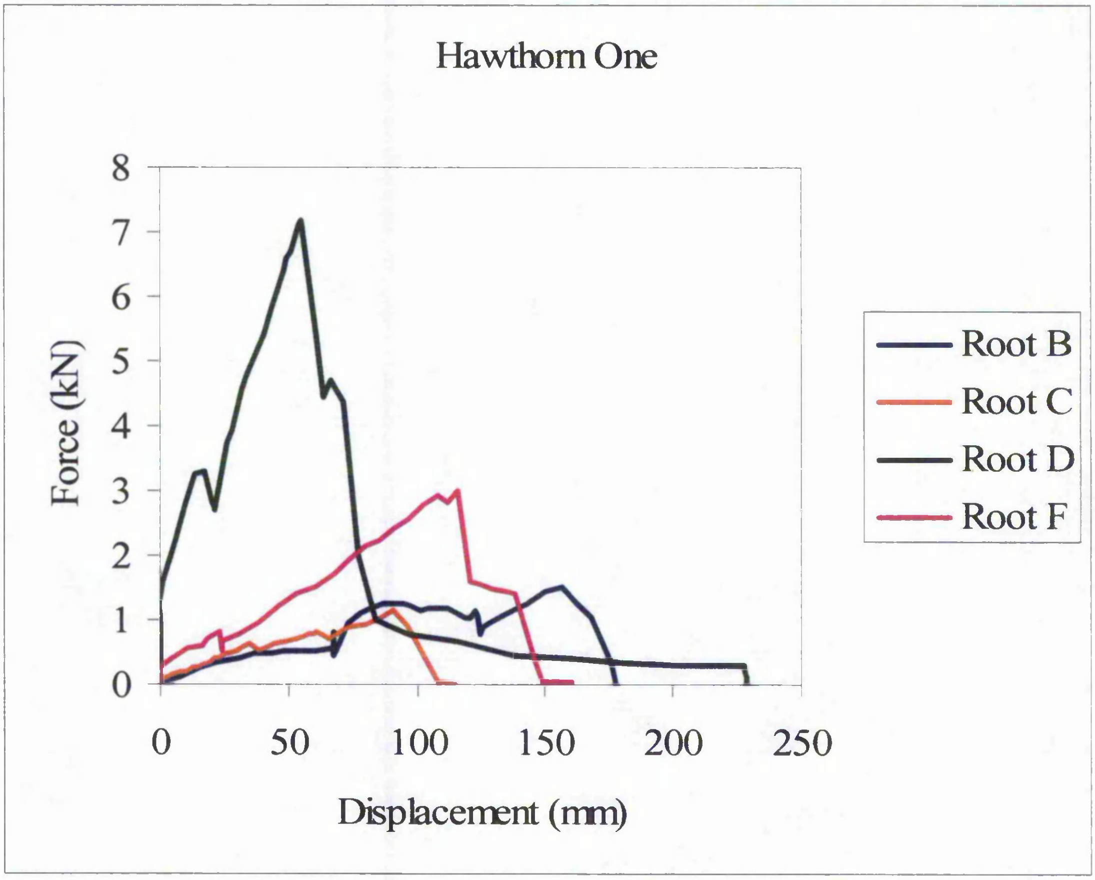


Figure A3. Root pull out graphs of Hawthorn 1 roots B, C, D and F.

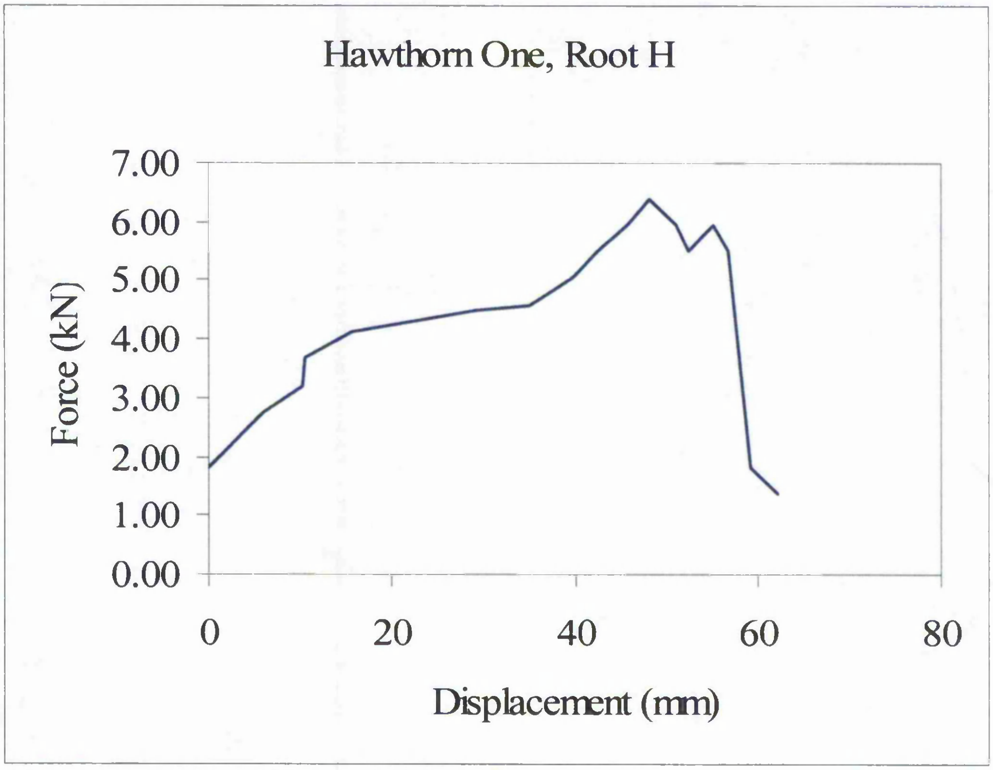


Figure A4. Root pull out graph of Hawthorn root 1H.

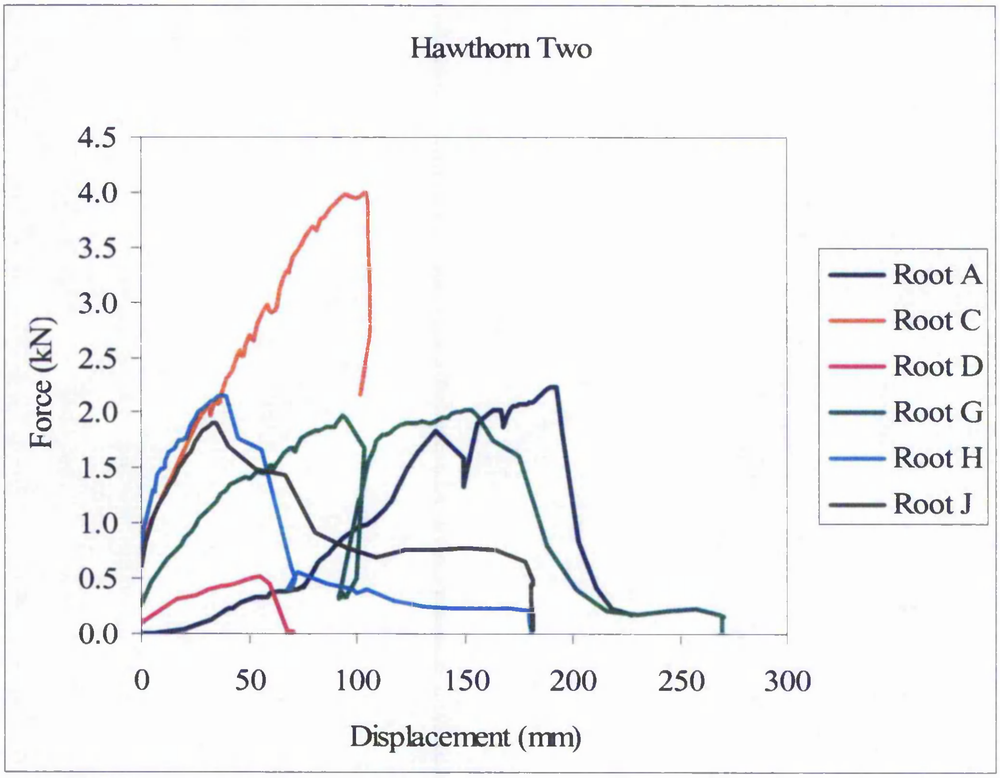


Figure A5. Root pull out graphs of Hawthorn 2 roots A, C, D, G, H and J.

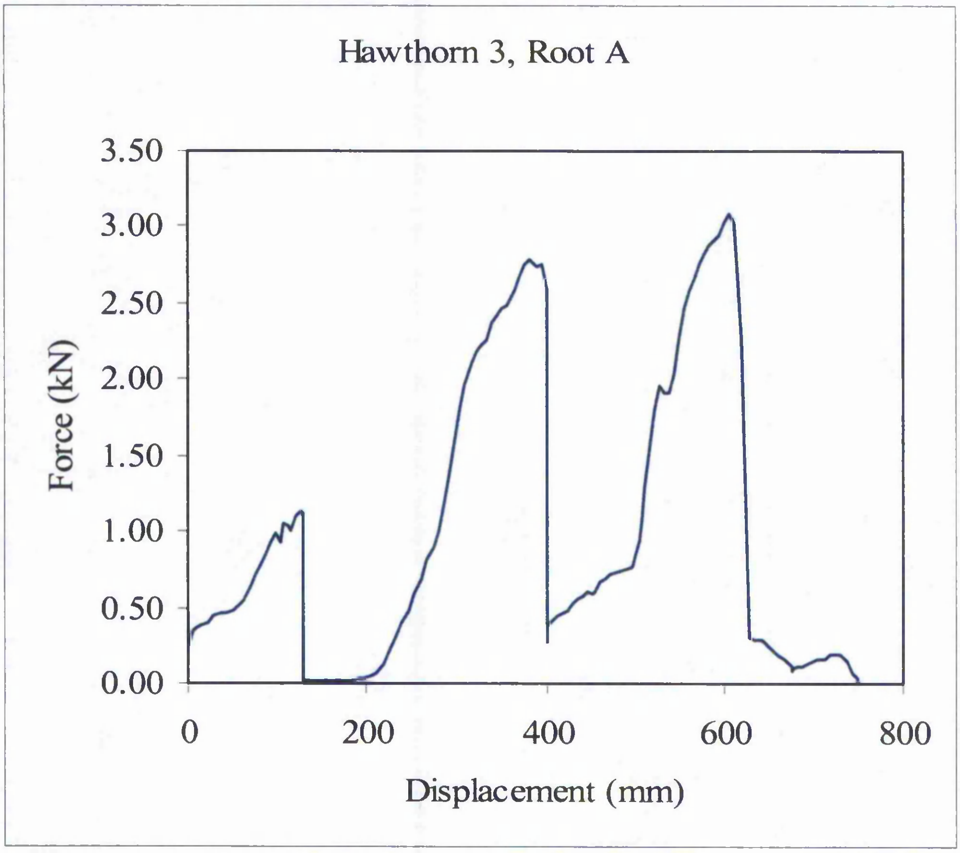


Figure A6. Root pull out graph of Hawthorn root 3A.

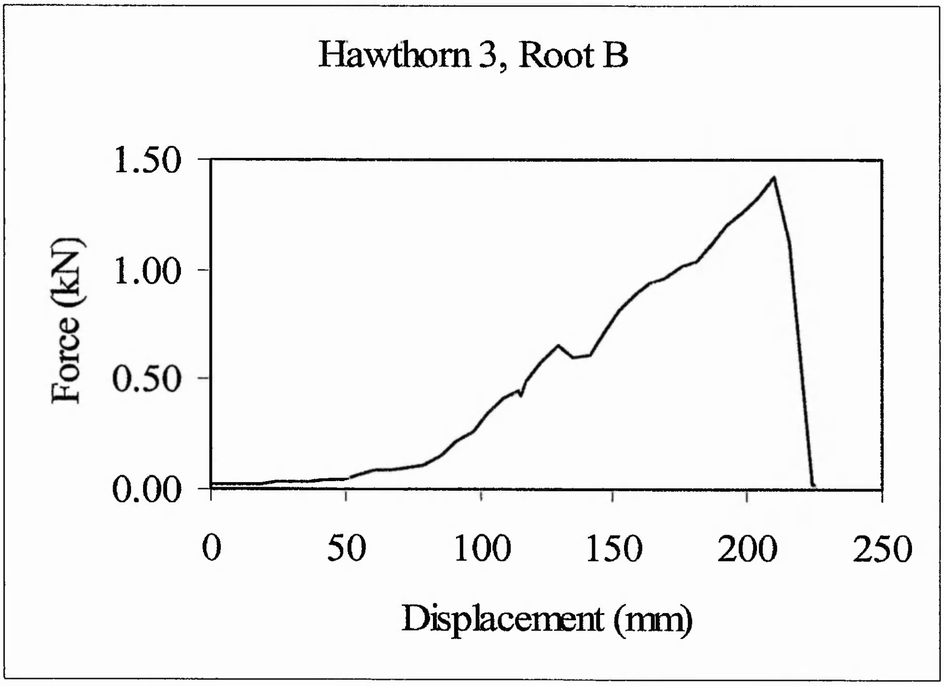


Figure A7. Root pull out graph of Hawthorn root 3B.

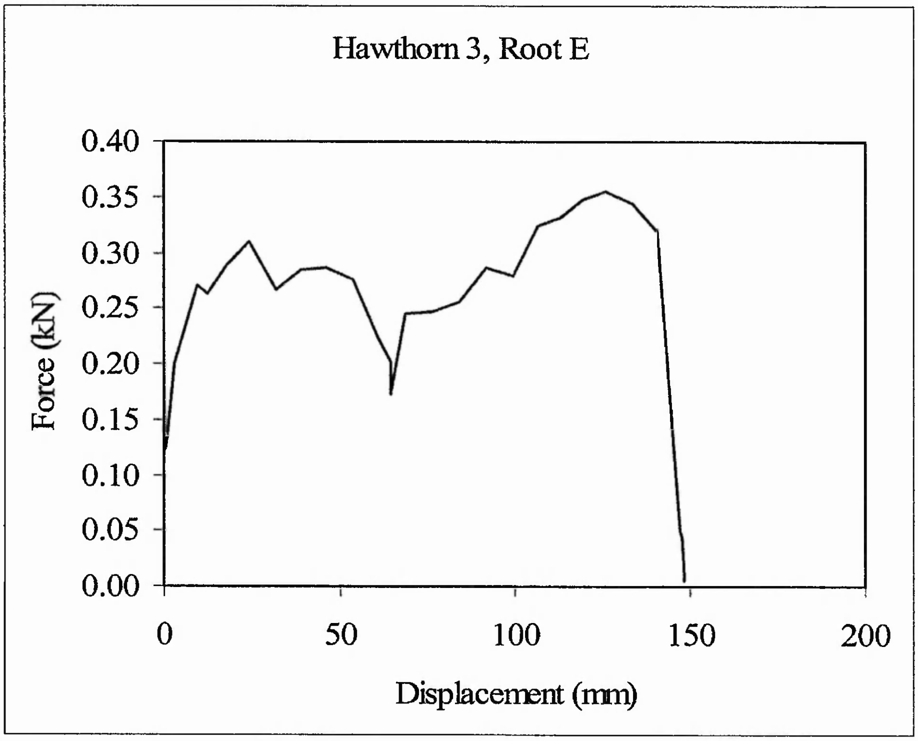


Figure A8. Root pull out graph of Hawthorn root 3E.

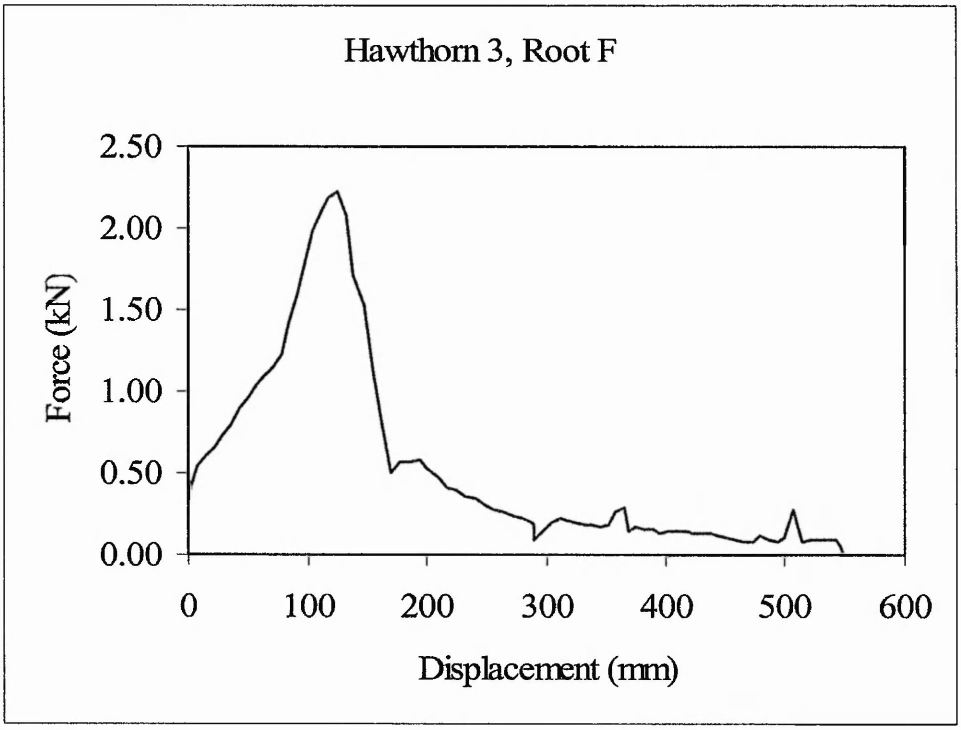


Figure A9. Root pull out graph of Hawthorn root 3F.

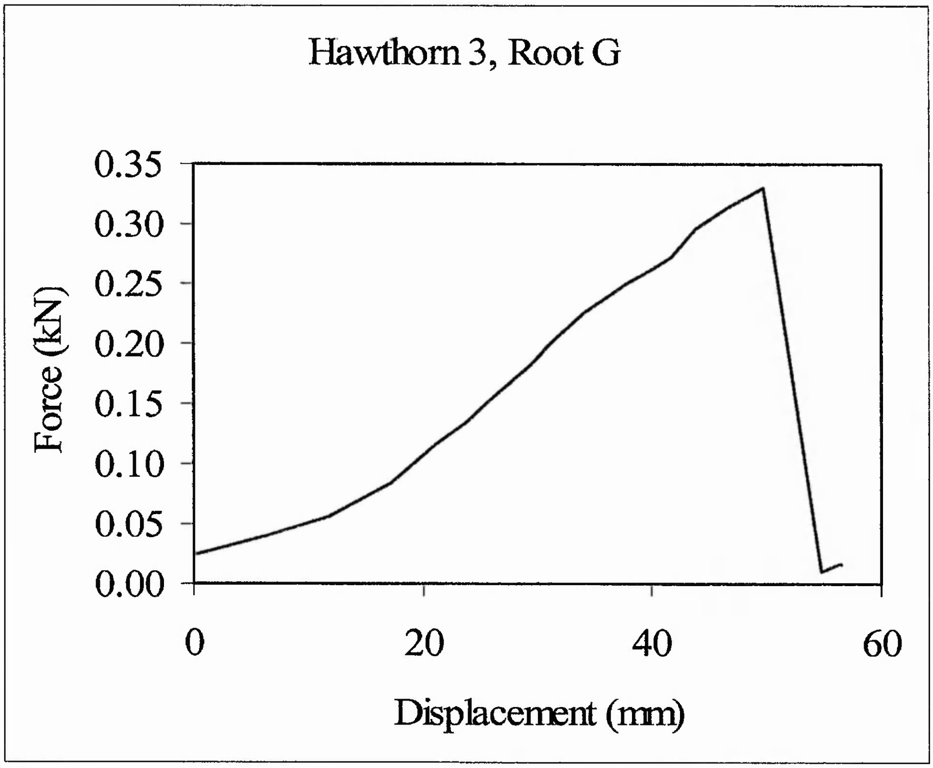


Figure A10. Root pull out graph of Hawthorn root 3G.

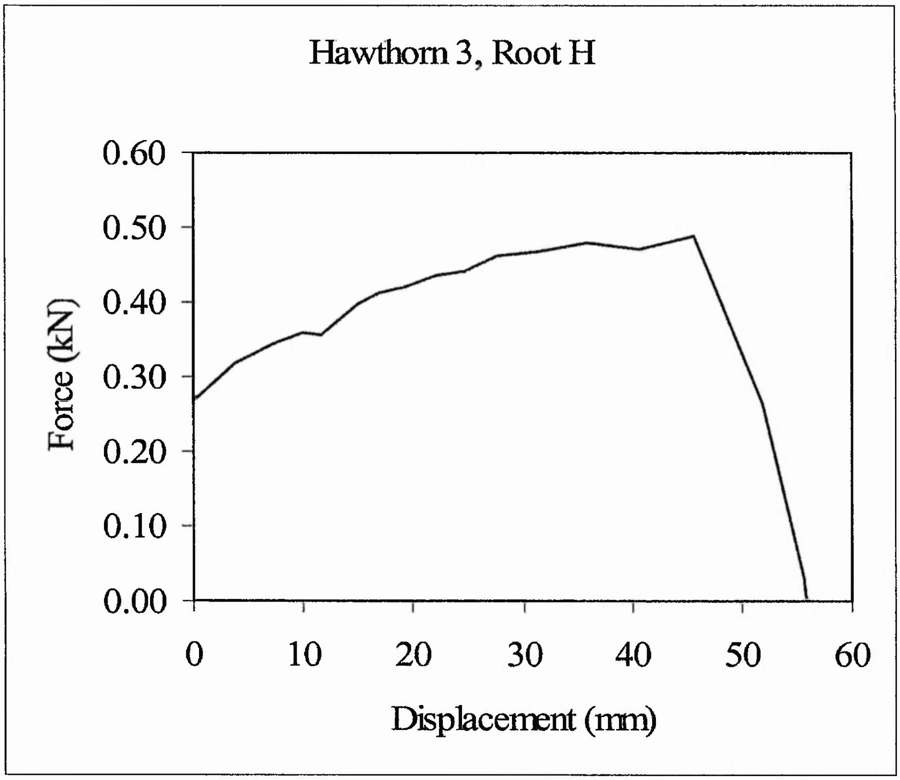


Figure A11. Root pull out graph of Hawthorn root 3H.

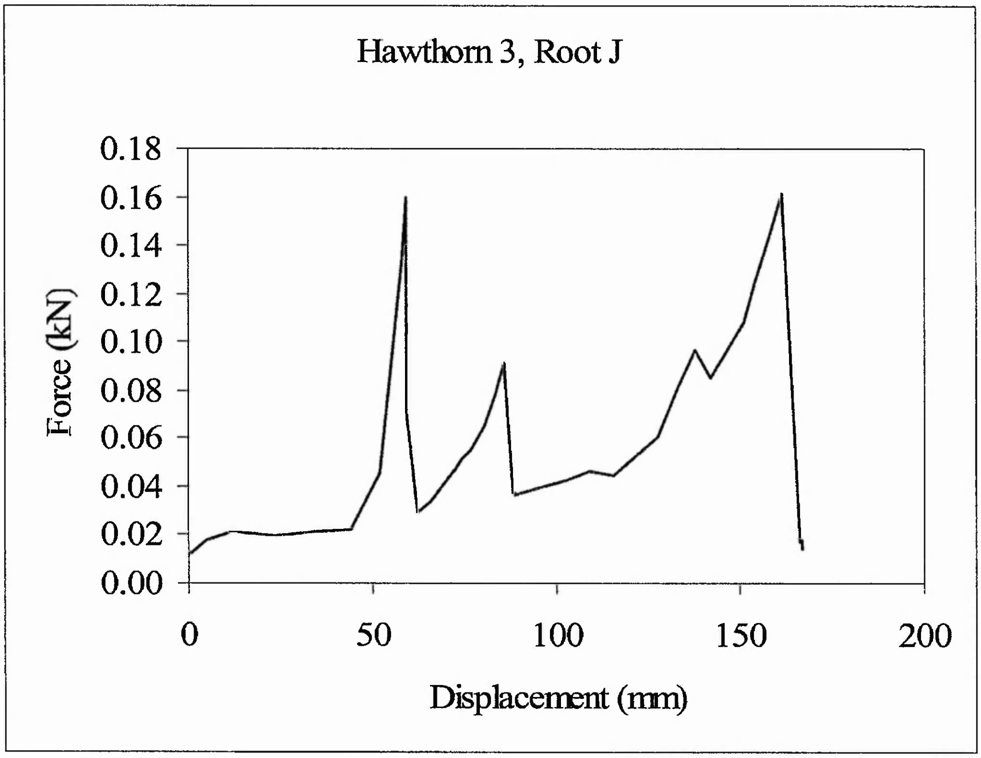


Figure A12. Root pull out graph of Hawthorn root 3J.

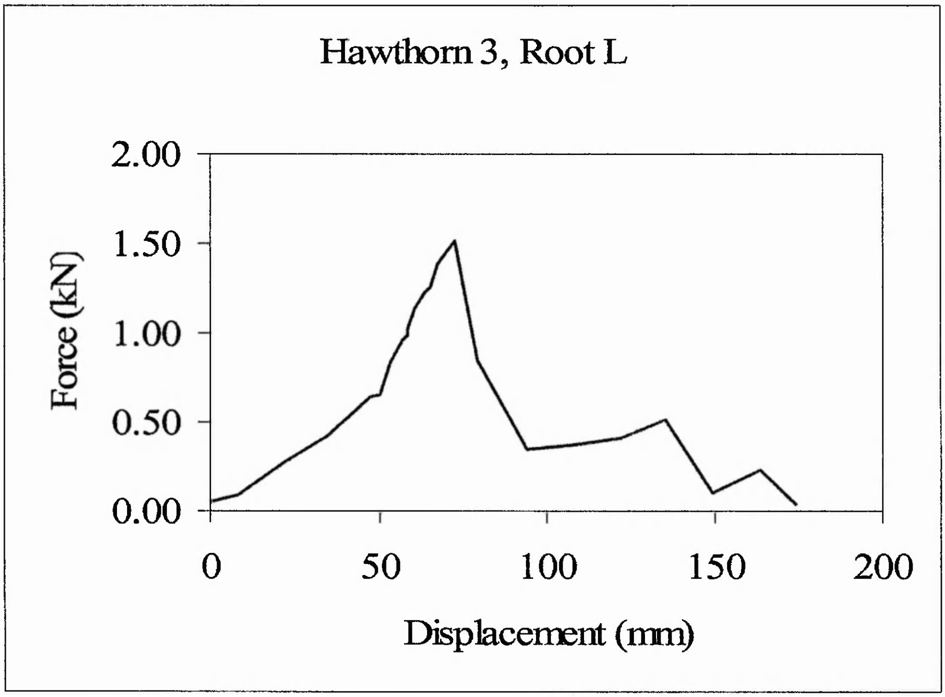


Figure A13. Root pull out graph of Hawthorn root 3L.

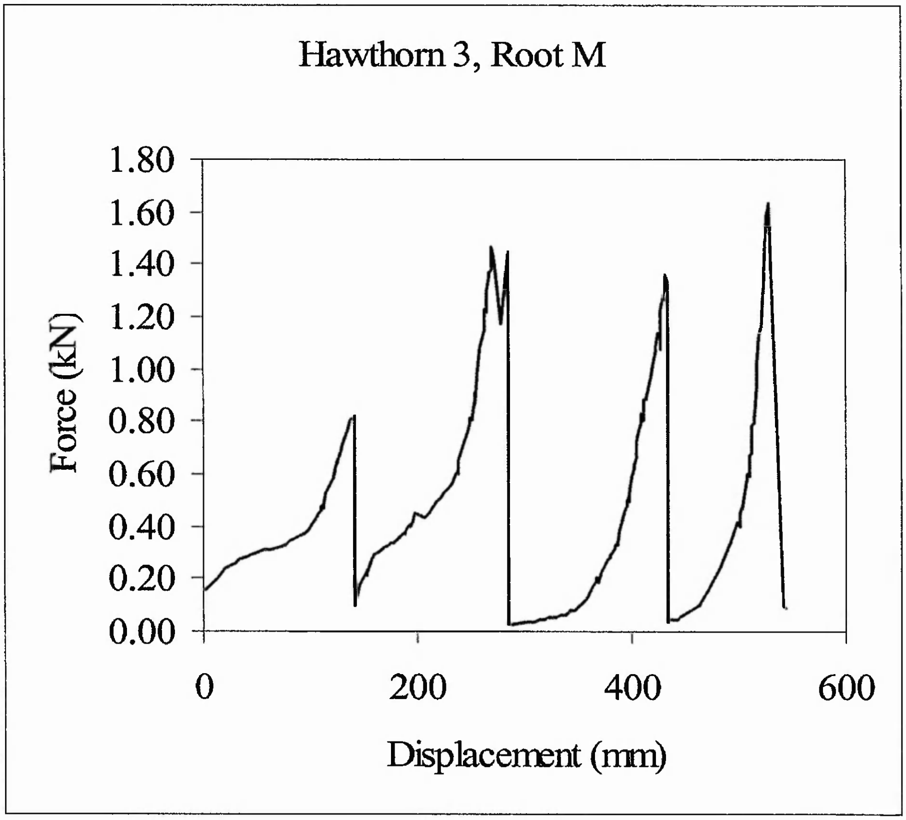


Figure A14. Root pull out graph of Hawthorn root 3M.

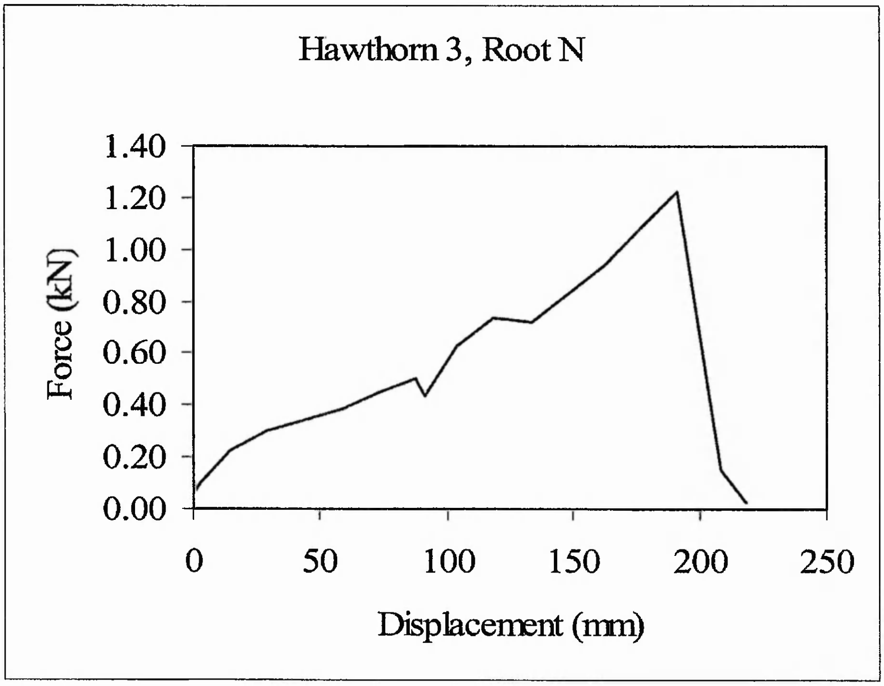


Figure A15. Root pull out graph of Hawthorn root 3N.

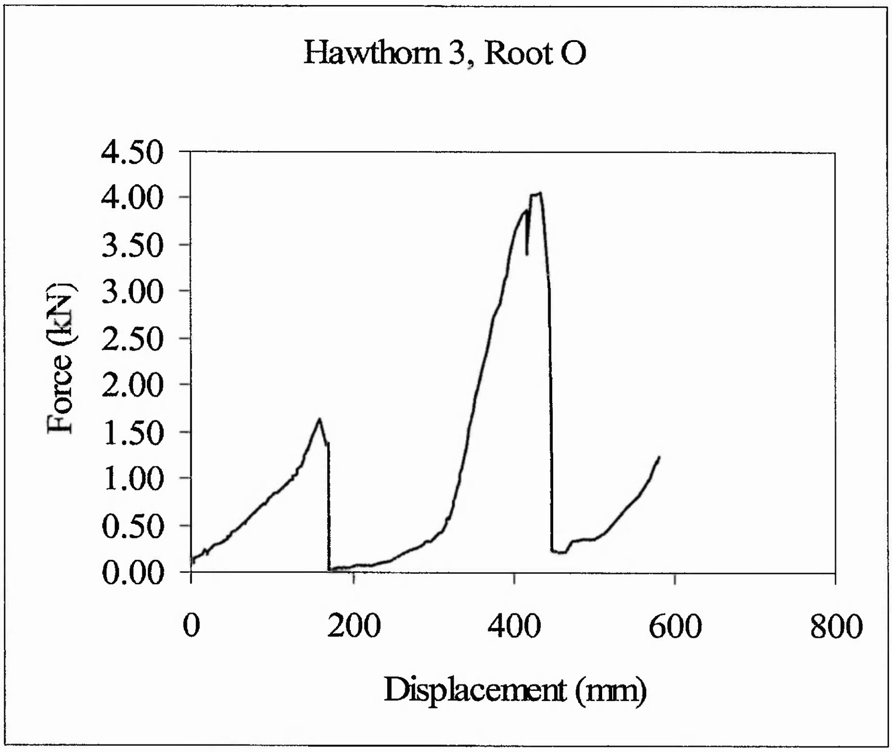


Figure A16. Root pull out graph of Hawthorn root 3O.

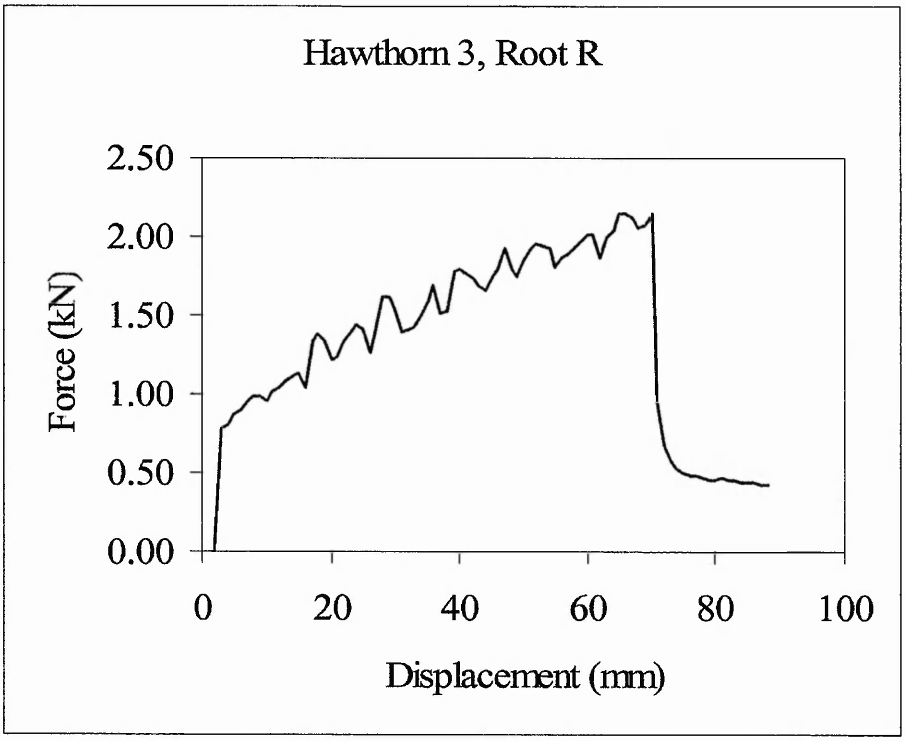


Figure A17. Root pull out graph of Hawthorn root 3R.

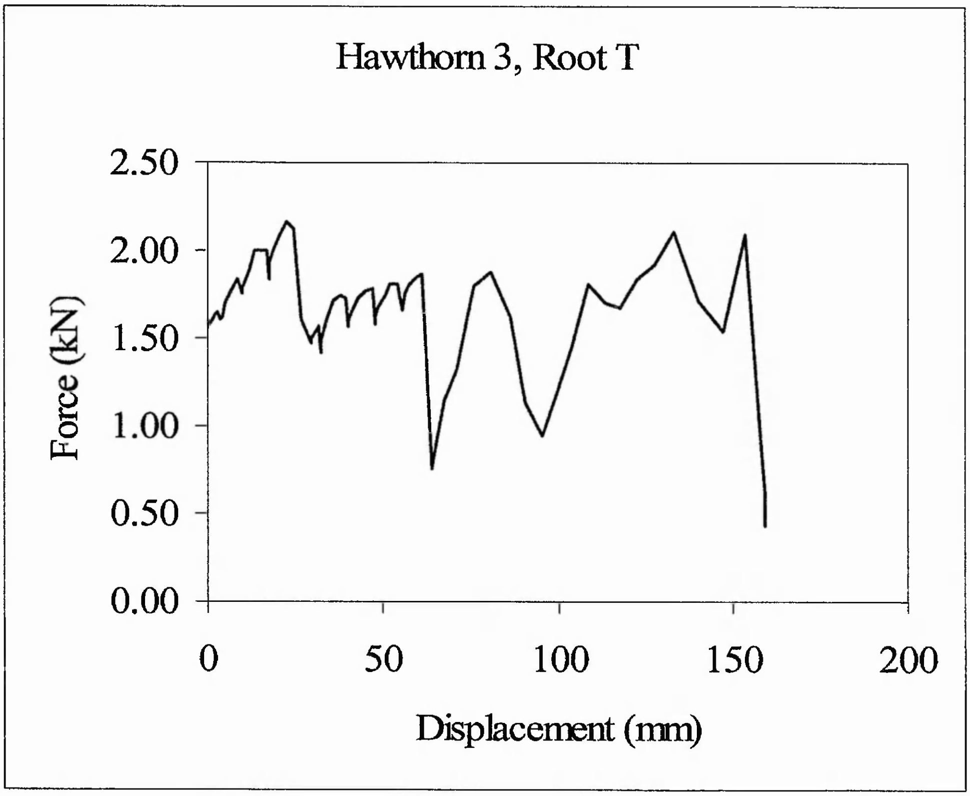


Figure A18. Root pull out graph of Hawthorn root 3T.

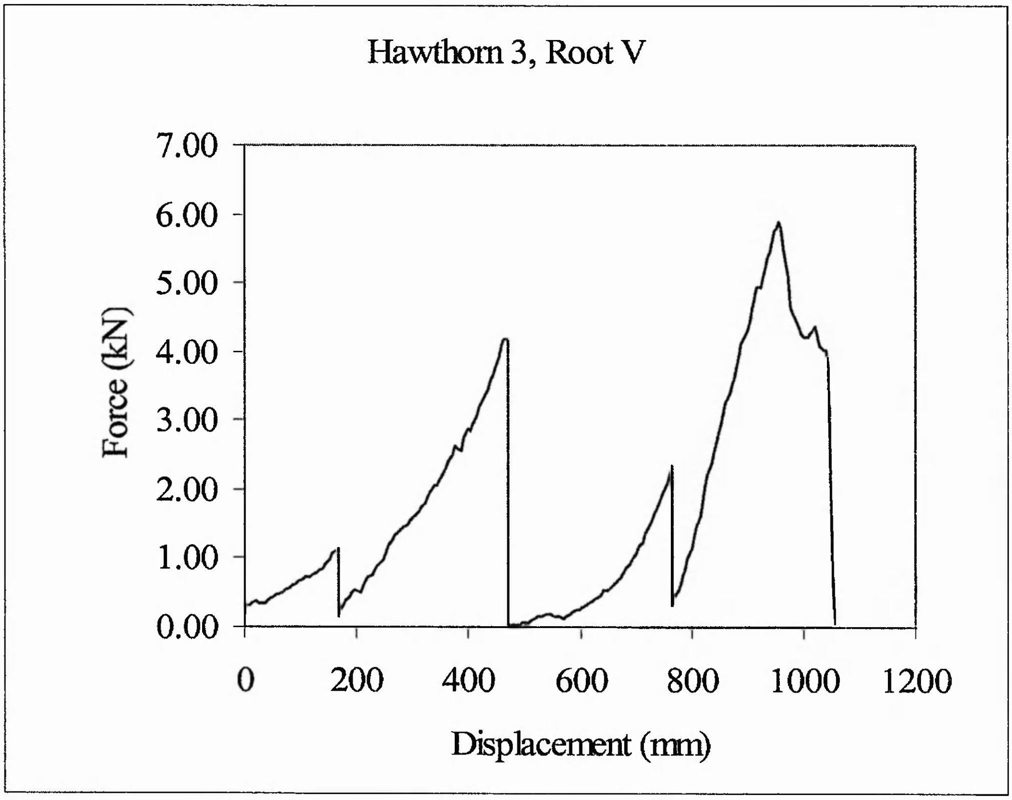


Figure A19. Root pull out graph of Hawthorn root 3V.

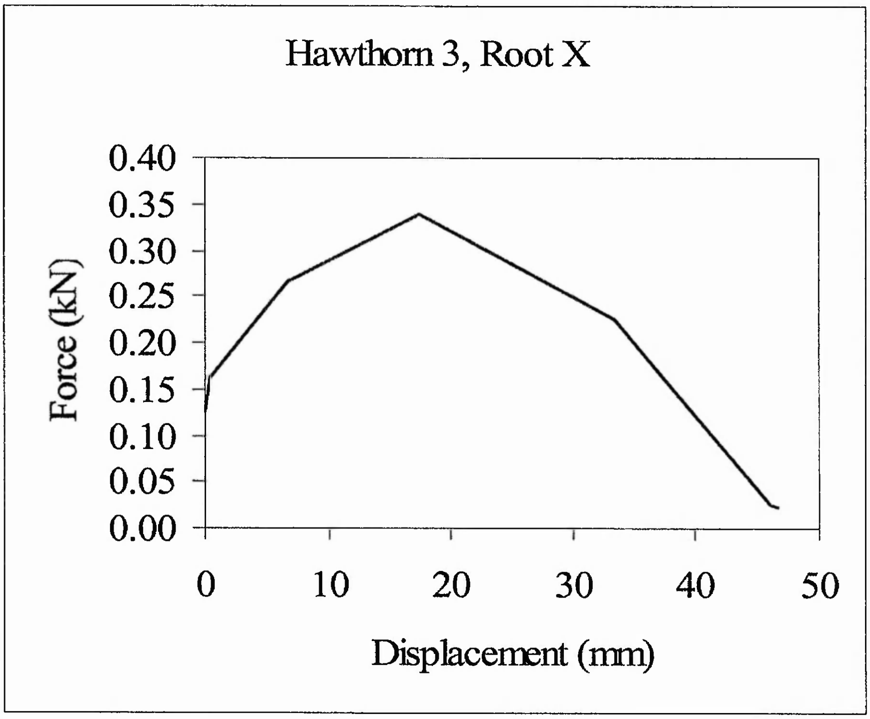


Figure A20. Root pull out graph of Hawthorn root 3X.

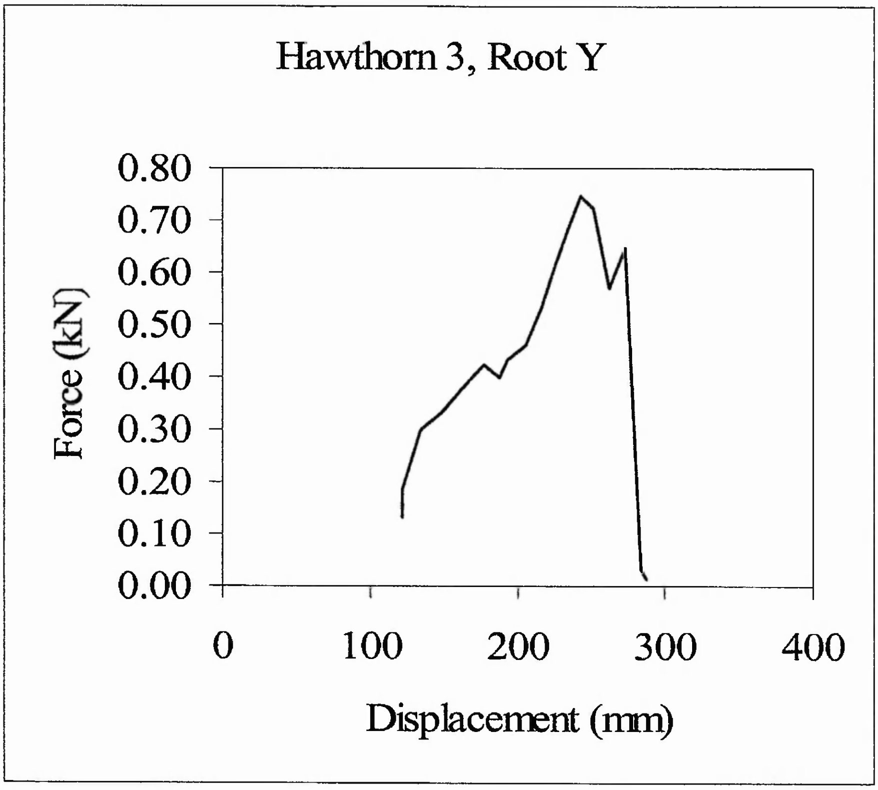


Figure A21. Root pull out graph of Hawthorn root 3Y.

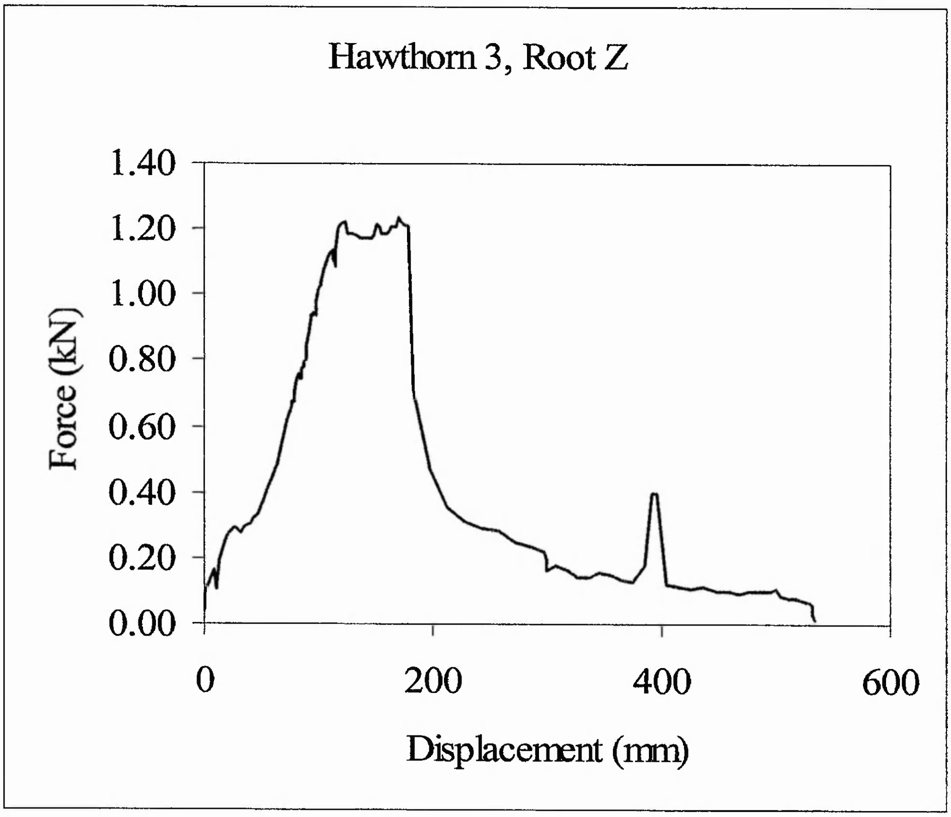


Figure A22. Root pull out graph of Hawthorn root 3Z.

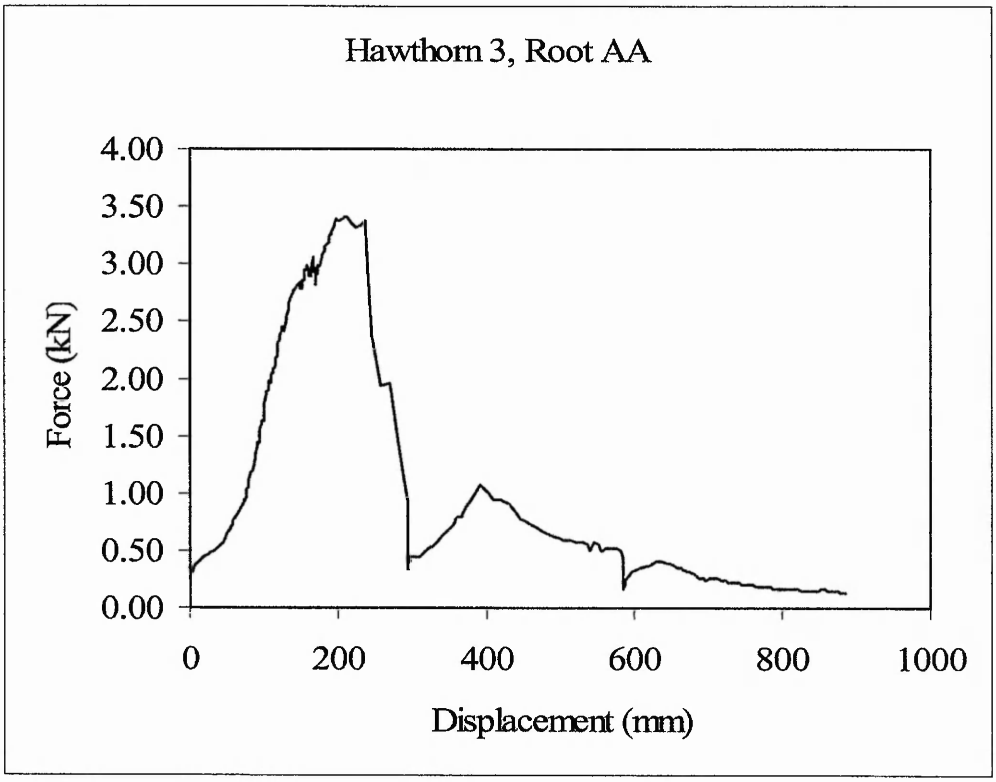


Figure A23. Root pull out graph of Hawthorn root 3AA.

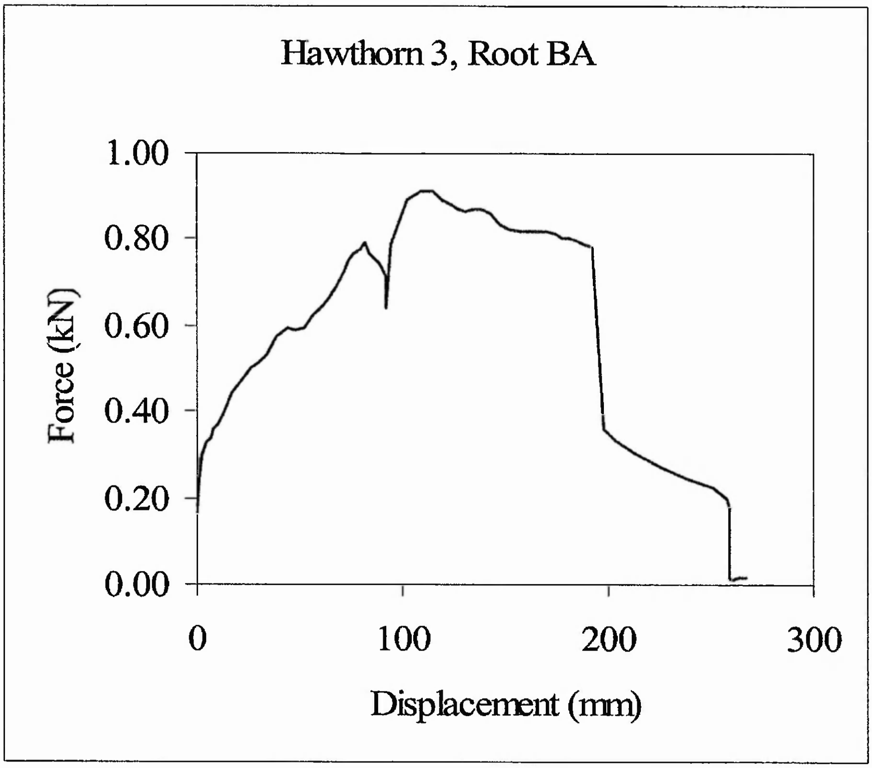


Figure A24. Root pull out graph of Hawthorn root 3BA.

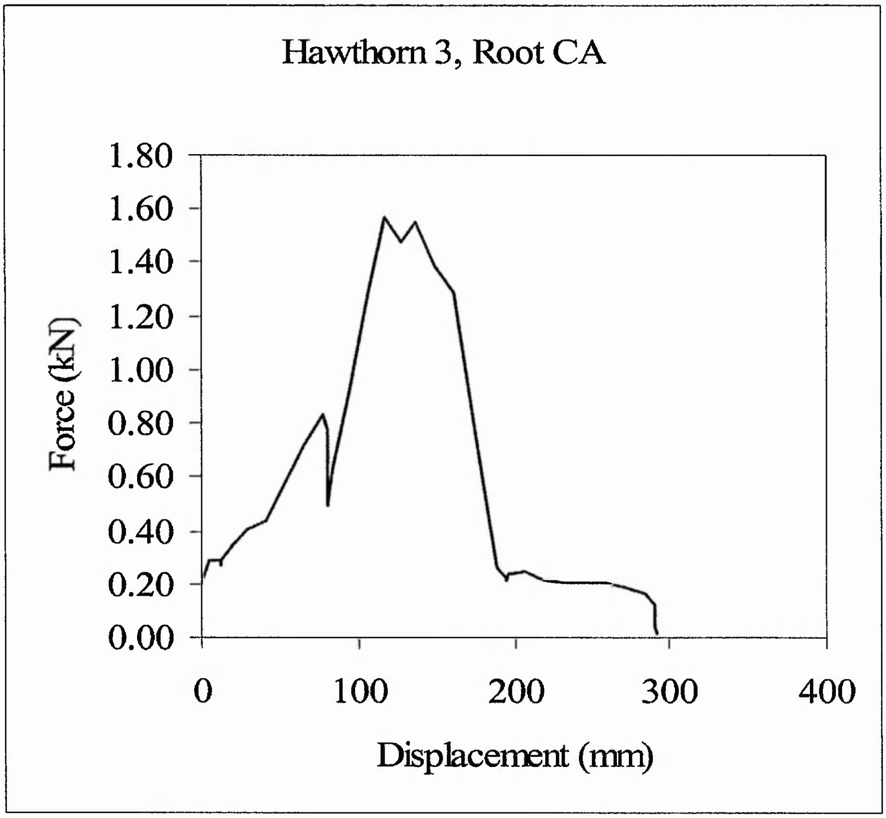


Figure A25. Root pull out graph of Hawthorn root 3CA.

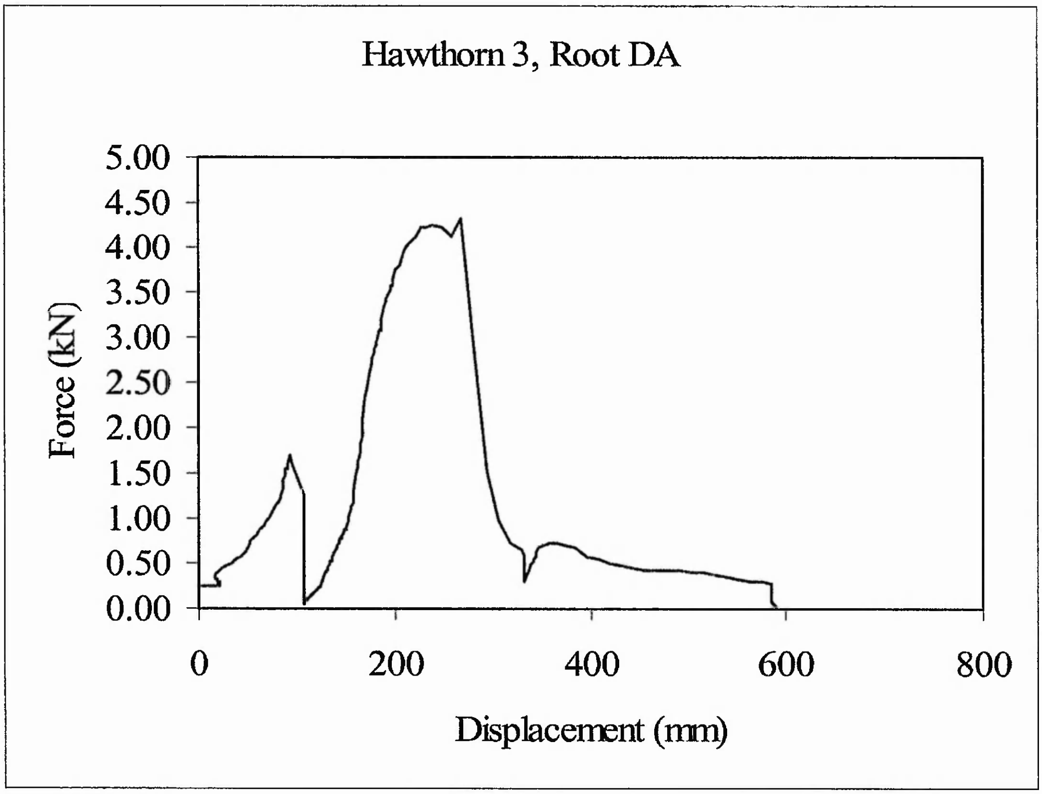


Figure A26. Root pull out graph of Hawthorn root 3DA.

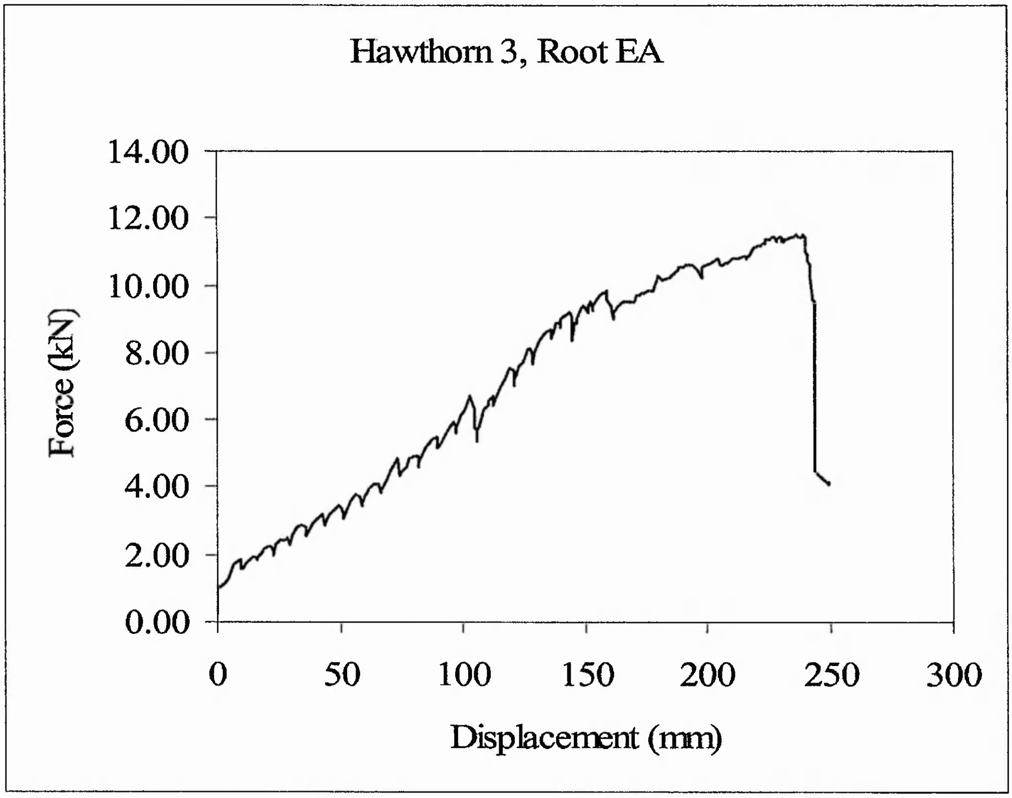


Figure A27. Root pull out graph of Hawthorn root 3EA.

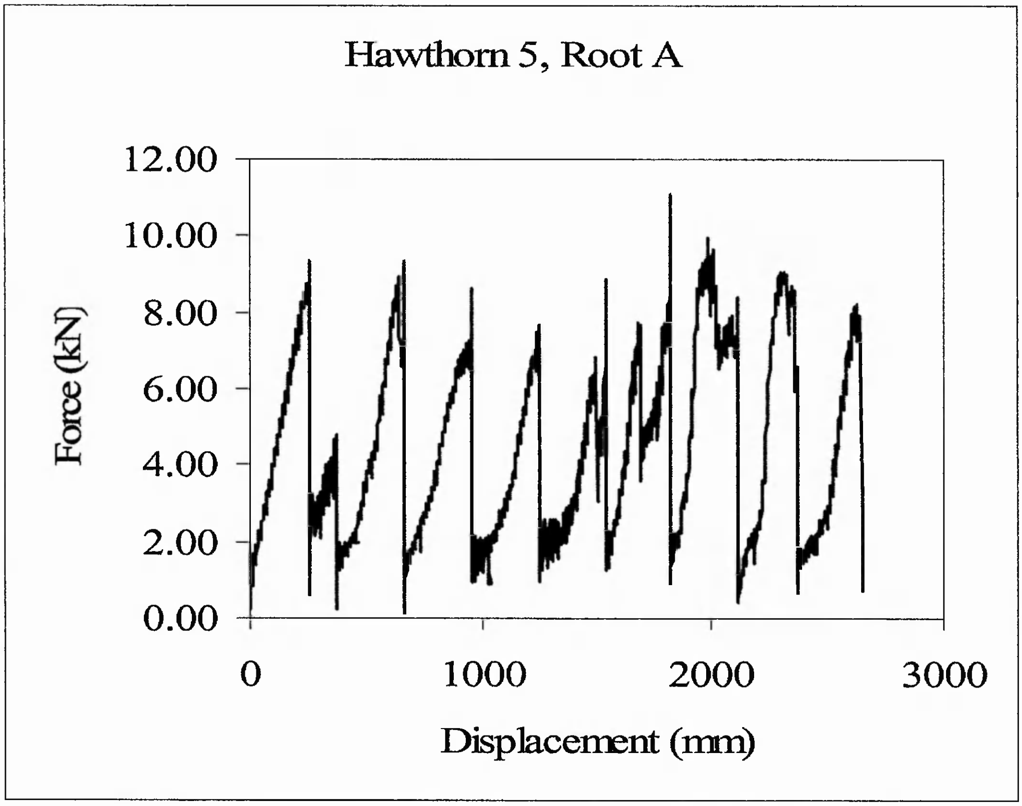


Figure A28. Root pull out graph of Hawthorn root 5A.

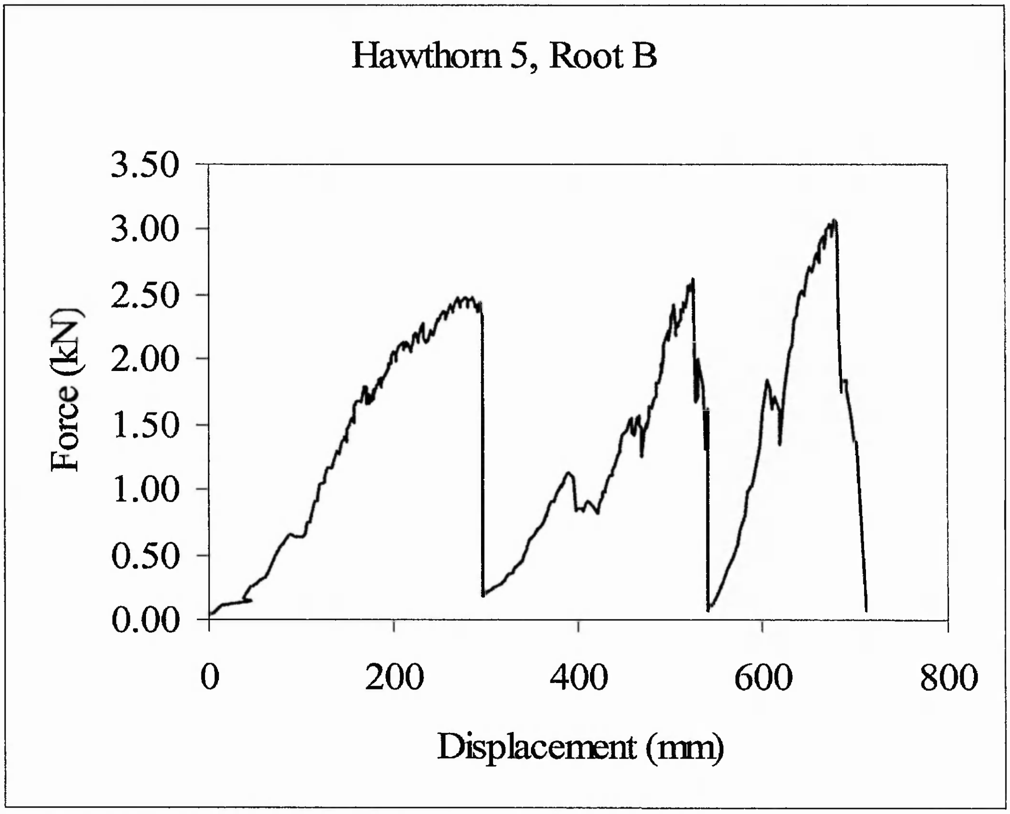


Figure A29. Root pull out graph of Hawthorn root 5B.

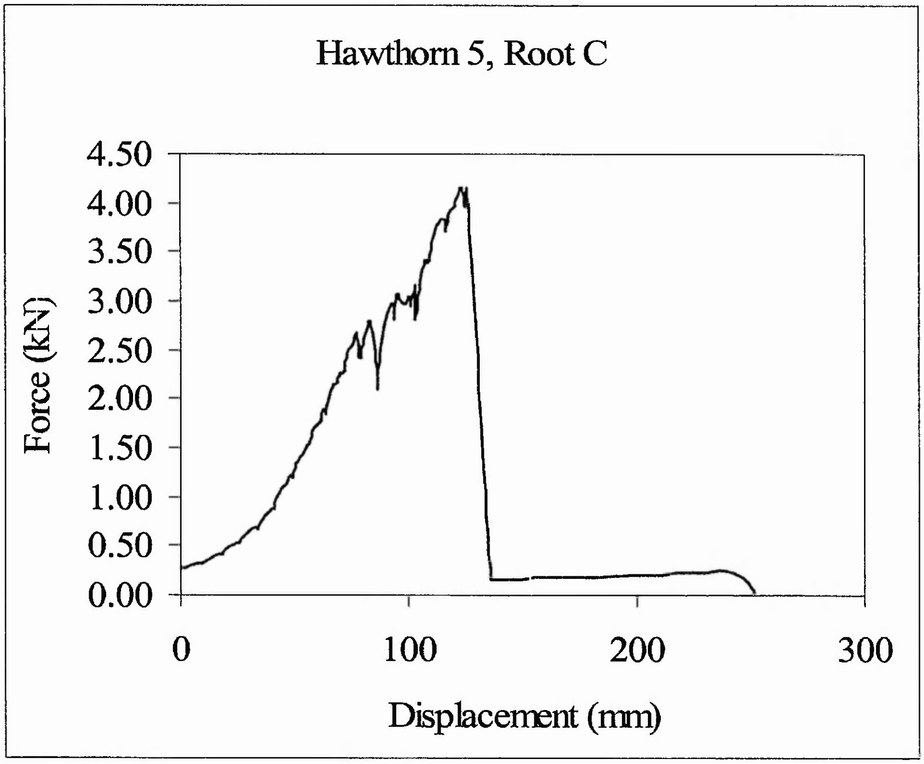


Figure A30. Root pull out graph of Hawthorn root 5C.

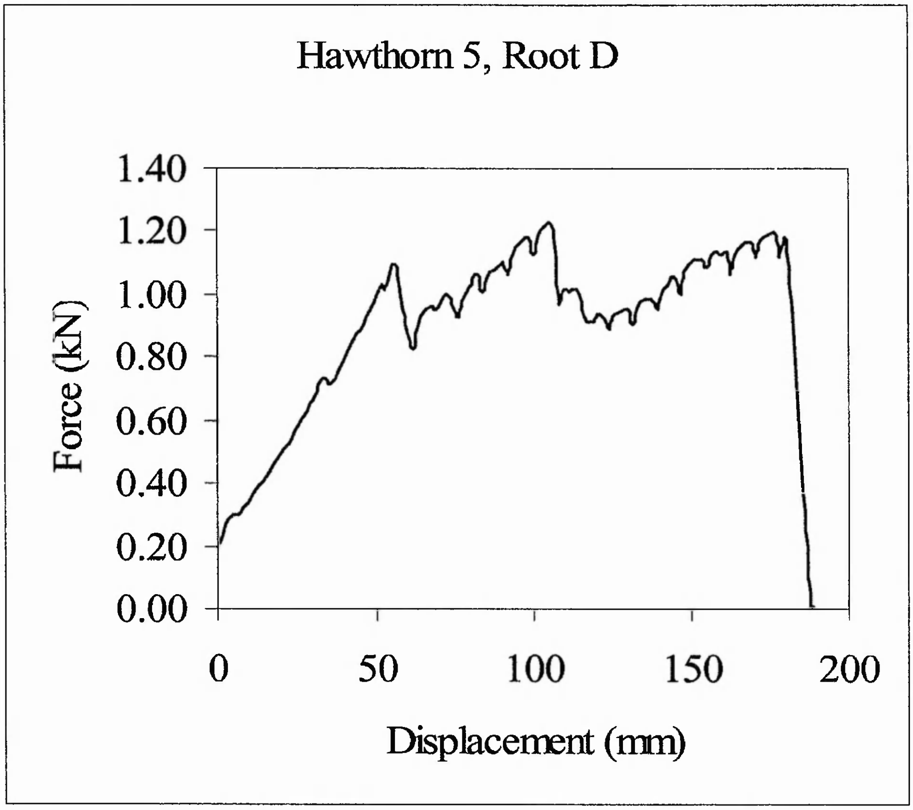


Figure A31. Root pull out graph of Hawthorn root 5D.

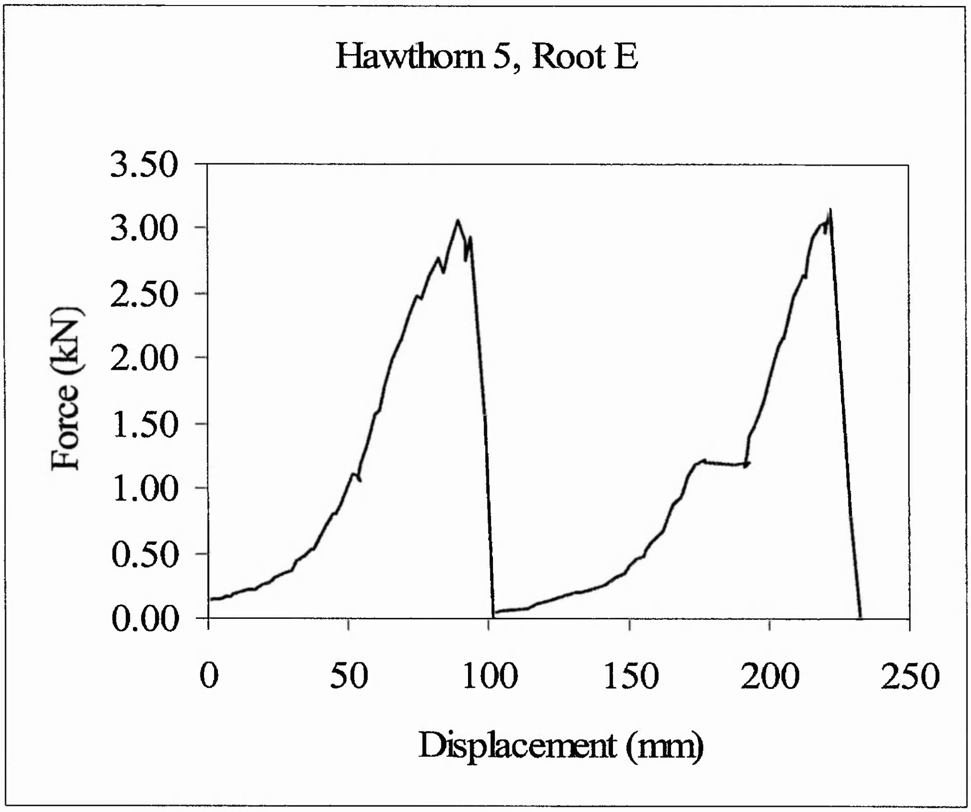
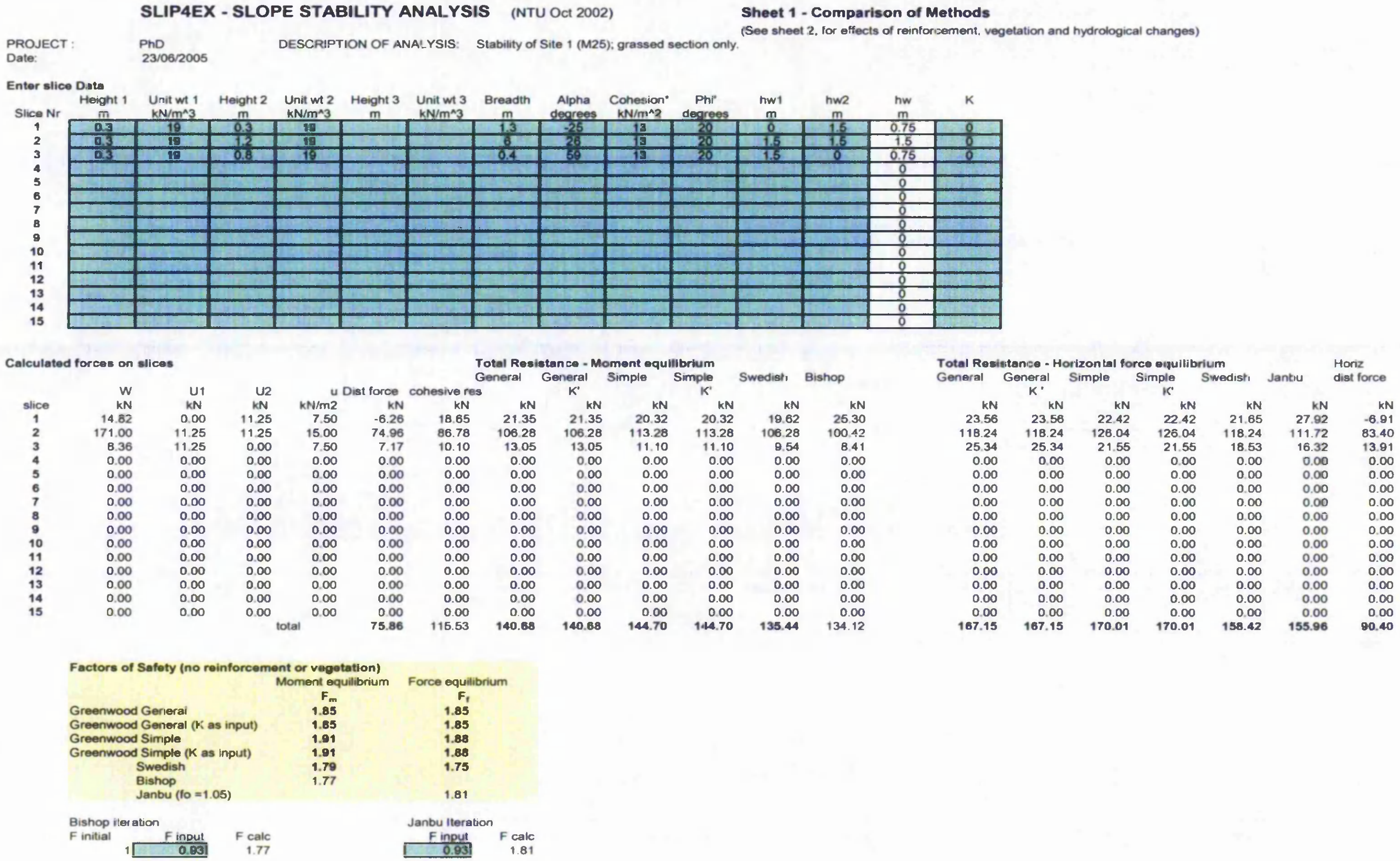


Figure A32. Root pull out graph of Hawthorn root 5E.

Appendix 2: SLIP4EX spreadsheets showing variation in stability of the three study areas

Figure B1 (a) Spreadsheet showing input parameters for Site 1 – Case 1A – grass vegetation cover



SLIP4EX - SLOPE STABILITY ANALYSIS (NTU Oct 2002)

Sheet 1 - Comparison of Methods

(See sheet 2, for effects of reinforcement, vegetation and hydrological changes)

PROJECT : PhD

DESCRIPTION OF ANALYSIS: Stability of Site 1 (M25); grassed section only.

Date: 23/06/2005

Enter slice Data

Slice Nr	Height 1 m	Unit wt 1 kN/m^3	Height 2 m	Unit wt 2 kN/m^3	Height 3 m	Unit wt 3 kN/m^3	Breadth m	Alpha degrees	Cohesion' kN/m^2	Phi' degrees	hw1 m	hw2 m	hw m	K
1	0.3	19	0.3	19			1.3	-25	13	20	0	1.5	0.75	0
2	0.3	19	1.2	19			6	26	13	20	1.5	1.5	1.5	0
3	0.3	19	0.8	19			0.4	59	13	20	1.5	0	0.75	0
4													0	
5													0	
6													0	
7													0	
8													0	
9													0	
10													0	
11													0	
12													0	
13													0	
14													0	
15													0	

Calculated forces on slices

							Total Resistance - Moment equilibrium					
							General	General K'	Simple	Simple K'	Swedish	Bishop
	W	U1	U2	u	Dist force	cohesive res						
slice	kN	kN	kN	kN/m2	kN	kN	kN	kN	kN	kN	kN	kN
1	14.82	0.00	11.25	7.50	-6.26	18.65	21.35	21.35	20.32	20.32	19.62	25.30
2	171.00	11.25	11.25	15.00	74.96	86.78	106.28	106.28	113.28	113.28	106.28	100.42
3	8.36	11.25	0.00	7.50	7.17	10.10	13.05	13.05	11.10	11.10	9.54	8.41
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				total	75.86	115.53	140.68	140.68	144.70	144.70	135.44	134.12

	Total Resistance - Horizontal force equilibrium						Horiz
	General	General K '	Simple	Simple K'	Swedish	Janbu	dist force
slice	kN	kN	kN	kN	kN	kN	kN
1	23.56	23.56	22.42	22.42	21.65	27.92	-6.91
2	118.24	118.24	126.04	126.04	118.24	111.72	83.40
3	25.34	25.34	21.55	21.55	18.53	16.32	13.91
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	167.15	167.15	170.01	170.01	158.42	155.96	90.40

Factors of Safety (no reinforcement or vegetation)

	Moment equilibrium F_m	Force equilibrium F_f
Greenwood General	1.85	1.85
Greenwood General (K as input)	1.85	1.85
Greenwood Simple	1.91	1.88
Greenwood Simple (K as input)	1.91	1.88
Swedish	1.79	1.75
Bishop	1.77	
Janbu (fo =1.05)		1.81

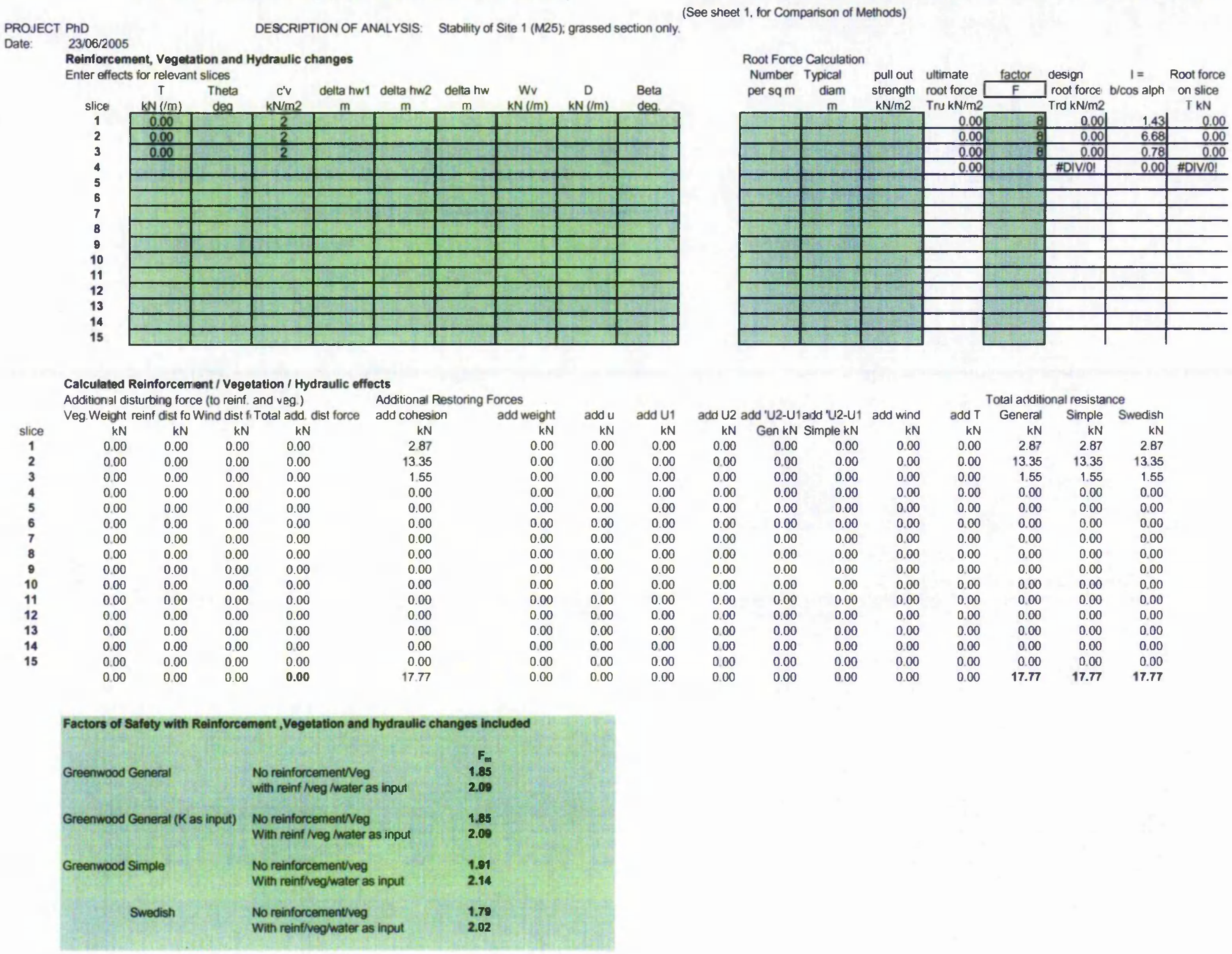
Bishop iteration

F initial	F input	F calc
1	0.93	1.77

Janbu Iteration

F input	F calc
0.93	1.81

Figure B1 (b) Spreadsheet showing vegetation parameters for Site 1 – Case 1A – grass vegetation cover.



SLIP4EX - SLOPE STABILITY ANALYSIS (NTU Oct 2002)

Sheet 2 - EFFECTS OF REINFORCEMENT, VEGETATION AND HYDROLOGICAL

(See sheet 1, for Comparison of Methods)

PROJECT PhD

DESCRIPTION OF ANALYSIS: Stability of Site 1 (M25); grassed section only.

Date: 23/06/2005

Reinforcement, Vegetation and Hydraulic changes

Enter effects for relevant slices

slice	T kN (/m)	Theta deg	c'v kN/m2	delta hw1 m	delta hw2 m	delta hw m	Wv kN (/m)	D kN (/m)	Beta deg.
1	0.00		2						
2	0.00		2						
3	0.00		2						
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

Root Force Calculation

Number per sq m	Typical diam m	pull out strength kN/m2	ultimate root force Tru kN/m2	factor F	design root force Trd kN/m2	l = b/cos alph	Root force on slice T kN
			0.00	8	0.00	1.43	0.00
			0.00	8	0.00	6.68	0.00
			0.00	8	0.00	0.78	0.00
			0.00		#DIV/0!	0.00	#DIV/0!

Calculated Reinforcement / Vegetation / Hydraulic effects

	Additional disturbing force (to reinf. and veg.)				Additional Restoring Forces									Total additional resistance		
slice	Veg.Weight kN	reinf dist fo kN	Wind dist f kN	Total add. dist force kN	add cohesion kN	add weight kN	add u kN	add U1 kN	add U2 kN	add 'U2-U1 Gen kN	add 'U2-U1 Simple kN	add wind kN	add T kN	General kN	Simple kN	Swedish kN
1	0.00	0.00	0.00	0.00	2.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.87	2.87	2.87
2	0.00	0.00	0.00	0.00	13.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.35	13.35	13.35
3	0.00	0.00	0.00	0.00	1.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.55	1.55	1.55
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	**0.00**	17.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**17.77**	**17.77**	**17.77**

Factors of Safety with Reinforcement ,Vegetation and hydraulic changes included

		F_m
Greenwood General	No reinforcement/Veg	**1.85**
	with reinf /veg /water as input	**2.09**
Greenwood General (K as input)	No reinforcement/Veg	**1.85**
	With reinf /veg /water as input	**2.09**
Greenwood Simple	No reinforcement/veg	**1.91**
	With reinf/veg/water as input	**2.14**
Swedish	No reinforcement/veg	**1.79**
	With reinf/veg/water as input	**2.02**

Figure B2 (a) Spreadsheet showing input parameters for Site 1- Case 1B – vegetation cover of immature trees.

SLIP4EX - SLOPE STABILITY ANALYSIS (NTU Oct 2002)

Sheet 1 - Comparison of Methods

(See sheet 2, for effects of reinforcement, vegetation and hydrological changes)

PROJECT PhD

Date: 24/06/2005

DESCRIPTION OF ANALYSIS: Stability of Site 1 (M25): section with immature vegetation

Enter slice Data

Slice Nr	Height 1 m	Unit wt 1 kN/m^3	Height 2 m	Unit wt 2 kN/m^3	Height 3 m	Unit wt 3 kN/m^3	Breadth m	Alpha degrees	Cohesion* kN/m^2	Phi' degrees	hw1 m	hw2 m	hw m	K
1	0.7	19					1.3	-25	13	20	0	1.5	0.75	0
2	1.5	19					6	26	13	20	1.5	1.2	1.35	0
3	0.8	19					0.4	59	13	20	1.2	0	0.6	0
4													0	0
5													0	
6													0	
7													0	
8													0	
9													0	
10													0	
11													0	
12													0	
13													0	
14													0	
15													0	

Calculated forces on slices

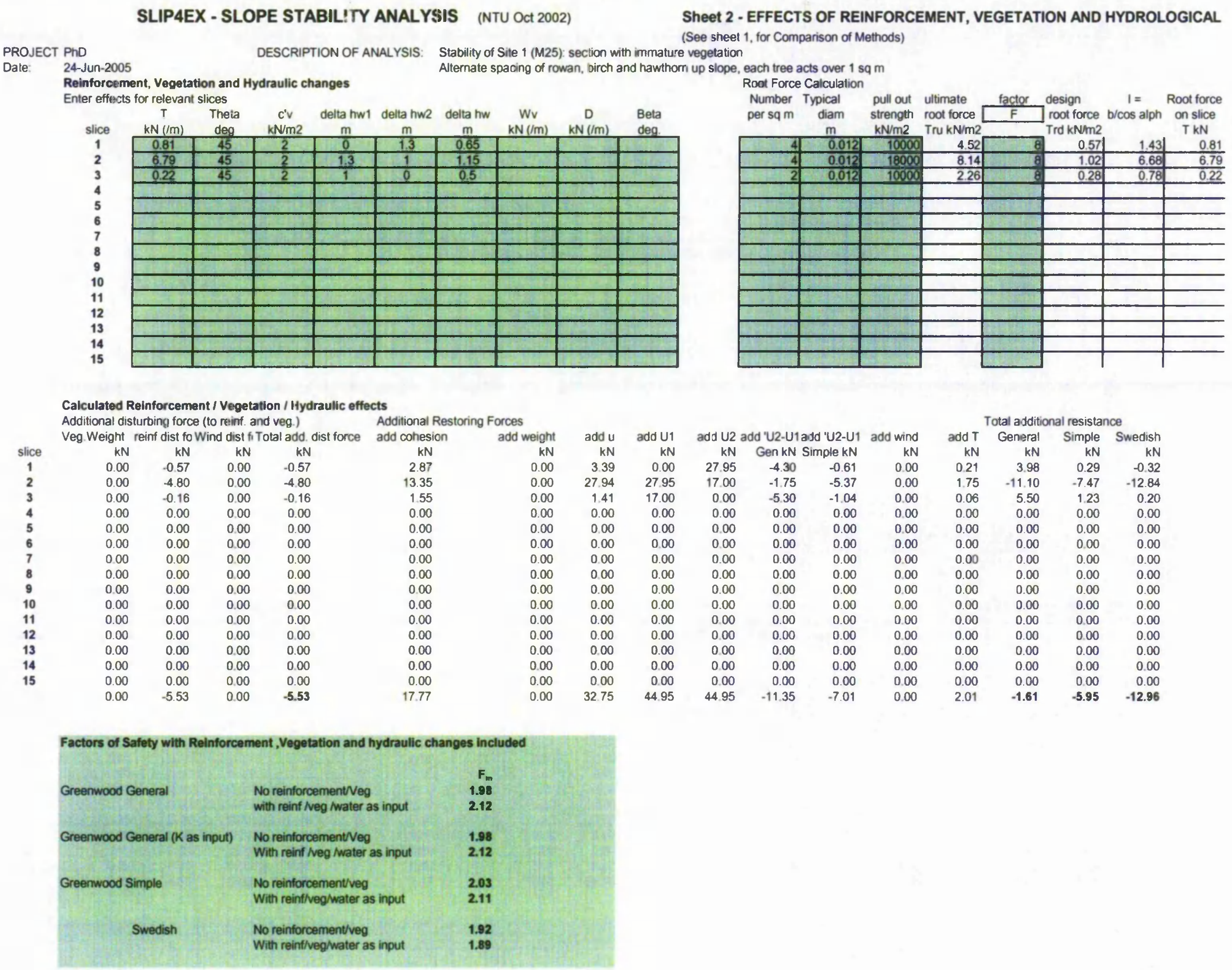
							Total Resistance - Moment equilibrium					
							General	General	Simple	Simple	Swedish	Bishop
	W	U1	U2	u	Dist force	cohesive res		K'		K'		
slice	kN	kN	kN	kN/m2	kN	kN	kN	kN	kN	kN	kN	kN
1	17.29	0.00	11.25	7.50	-7.31	18.65	22.17	22.17	21.13	21.13	20.43	26.51
2	171.00	11.25	7.20	13.50	74.96	86.78	110.57	110.57	116.23	116.23	109.92	103.48
3	6.08	7.20	0.00	6.00	5.21	10.10	11.79	11.79	10.79	10.79	9.54	7.69
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				total	**72.87**	115.53	**144.52**	**144.52**	**148.15**	**148.15**	**139.90**	137.68

Total Resistance - Horizontal force equilibrium						Horiz
General	General	Simple	Simple	Swedish	Janbu	dist force
	K '		K'			
kN	kN	kN	kN	kN	kN	kN
24.46	24.46	23.32	23.32	22.55	29.25	-8.06
123.02	123.02	129.31	129.31	122.30	115.13	83.40
22.88	22.88	20.94	20.94	18.52	14.93	10.12
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
170.36	**170.36**	**173.57**	**173.57**	**163.37**	**159.31**	**85.46**

Factors of Safety (no reinforcement or vegetation)

	Moment equilibrium F_m	Force equilibrium F_f
Greenwood General	**1.98**	**1.99**
Greenwood General (K as input)	**1.98**	**1.99**
Greenwood Simple	**2.03**	**2.03**
Greenwood Simple (K as input)	**2.03**	**2.03**
Swedish	**1.92**	**1.91**
Bishop	1.89	
Janbu (fo =1.05)		1.96

Figure B2 (b) Spreadsheet showing vegetation parameters for Site 1- Case 1B – vegetation cover of immature trees.



SLIP4EX - SLOPE STABIL!TY ANALYSIS (NTU Oct 2002)

Sheet 2 - EFFECTS OF REINFORCEMENT, VEGETATION AND HYDROLOGICAL

(See sheet 1, for Comparison of Methods)

PROJECT PhD
Date: 24-Jun-2005

DESCRIPTION OF ANALYSIS: Stability of Site 1 (M25): section with immature vegetation
Alternate spacing of rowan, birch and hawthorn up slope, each tree acts over 1 sq m

Reinforcement, Vegetation and Hydraulic changes

Enter effects for relevant slices

Root Force Calculation

slice	T kN (/m)	Theta deg	c'v kN/m2	delta hw1 m	delta hw2 m	delta hw m	Wv kN (/m)	D kN (/m)	Beta deg.	Number per sq m	Typical diam m	pull out strength kN/m2	ultimate root force Tru kN/m2	factor F	design root force Trd kN/m2	I = b/cos alph	Root force on slice T kN
1	0.81	45	2	0	1.3	0.65				4	0.012	10000	4.52	8	0.57	1.43	0.81
2	6.79	45	2	1.3	1	1.15				4	0.012	18000	8.14	8	1.02	6.68	6.79
3	0.22	45	2	1	0	0.5				2	0.012	10000	2.26	8	0.28	0.78	0.22
4																	
5																	
6																	
7																	
8																	
9																	
10																	
11																	
12																	
13																	
14																	
15																	

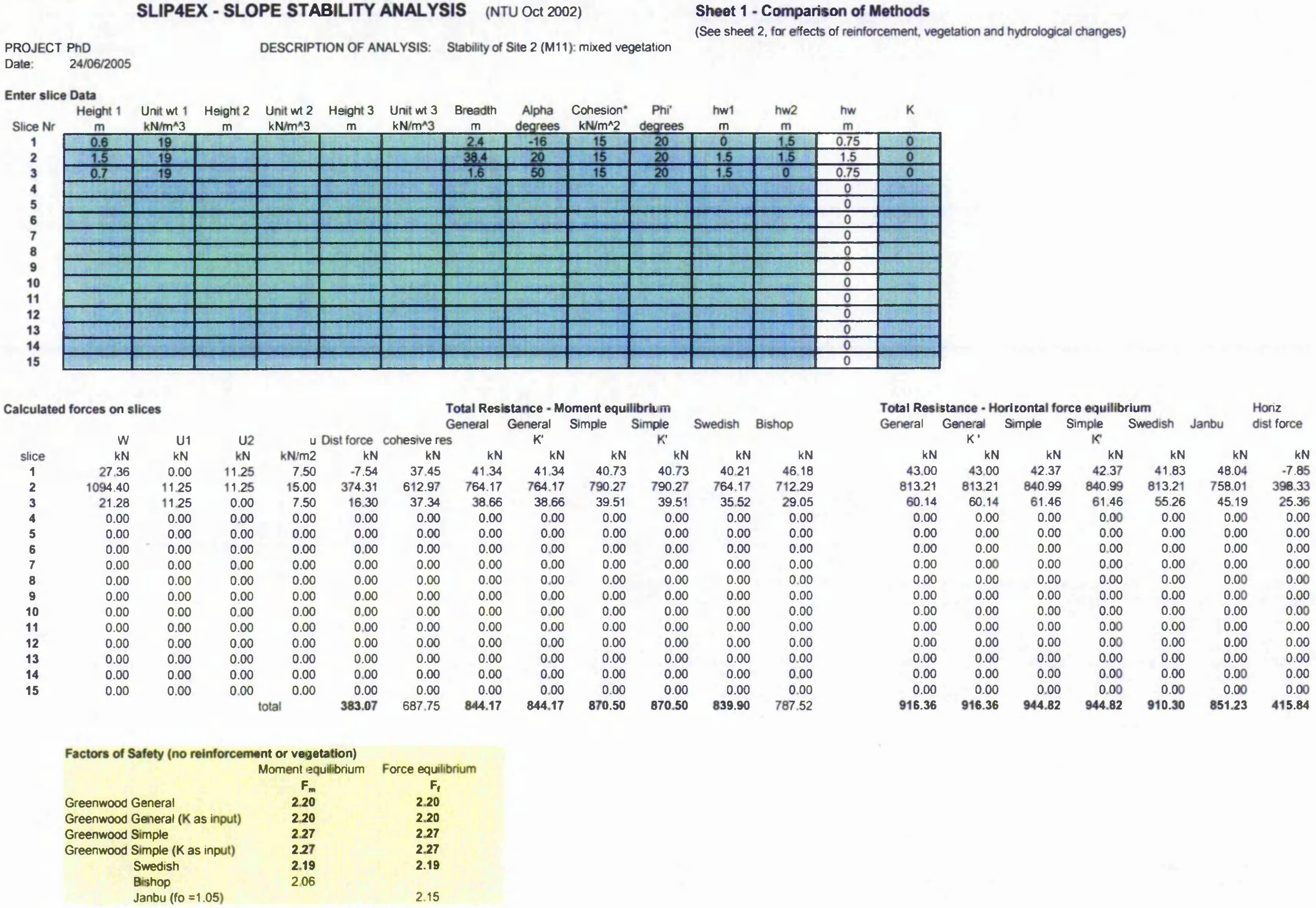
Calculated Reinforcement / Vegetation / Hydraulic effects

	Additional disturbing force (to reinf. and veg.)				Additional Restoring Forces									Total additional resistance		
slice	Veg.Weight kN	reinf dist fo kN	Wind dist fi kN	Total add. dist force kN	add cohesion kN	add weight kN	add u kN	add U1 kN	add U2 kN	add 'U2-U1 Gen kN	add 'U2-U1 Simple kN	add wind kN	add T kN	General kN	Simple kN	Swedish kN
1	0.00	-0.57	0.00	-0.57	2.87	0.00	3.39	0.00	27.95	-4.30	-0.61	0.00	0.21	3.98	0.29	-0.32
2	0.00	-4.80	0.00	-4.80	13.35	0.00	27.94	27.95	17.00	-1.75	-5.37	0.00	1.75	-11.10	-7.47	-12.84
3	0.00	-0.16	0.00	-0.16	1.55	0.00	1.41	17.00	0.00	-5.30	-1.04	0.00	0.06	5.50	1.23	0.20
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	-5.53	0.00	**-5.53**	17.77	0.00	32.75	44.95	44.95	-11.35	-7.01	0.00	2.01	**-1.61**	**-5.95**	**-12.96**

Factors of Safety with Reinforcement ,Vegetation and hydraulic changes included

		F_m
Greenwood General	No reinforcement/Veg	**1.98**
	with reinf /veg /water as input	**2.12**
Greenwood General (K as input)	No reinforcement/Veg	**1.98**
	With reinf /veg /water as input	**2.12**
Greenwood Simple	No reinforcement/veg	**2.03**
	With reinf/veg/water as input	**2.11**
Swedish	No reinforcement/veg	**1.92**
	With reinf/veg/water as input	**1.89**

Figure B3 (a) Spreadsheet showing input parameters for Site 2 – Mature vegetation cover.



SLIP4EX - SLOPE STABILITY ANALYSIS (NTU Oct 2002)

Sheet 1 - Comparison of Methods

(See sheet 2, for effects of reinforcement, vegetation and hydrological changes)

PROJECT PhD
Date: 24/06/2005

DESCRIPTION OF ANALYSIS: Stability of Site 2 (M11): mixed vegetation

Enter slice Data

Slice Nr	Height 1 m	Unit wt 1 kN/m^3	Height 2 m	Unit wt 2 kN/m^3	Height 3 m	Unit wt 3 kN/m^3	Breadth m	Alpha degrees	Cohesion* kN/m^2	Phi' degrees	hw1 m	hw2 m	hw m	K
1	0.6	19					2.4	-16	15	20	0	1.5	0.75	0
2	1.5	19					38.4	20	15	20	1.5	1.5	1.5	0
3	0.7	19					1.6	50	15	20	1.5	0	0.75	0
4													0	
5													0	
6													0	
7													0	
8													0	
9													0	
10													0	
11													0	
12													0	
13													0	
14													0	
15													0	

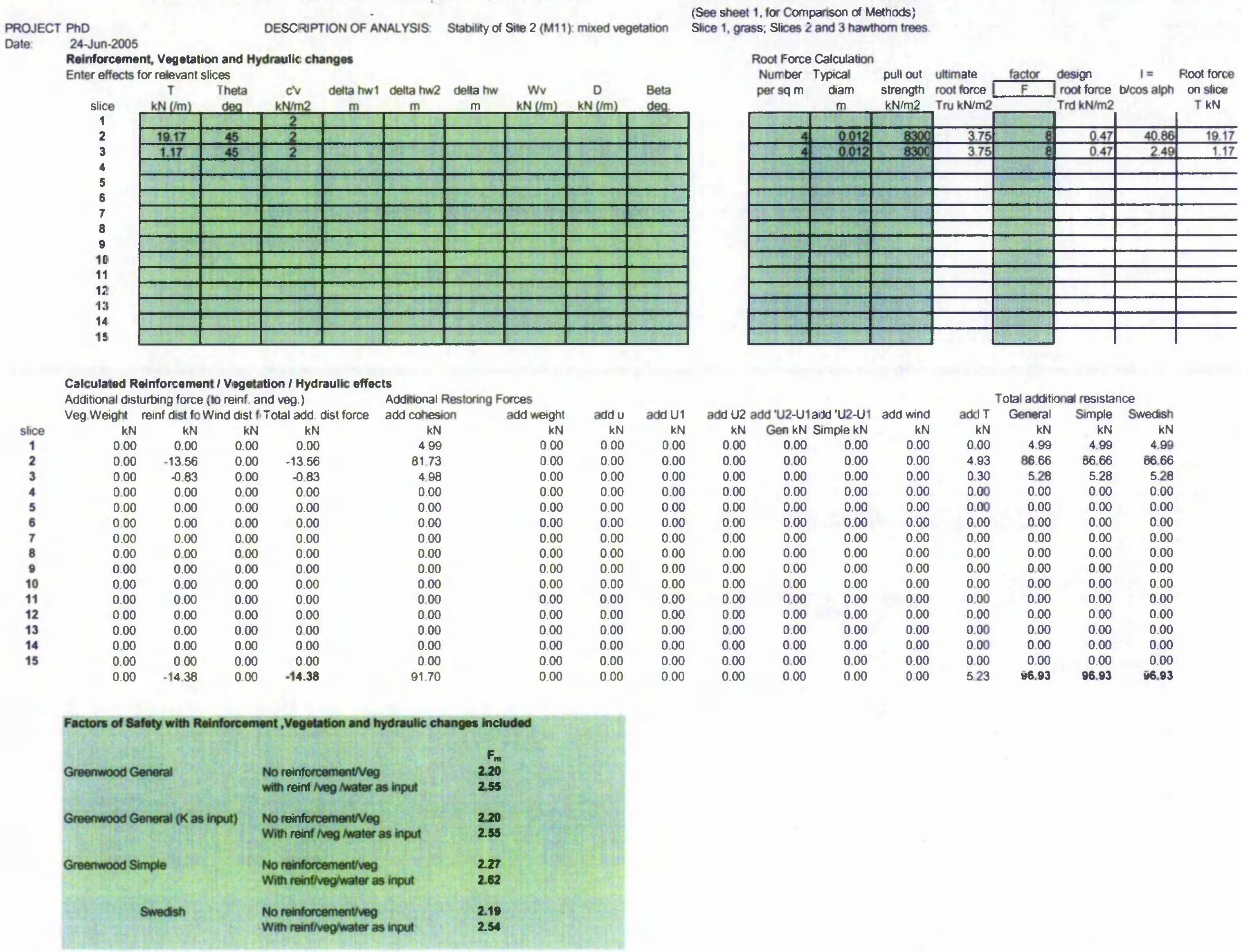
Calculated forces on slices

							Total Resistance - Moment equilibrium						**Total Resistance - Horizontal force equilibrium**						Horiz
							General	General K'	Simple	Simple K'	Swedish	Bishop	General	General K'	Simple	Simple K'	Swedish	Janbu	dist force
slice	W kN	U1 kN	U2 kN	u kN/m2	Dist force kN	cohesive res kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN
1	27.36	0.00	11.25	7.50	-7.54	37.45	41.34	41.34	40.73	40.73	40.21	46.18	43.00	43.00	42.37	42.37	41.83	48.04	-7.85
2	1094.40	11.25	11.25	15.00	374.31	612.97	764.17	764.17	790.27	790.27	764.17	712.29	813.21	813.21	840.99	840.99	813.21	758.01	398.33
3	21.28	11.25	0.00	7.50	16.30	37.34	38.66	38.66	39.51	39.51	35.52	29.05	60.14	60.14	61.46	61.46	55.26	45.19	25.36
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				total	**383.07**	687.75	**844.17**	**844.17**	**870.50**	**870.50**	**839.90**	787.52	**916.36**	**916.36**	**944.82**	**944.82**	**910.30**	**851.23**	**415.84**

Factors of Safety (no reinforcement or vegetation)

	Moment equilibrium F_m	Force equilibrium F_f
Greenwood General	**2.20**	**2.20**
Greenwood General (K as input)	**2.20**	**2.20**
Greenwood Simple	**2.27**	**2.27**
Greenwood Simple (K as input)	**2.27**	**2.27**
Swedish	**2.19**	**2.19**
Bishop	2.06	
Janbu (fo =1.05)		2.15

Figure B3 (b) Spreadsheet showing vegetation parameters for Site 2 – Mature vegetation cover.



SLIP4EX - SLOPE STABILITY ANALYSIS (NTU Oct 2002)

Sheet 2 - EFFECTS OF REINFORCEMENT, VEGETATION AND HYDROLOGICAL

(See sheet 1, for Comparison of Methods)

PROJECT PhD

Date: 24-Jun-2005

DESCRIPTION OF ANALYSIS: Stability of Site 2 (M11): mixed vegetation

Slice 1, grass; Slices 2 and 3 hawthorn trees.

Reinforcement, Vegetation and Hydraulic changes

Enter effects for relevant slices

slice	T kN (/m)	Theta deg	c'v kN/m2	delta hw1 m	delta hw2 m	delta hw m	Wv kN (/m)	D kN (/m)	Beta deg
1			2						
2	19.17	45	2						
3	1.17	45	2						
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

Root Force Calculation

Number per sq m	Typical diam m	pull out strength kN/m2	ultimate root force Tru kN/m2	factor F	design root force Trd kN/m2	l = b/cos alph	Root force on slice T kN
4	0.012	8300	3.75	8	0.47	40.86	19.17
4	0.012	8300	3.75	8	0.47	2.49	1.17

Calculated Reinforcement / Vegetation / Hydraulic effects

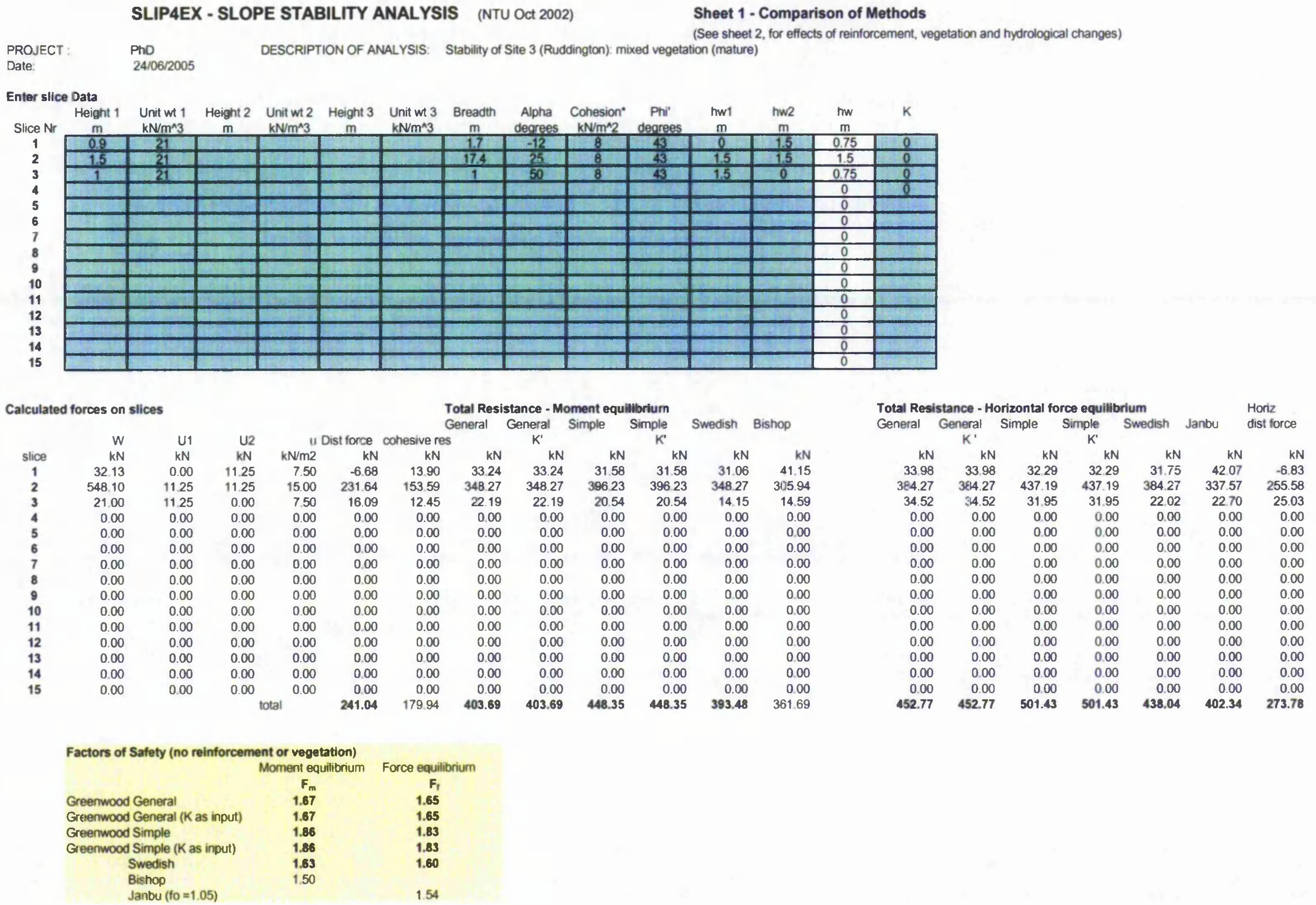
	Additional disturbing force (to reinf. and veg.)				Additional Restoring Forces									Total additional resistance		
slice	Veg.Weight kN	reinf dist fo kN	Wind dist f kN	Total add. dist force kN	add cohesion kN	add weight kN	add u kN	add U1 kN	add U2 kN	add 'U2-U1 Gen kN	add 'U2-U1 Simple kN	add wind kN	add T kN	General kN	Simple kN	Swedish kN
1	0.00	0.00	0.00	0.00	4.99	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.99	4.99	4.99
2	0.00	-13.56	0.00	-13.56	81.73	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.93	86.66	86.66	86.66
3	0.00	-0.83	0.00	-0.83	4.98	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	5.28	5.28	5.28
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	-14.38	0.00	**-14.38**	91.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.23	**96.93**	**96.93**	**96.93**

Factors of Safety with Reinforcement ,Vegetation and hydraulic changes included

		F_m
Greenwood General	No reinforcement/Veg	**2.20**
	with reinf /veg /water as input	**2.55**
Greenwood General (K as input)	No reinforcement/Veg	**2.20**
	With reinf /veg /water as input	**2.55**
Greenwood Simple	No reinforcement/veg	**2.27**
	With reinf/veg/water as input	**2.62**
Swedish	No reinforcement/veg	**2.19**
	With reinf/veg/water as input	**2.54**

Figure B4 (a) Spreadsheet showing input parameters for Site 3 - Case 3A – no wind loading.

Sheet 1



SLIP4EX - SLOPE STABILITY ANALYSIS (NTU Oct 2002)

Sheet 1 - Comparison of Methods

(See sheet 2, for effects of reinforcement, vegetation and hydrological changes)

PROJECT : PhD

DESCRIPTION OF ANALYSIS: Stability of Site 3 (Ruddington): mixed vegetation (mature)

Date: 24/06/2005

Enter slice Data

Slice Nr	Height 1 m	Unit wt 1 kN/m^3	Height 2 m	Unit wt 2 kN/m^3	Height 3 m	Unit wt 3 kN/m^3	Breadth m	Alpha degrees	Cohesion* kN/m^2	Phi' degrees	hw1 m	hw2 m	hw m	K
1	0.9	21					1.7	-12	8	43	0	1.5	0.75	0
2	1.5	21					17.4	25	8	43	1.5	1.5	1.5	0
3	1	21					1	50	8	43	1.5	0	0.75	0
4													0	0
5													0	
6													0	
7													0	
8													0	
9													0	
10													0	
11													0	
12													0	
13													0	
14													0	
15													0	

Calculated forces on slices / **Total Resistance - Moment equilibrium**

							General	General K'	Simple	Simple K'	Swedish	Bishop
slice	W kN	U1 kN	U2 kN	u kN/m2	Dist force kN	cohesive res kN	kN	kN	kN	kN	kN	kN
1	32.13	0.00	11.25	7.50	-6.68	13.90	33.24	33.24	31.58	31.58	31.06	41.15
2	548.10	11.25	11.25	15.00	231.64	153.59	348.27	348.27	396.23	396.23	348.27	305.94
3	21.00	11.25	0.00	7.50	16.09	12.45	22.19	22.19	20.54	20.54	14.15	14.59
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				total	**241.04**	179.94	**403.69**	**403.69**	**448.35**	**448.35**	**393.48**	361.69

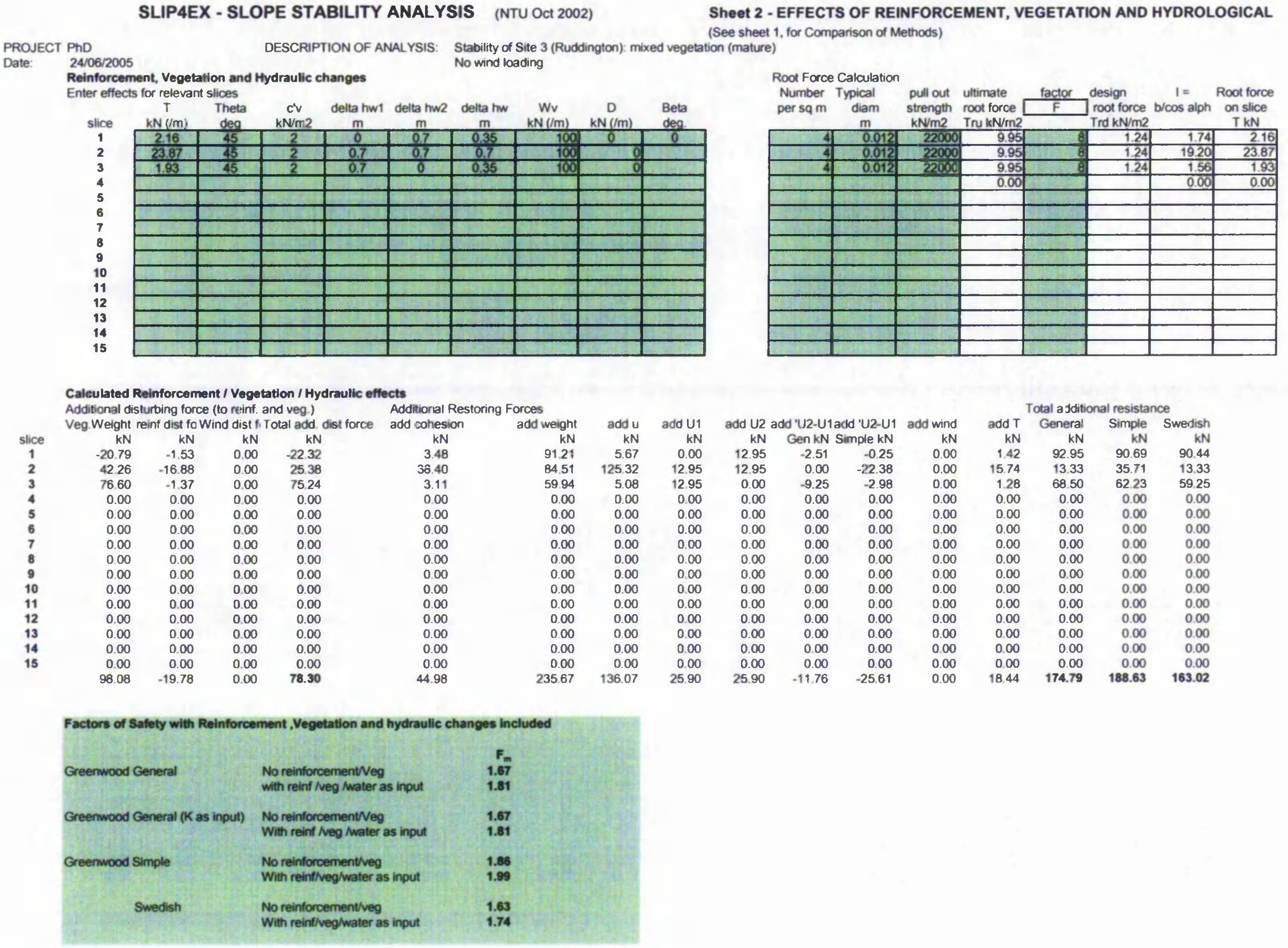
Total Resistance - Horizontal force equilibrium

slice	General kN	General K ' kN	Simple kN	Simple K' kN	Swedish kN	Janbu kN	Horiz dist force kN
1	33.98	33.98	32.29	32.29	31.75	42.07	-6.83
2	384.27	384.27	437.19	437.19	384.27	337.57	255.58
3	34.52	34.52	31.95	31.95	22.02	22.70	25.03
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	452.77	**452.77**	**501.43**	**501.43**	**438.04**	**402.34**	**273.78**

Factors of Safety (no reinforcement or vegetation)

	Moment equilibrium F_m	Force equilibrium F_f
Greenwood General	**1.67**	**1.65**
Greenwood General (K as input)	**1.67**	**1.65**
Greenwood Simple	**1.86**	**1.83**
Greenwood Simple (K as input)	**1.86**	**1.83**
Swedish	**1.63**	**1.60**
Bishop	1.50	
Janbu (fo =1.05)		1.54

Figure B4 (b) Spreadsheet showing vegetation parameters for Site 3 - Case 3A – no wind loading.



SLIP4EX - SLOPE STABILITY ANALYSIS (NTU Oct 2002)

Sheet 2 - EFFECTS OF REINFORCEMENT, VEGETATION AND HYDROLOGICAL
(See sheet 1, for Comparison of Methods)

PROJECT PhD
Date: 24/06/2005

DESCRIPTION OF ANALYSIS: Stability of Site 3 (Ruddington): mixed vegetation (mature)
No wind loading

Reinforcement, Vegetation and Hydraulic changes
Enter effects for relevant slices

slice	T kN (/m)	Theta deg	c'v kN/m2	delta hw1 m	delta hw2 m	delta hw m	Wv kN (/m)	D kN (/m)	Beta deg.
1	2.16	45	2	0	0.7	0.35	100	0	0
2	23.87	45	2	0.7	0.7	0.7	100	0	
3	1.93	45	2	0.7	0	0.35	100	0	
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

Root Force Calculation

slice	Number per sq m	Typical diam m	pull out strength kN/m2	ultimate root force Tru kN/m2	factor F	design root force Trd kN/m2	I = b/cos alph	Root force on slice T kN
1	4	0.012	22000	9.95	8	1.24	1.74	2.16
2	4	0.012	22000	9.95	8	1.24	19.20	23.87
3	4	0.012	22000	9.95	8	1.24	1.56	1.93
4				0.00			0.00	0.00
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								

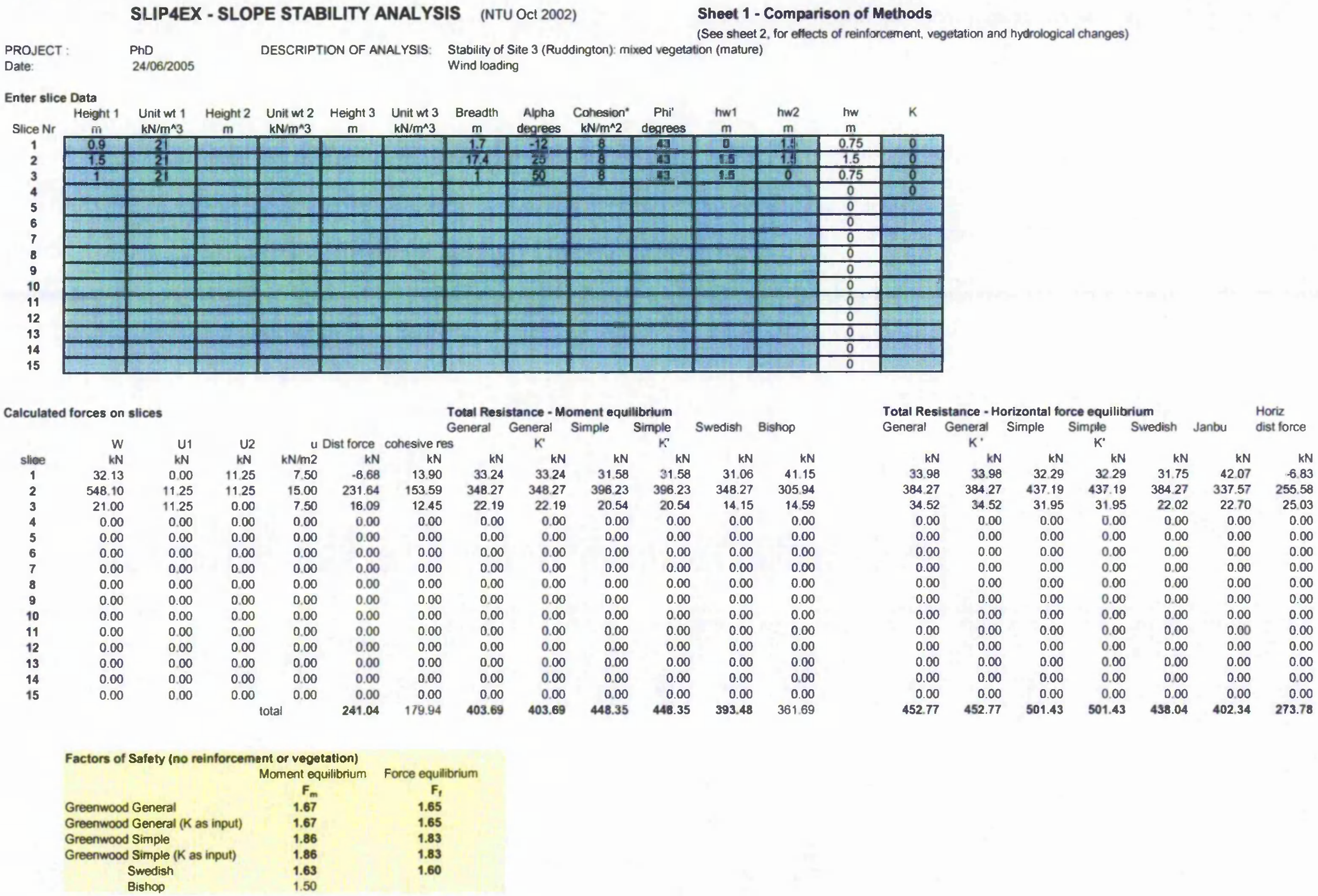
Calculated Reinforcement / Vegetation / Hydraulic effects

	Additional disturbing force (to reinf. and veg.)				Additional Restoring Forces									Total additional resistance		
slice	Veg.Weight kN	reinf dist fo kN	Wind dist f kN	Total add. dist force kN	add cohesion kN	add weight kN	add u kN	add U1 kN	add U2 kN	add 'U2-U1 Gen kN	add 'U2-U1 Simple kN	add wind kN	add T kN	General kN	Simple kN	Swedish kN
1	-20.79	-1.53	0.00	-22.32	3.48	91.21	5.67	0.00	12.95	-2.51	-0.25	0.00	1.42	92.95	90.69	90.44
2	42.26	-16.88	0.00	25.38	36.40	84.51	125.32	12.95	12.95	0.00	-22.38	0.00	15.74	13.33	35.71	13.33
3	76.60	-1.37	0.00	75.24	3.11	59.94	5.08	12.95	0.00	-9.25	-2.98	0.00	1.28	68.50	62.23	59.25
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	98.08	-19.78	0.00	**78.30**	44.98	235.67	136.07	25.90	25.90	-11.76	-25.61	0.00	18.44	**174.79**	**188.63**	**163.02**

Factors of Safety with Reinforcement ,Vegetation and hydraulic changes included

		F_m
Greenwood General	No reinforcement/Veg	**1.67**
	with reinf /veg /water as input	**1.81**
Greenwood General (K as input)	No reinforcement/Veg	**1.67**
	With reinf /veg /water as input	**1.81**
Greenwood Simple	No reinforcement/veg	**1.86**
	With reinf/veg/water as input	**1.99**
Swedish	No reinforcement/veg	**1.63**
	With reinf/veg/water as input	**1.74**

Figure B5 (a) Spreadsheet showing input parameters for Site 3 – Case 3B – wind loading
Sheet 1



SLIP4EX - SLOPE STABILITY ANALYSIS (NTU Oct 2002) **Sheet 1 - Comparison of Methods**

(See sheet 2, for effects of reinforcement, vegetation and hydrological changes)

PROJECT : PhD DESCRIPTION OF ANALYSIS: Stability of Site 3 (Ruddington): mixed vegetation (mature)
Date: 24/06/2005 Wind loading

Enter slice Data

Slice Nr	Height 1 m	Unit wt 1 kN/m^3	Height 2 m	Unit wt 2 kN/m^3	Height 3 m	Unit wt 3 kN/m^3	Breadth m	Alpha degrees	Cohesion' kN/m^2	Phi' degrees	hw1 m	hw2 m	hw m	K
1	0.9	21					1.7	-12	8	43	0	1.5	0.75	0
2	1.5	21					17.4	25	8	43	1.5	1.5	1.5	0
3	1	21					1	50	8	43	1.5	0	0.75	0
4													0	0
5													0	
6													0	
7													0	
8													0	
9													0	
10													0	
11													0	
12													0	
13													0	
14													0	
15													0	

Calculated forces on slices

							Total Resistance - Moment equilibrium					
							General	General K'	Simple	Simple K'	Swedish	Bishop
slice	W kN	U1 kN	U2 kN	u kN/m2	Dist force kN	cohesive res kN	kN	kN	kN	kN	kN	kN
1	32.13	0.00	11.25	7.50	-6.68	13.90	33.24	33.24	31.58	31.58	31.06	41.15
2	548.10	11.25	11.25	15.00	231.64	153.59	348.27	348.27	396.23	396.23	348.27	305.94
3	21.00	11.25	0.00	7.50	16.09	12.45	22.19	22.19	20.54	20.54	14.15	14.59
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				total	241.04	179.94	403.69	403.69	448.35	448.35	393.48	361.69

	Total Resistance - Horizontal force equilibrium						Horiz
	General	General K'	Simple	Simple K'	Swedish	Janbu	dist force
slice	kN	kN	kN	kN	kN	kN	kN
1	33.98	33.98	32.29	32.29	31.75	42.07	-6.83
2	384.27	384.27	437.19	437.19	384.27	337.57	255.58
3	34.52	34.52	31.95	31.95	22.02	22.70	25.03
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
total	452.77	452.77	501.43	501.43	438.04	402.34	273.78

Factors of Safety (no reinforcement or vegetation)

	Moment equilibrium F_m	Force equilibrium F_f
Greenwood General	1.67	1.65
Greenwood General (K as input)	1.67	1.65
Greenwood Simple	1.86	1.83
Greenwood Simple (K as input)	1.86	1.83
Swedish	1.63	1.60
Bishop	1.50	

Figure B5 (b) Spreadsheet showing vegetation parameters for Site 3 – Case 3B – wind loading.
Sheet 2

SLIP4EX - SLOPE STABILITY ANALYSIS (NTU Oct 2002)

Sheet 2 - EFFECTS OF REINFORCEMENT, VEGETATION AND HYDROLOGICAL
(See sheet 1, for Comparison of Methods)

PROJECT PhD
Date: 24/06/2005

DESCRIPTION OF ANALYSIS: Stability of Site 3 (Ruddington): mixed vegetation (mature)
Wind loading

Reinforcement, Vegetation and Hydraulic changes
Enter effects for relevant slices

Root Force Calculation

slice	T kN (/m)	Theta deg	c'v kN/m2	delta hw1 m	delta hw2 m	delta hw m	Wv kN (/m)	D kN (/m)	Beta deg.	Number per sq m	Typical diam m	pull out strength kN/m2	ultimate root force Tru kN/m2	factor F	design root force Trd kN/m2	l = b/cos alph	Root force on slice T kN
1	2.16	45	2	0	0.7	0.35	100	1	0	4	0.012	22000	9.95	8	1.24	1.74	2.16
2	23.87	45	2	0.7	0.7	0.7	100	1	25	4	0.012	22000	9.95	8	1.24	19.20	23.87
3	1.93	45	2	0.7	0	0.35	100	1	25	4	0.012	22000	9.95	8	1.24	1.56	1.93
4													0.00			0.00	0.00
5																	
6																	
7																	
8																	
9																	
10																	
11																	
12																	
13																	
14																	
15																	

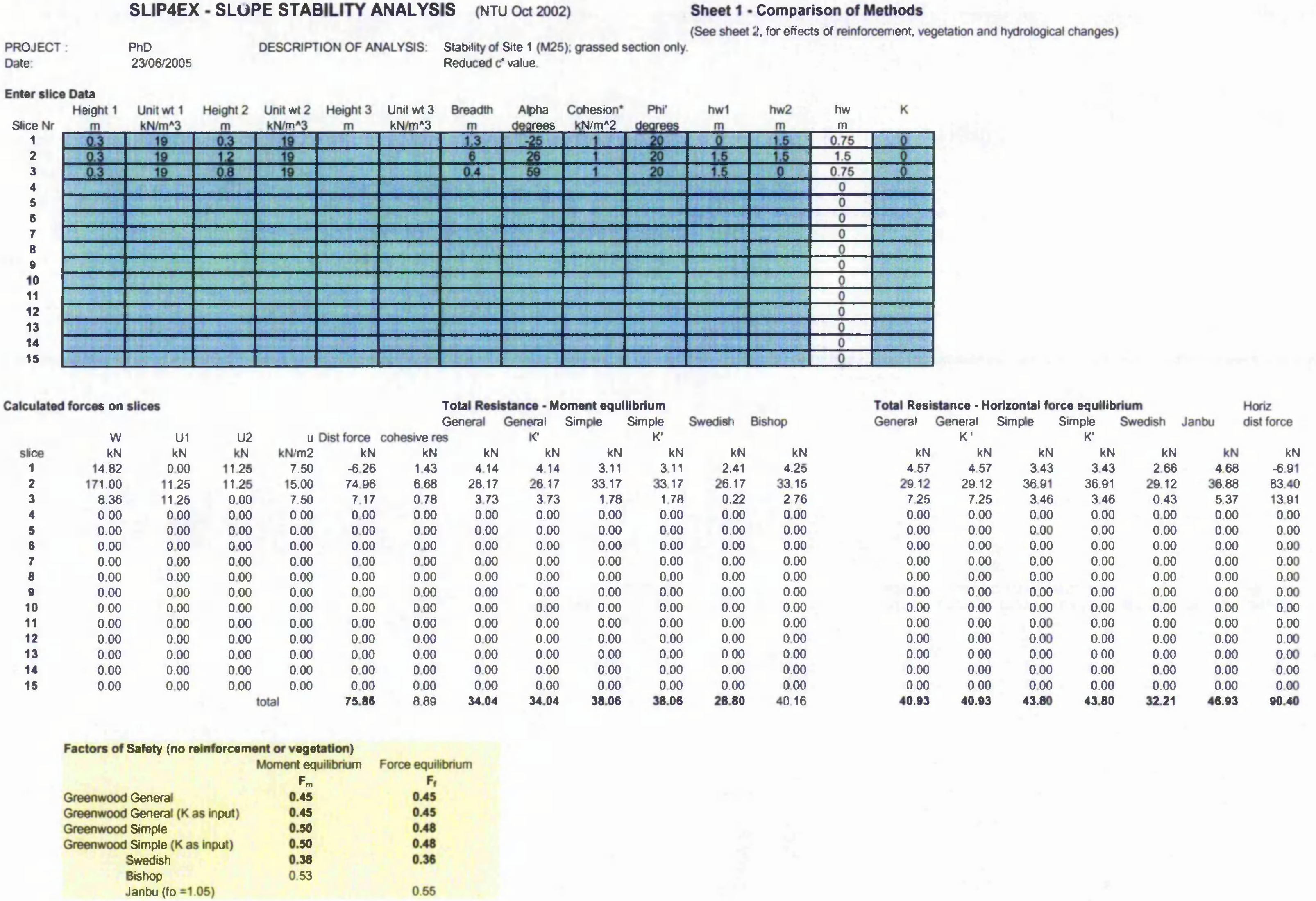
Calculated Reinforcement / Vegetation / Hydraulic effects

	Additional disturbing force (to reinf. and veg.)				Additional Restoring Forces									Total additional resistance		
	Veg.Weight	reinf dist fo	Wind dist f	Total add. dist force	add cohesion	add weight	add u	add U1	add U2	add 'U2-U1	add 'U2-U1	add wind	add T	General	Simple	Swedish
slice	kN	kN	kN	kN	kN	kN	kN	kN	kN	Gen kN	Simple kN	kN	kN	kN	kN	kN
1	-20.79	-1.53	0.98	-21.34	3.48	91.21	5.67	0.00	12.95	-2.51	-0.25	-0.19	1.42	93.15	90.88	90.64
2	42.26	-16.88	1.00	26.38	38.40	84.51	125.32	12.95	12.95	0.00	-22.38	0.00	15.74	13.33	35.71	13.33
3	76.60	-1.37	0.91	76.14	3.11	59.94	5.08	12.95	0.00	-9.25	-2.98	0.39	1.28	68.11	61.84	58.86
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	98.08	-19.78	2.88	**81.18**	44.98	235.67	136.07	25.90	25.90	-11.76	-25.61	0.20	18.44	**174.59**	**188.43**	**162.82**

Factors of Safety with Reinforcement ,Vegetation and hydraulic changes included

		F_m
Greenwood General	No reinforcement/Veg	**1.67**
	with reinf /veg /water as input	**1.79**
Greenwood General (K as input)	No reinforcement/Veg	**1.67**
	With reinf /veg /water as input	**1.79**
Greenwood Simple	No reinforcement/veg	**1.86**
	With reinf/veg/water as input	**1.98**
Swedish	No reinforcement/veg	**1.63**
	With reinf/veg/water as input	**1.73**

Figure B6 (a) Spreadsheet showing modified input parameters for Site 1 – Case 1A – grass vegetation cover.
Sheet 1



SLIP4EX - SLOPE STABILITY ANALYSIS (NTU Oct 2002)

Sheet 1 - Comparison of Methods
(See sheet 2, for effects of reinforcement, vegetation and hydrological changes)

PROJECT : PhD
Date: 23/06/2005
DESCRIPTION OF ANALYSIS: Stability of Site 1 (M25); grassed section only.
Reduced c' value.

Enter slice Data

Slice Nr	Height 1 m	Unit wt 1 kN/m^3	Height 2 m	Unit wt 2 kN/m^3	Height 3 m	Unit wt 3 kN/m^3	Breadth m	Alpha degrees	Cohesion* kN/m^2	Phi' degrees	hw1 m	hw2 m	hw m	K
1	0.3	19	0.3	19			1.3	-25	1	20	0	1.5	0.75	0
2	0.3	19	1.2	19			6	26	1	20	1.5	1.5	1.5	0
3	0.3	19	0.8	19			0.4	59	1	20	1.5	0	0.75	0
4													0	
5													0	
6													0	
7													0	
8													0	
9													0	
10													0	
11													0	
12													0	
13													0	
14													0	
15													0	

Calculated forces on slices

							Total Resistance - Moment equilibrium					
							General	General K'	Simple	Simple K'	Swedish	Bishop
slice	W kN	U1 kN	U2 kN	u kN/m2	Dist force kN	cohesive res kN	kN	kN	kN	kN	kN	kN
1	14.82	0.00	11.25	7.50	-6.26	1.43	4.14	4.14	3.11	3.11	2.41	4.25
2	171.00	11.25	11.25	15.00	74.96	6.68	26.17	26.17	33.17	33.17	26.17	33.15
3	8.36	11.25	0.00	7.50	7.17	0.78	3.73	3.73	1.78	1.78	0.22	2.76
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				total	75.86	8.89	34.04	34.04	38.06	38.06	28.80	40.16

	Total Resistance - Horizontal force equilibrium						Horiz
	General	General K '	Simple	Simple K'	Swedish	Janbu	dist force
slice	kN	kN	kN	kN	kN	kN	kN
1	4.57	4.57	3.43	3.43	2.66	4.68	-6.91
2	29.12	29.12	36.91	36.91	29.12	36.88	83.40
3	7.25	7.25	3.46	3.46	0.43	5.37	13.91
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	40.93	40.93	43.80	43.80	32.21	46.93	90.40

Factors of Safety (no reinforcement or vegetation)

	Moment equilibrium F_m	Force equilibrium F_f
Greenwood General	0.45	0.45
Greenwood General (K as input)	0.45	0.45
Greenwood Simple	0.50	0.48
Greenwood Simple (K as input)	0.50	0.48
Swedish	0.38	0.36
Bishop	0.53	
Janbu (fo =1.05)		0.55

Figure B6 (b) Spreadsheet showing vegetation parameters for modified soil conditions for Site 1 – Case 1A – grass vegetation cover. Sheet 2

PROJECT PhD
Date: 23/06/2005

DESCRIPTION OF ANALYSIS: Stability of Site 1 (M25); grassed section only. Increased c'v value.

Reinforcement, Vegetation and Hydraulic changes

Enter effects for relevant slices

slice	T kN (/m)	Theta deg	c'v kN/m2	delta hw1 m	delta hw2 m	delta hw m	Wv kN (/m)	D kN (/m)	Beta deg.
1	0.00		5						
2	0.00		5						
3	0.00		5						
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

Root Force Calculation

Number per sq m	Typical diam m	pull out strength kN/m2	ultimate root force Tru kN/m2	factor F	design root force Trd kN/m2	l = b/cos alph	Root force on slice T kN
			0.00	8	0.00	1.43	0.00
			0.00	8	0.00	6.68	0.00
			0.00	8	0.00	0.78	0.00
			0.00		#DIV/0!	0.00	#DIV/0!

Calculated Reinforcement / Vegetation / Hydraulic effects

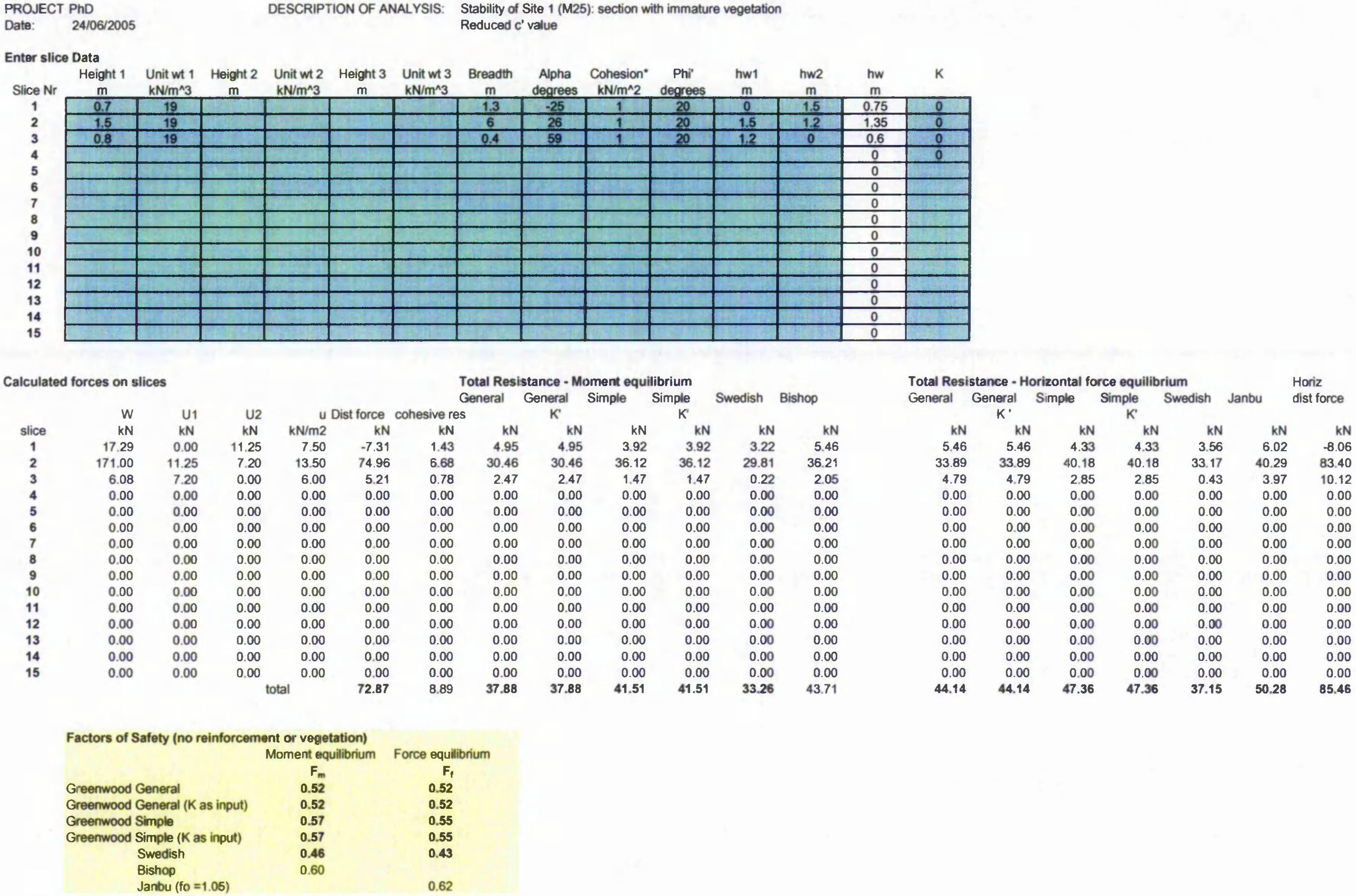
	Additional disturbing force (to reinf. and veg.)				Additional Restoring Forces									Total additional resistance		
slice	Veg.Weight kN	reinf dist fo kN	Wind dist f kN	Total add. dist force kN	add cohesion kN	add weight kN	add u kN	add U1 kN	add U2 kN	add 'U2-U1 Gen kN	add 'U2-U1 Simple kN	add wind kN	add T kN	General kN	Simple kN	Swedish kN
1	0.00	0.00	0.00	0.00	7.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.17	7.17	7.17
2	0.00	0.00	0.00	0.00	33.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	33.38	33.38	33.38
3	0.00	0.00	0.00	0.00	3.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.88	3.88	3.88
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	**0.00**	44.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**44.43**	**44.43**	**44.43**

Factors of Safety with Reinforcement ,Vegetation and hydraulic changes included

		F_m
Greenwood General	No reinforcement/Veg	**0.45**
	with reinf /veg /water as input	**1.03**
Greenwood General (K as input)	No reinforcement/Veg	**0.45**
	With reinf /veg /water as input	**1.03**
Greenwood Simple	No reinforcement/veg	**0.50**
	With reinf/veg/water as input	**1.09**
Swedish	No reinforcement/veg	**0.38**
	With reinf/veg/water as input	**0.97**

Figure B7 (a) Spreadsheet showing modified soil input parameters for Site 1- Case 1B – vegetation cover of immature trees.

Sheet 1



PROJECT PhD
Date: 24/06/2005

DESCRIPTION OF ANALYSIS: Stability of Site 1 (M25): section with immature vegetation
Reduced c' value

Enter slice Data

Slice Nr	Height 1 m	Unit wt 1 kN/m^3	Height 2 m	Unit wt 2 kN/m^3	Height 3 m	Unit wt 3 kN/m^3	Breadth m	Alpha degrees	Cohesion* kN/m^2	Phi' degrees	hw1 m	hw2 m	hw m	K
1	0.7	19					1.3	-25	1	20	0	1.5	0.75	0
2	1.5	19					6	26	1	20	1.5	1.2	1.35	0
3	0.8	19					0.4	59	1	20	1.2	0	0.6	0
4													0	0
5													0	
6													0	
7													0	
8													0	
9													0	
10													0	
11													0	
12													0	
13													0	
14													0	
15													0	

Calculated forces on slices

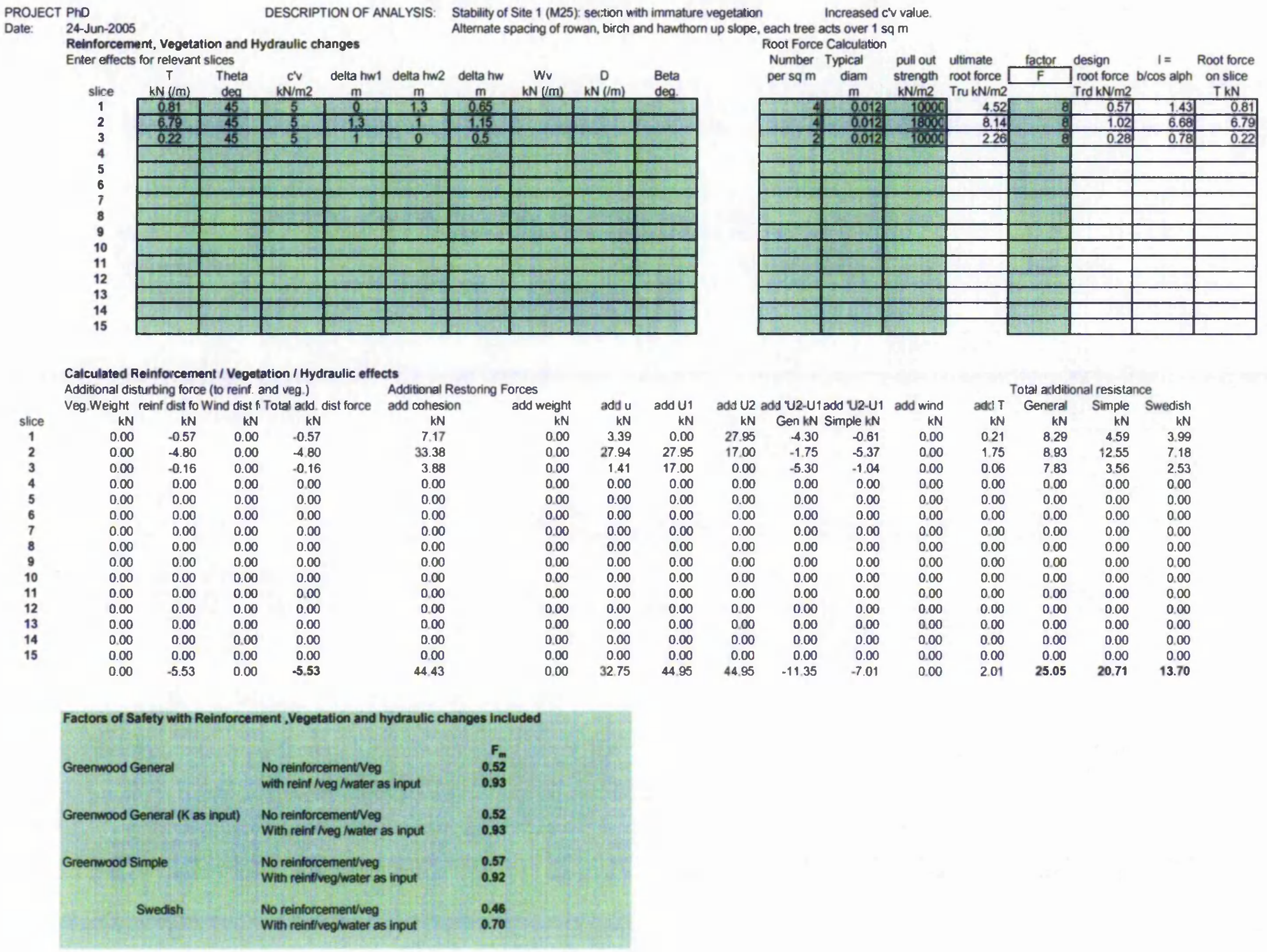
							Total Resistance - Moment equilibrium					
							General	General K'	Simple	Simple K'	Swedish	Bishop
slice	W kN	U1 kN	U2 kN	u kN/m2	Dist force kN	cohesive res kN	kN	kN	kN	kN	kN	kN
1	17.29	0.00	11.25	7.50	-7.31	1.43	4.95	4.95	3.92	3.92	3.22	5.46
2	171.00	11.25	7.20	13.50	74.96	6.68	30.46	30.46	36.12	36.12	29.81	36.21
3	6.08	7.20	0.00	6.00	5.21	0.78	2.47	2.47	1.47	1.47	0.22	2.05
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				total	72.87	8.89	**37.88**	**37.88**	**41.51**	**41.51**	**33.26**	43.71

	Total Resistance - Horizontal force equilibrium						Horiz
	General	General K '	Simple	Simple K'	Swedish	Janbu	dist force
slice	kN	kN	kN	kN	kN	kN	kN
1	5.46	5.46	4.33	4.33	3.56	6.02	-8.06
2	33.89	33.89	40.18	40.18	33.17	40.29	83.40
3	4.79	4.79	2.85	2.85	0.43	3.97	10.12
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
total	**44.14**	**44.14**	**47.36**	**47.36**	**37.15**	**50.28**	**85.46**

Factors of Safety (no reinforcement or vegetation)

	Moment equilibrium F_m	Force equilibrium F_f
Greenwood General	**0.52**	**0.52**
Greenwood General (K as input)	**0.52**	**0.52**
Greenwood Simple	**0.57**	**0.55**
Greenwood Simple (K as input)	**0.57**	**0.55**
Swedish	**0.46**	**0.43**
Bishop	0.60	
Janbu (fo =1.05)		0.62

Figure B7 (b) Spreadsheet showing vegetation parameters for modified soil conditions for Site 1 – Case 1B – vegetation cover of immature trees. Sheet 2



PROJECT PhD DESCRIPTION OF ANALYSIS: Stability of Site 1 (M25): section with immature vegetation Increased c'v value.
Date: 24-Jun-2005 Alternate spacing of rowan, birch and hawthorn up slope, each tree acts over 1 sq m

Reinforcement, Vegetation and Hydraulic changes

Enter effects for relevant slices

slice	T kN (/m)	Theta deg	c'v kN/m2	delta hw1 m	delta hw2 m	delta hw m	Wv kN (/m)	D kN (/m)	Beta deg.
1	0.81	45	5	0	1.3	0.65			
2	6.79	45	5	1.3	1	1.15			
3	0.22	45	5	1	0	0.5			
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

Root Force Calculation

slice	Number per sq m	Typical diam m	pull out strength kN/m2	ultimate root force Tru kN/m2	factor F	design root force Trd kN/m2	I = b/cos alph	Root force on slice T kN
1	4	0.012	10000	4.52	8	0.57	1.43	0.81
2	4	0.012	18000	8.14	8	1.02	6.68	6.79
3	2	0.012	10000	2.26	8	0.28	0.78	0.22
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								

Calculated Reinforcement / Vegetation / Hydraulic effects

	Additional disturbing force (to reinf. and veg.)				Additional Restoring Forces									Total additional resistance		
slice	Veg.Weight kN	reinf dist fo kN	Wind dist f kN	Total add. dist force kN	add cohesion kN	add weight kN	add u kN	add U1 kN	add U2 kN	add 'U2-U1 Gen kN	add 'U2-U1 Simple kN	add wind kN	add T kN	General kN	Simple kN	Swedish kN
1	0.00	-0.57	0.00	-0.57	7.17	0.00	3.39	0.00	27.95	-4.30	-0.61	0.00	0.21	8.29	4.59	3.99
2	0.00	-4.80	0.00	-4.80	33.38	0.00	27.94	27.95	17.00	-1.75	-5.37	0.00	1.75	8.93	12.55	7.18
3	0.00	-0.16	0.00	-0.16	3.88	0.00	1.41	17.00	0.00	-5.30	-1.04	0.00	0.06	7.83	3.56	2.53
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	-5.53	0.00	**-5.53**	44.43	0.00	32.75	44.95	44.95	-11.35	-7.01	0.00	2.01	**25.05**	**20.71**	**13.70**

Factors of Safety with Reinforcement ,Vegetation and hydraulic changes included

		F_m
Greenwood General	No reinforcement/Veg	**0.52**
	with reinf /veg /water as input	**0.93**
Greenwood General (K as input)	No reinforcement/Veg	**0.52**
	With reinf /veg /water as input	**0.93**
Greenwood Simple	No reinforcement/veg	**0.57**
	With reinf/veg/water as input	**0.92**
Swedish	No reinforcement/veg	**0.46**
	With reinf/veg/water as input	**0.70**

Figure B8 (a) Spreadsheet showing modified soil input parameters for Site 2 – Mature vegetation cover.

Sheet 1

PROJECT PhD

Date: 24/06/2005

DESCRIPTION OF ANALYSIS: Stability of Site 2 (M11): mixed vegetation
Reduced c' value.

Enter slice Data

Slice Nr	Height 1 m	Unit wt 1 kN/m^3	Height 2 m	Unit wt 2 kN/m^3	Height 3 m	Unit wt 3 kN/m^3	Breadth m	Alpha degrees	Cohesion* kN/m^2	Phi' degrees	hw1 m	hw2 m	hw m	K
1	0.6	19					2.4	-16	1	20	0	1.5	0.75	0
2	1.5	19					38.4	20	1	20	1.5	1.5	1.5	0
3	0.7	19					1.6	50	1	20	1.5	0	0.75	0
4													0	
5													0	
6													0	
7													0	
8													0	
9													0	
10													0	
11													0	
12													0	
13													0	
14													0	
15													0	

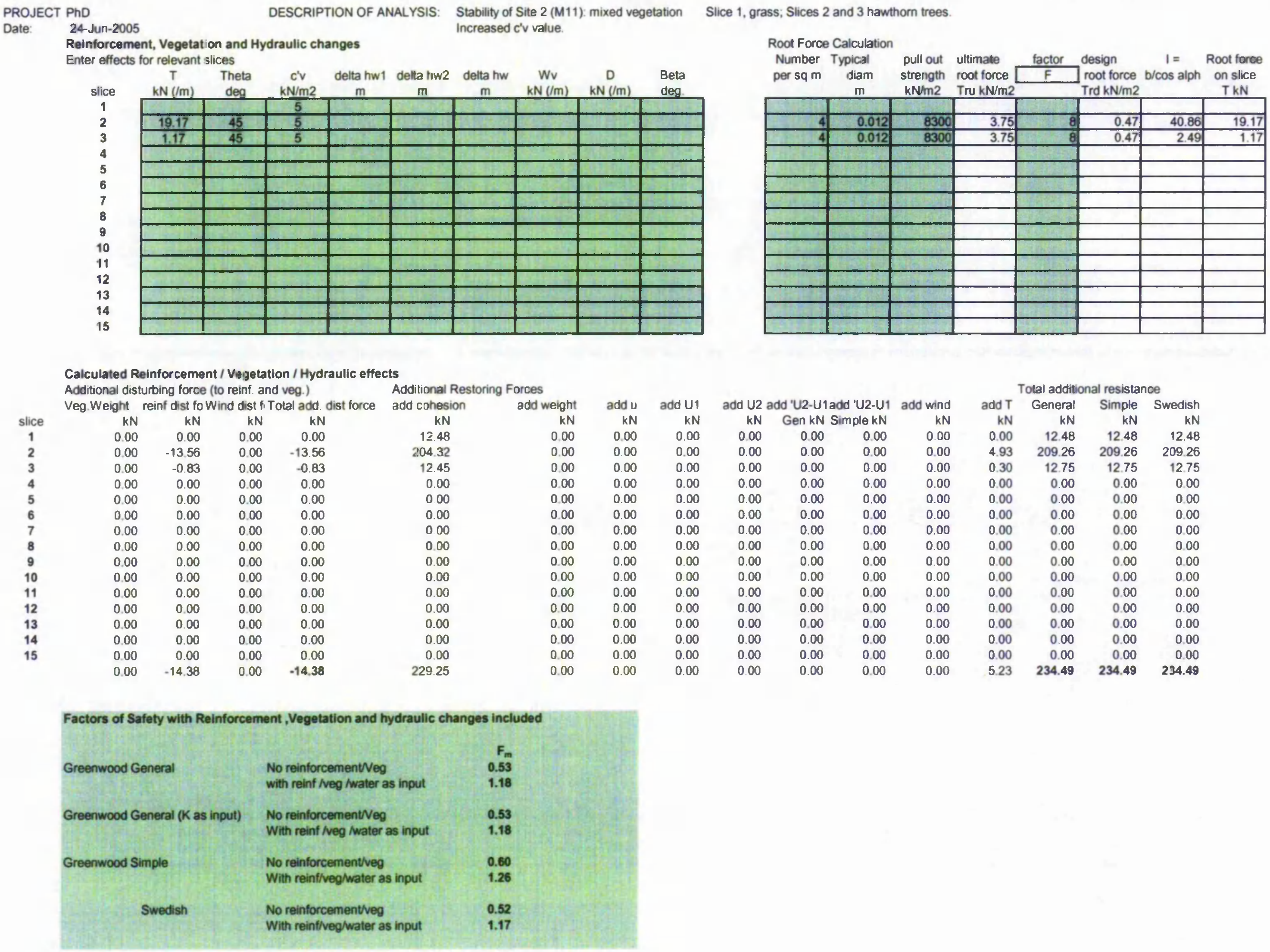
Calculated forces on slices

							Total Resistance - Moment equilibrium						**Total Resistance - Horizontal force equilibrium**						Horiz
							General	General K'	Simple	Simple K'	Swedish	Bishop	General	General K'	Simple	Simple K'	Swedish	Janbu	dist force
	W	U1	U2	u	Dist force	cohesive res													
slice	kN	kN	kN	kN/m2	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN
1	27.36	0.00	11.25	7.50	-7.54	2.50	6.38	6.38	5.77	5.77	5.25	6.80	6.64	6.64	6.00	6.00	5.47	7.08	-7.85
2	1094.40	11.25	11.25	15.00	374.31	40.86	192.07	192.07	218.17	218.17	192.07	211.53	204.40	204.40	232.17	232.17	204.40	225.10	398.33
3	21.28	11.25	0.00	7.50	16.30	2.49	3.81	3.81	4.66	4.66	0.67	5.28	5.93	5.93	7.25	7.25	1.05	8.22	25.36
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				total	383.07	45.85	202.26	202.26	228.60	228.60	198.00	223.61	216.96	216.96	245.42	245.42	210.91	240.39	415.84

Factors of Safety (no reinforcement or vegetation)

	Moment equilibrium F_m	Force equilibrium F_f
Greenwood General	0.53	0.52
Greenwood General (K as input)	0.53	0.52
Greenwood Simple	0.60	0.59
Greenwood Simple (K as input)	0.60	0.59
Swedish	0.52	0.51
Bishop	0.58	
Janbu (fo =1.05)		0.61

Figure B8 (b) Spreadsheet showing vegetation parameters for modified soil conditions for Site 2 – Mature vegetation cover. Sheet 2



PROJECT PhD　　DESCRIPTION OF ANALYSIS: Stability of Site 2 (M11): mixed vegetation　Slice 1, grass; Slices 2 and 3 hawthorn trees.
Date: 24-Jun-2005　　Increased c'v value.

Reinforcement, Vegetation and Hydraulic changes
Enter effects for relevant slices

slice	T kN (/m)	Theta deg	c'v kN/m2	delta hw1 m	delta hw2 m	delta hw m	Wv kN (/m)	D kN (/m)	Beta deg.
1			5						
2	19.17	45	5						
3	1.17	45	5						
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

Root Force Calculation

slice	Number per sq m	Typical diam m	pull out strength kN/m2	ultimate root force Tru kN/m2	factor F	design root force Trd kN/m2	I = b/cos alph	Root force on slice T kN
1								
2	4	0.012	8300	3.75	8	0.47	40.86	19.17
3	4	0.012	8300	3.75	8	0.47	2.49	1.17
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								

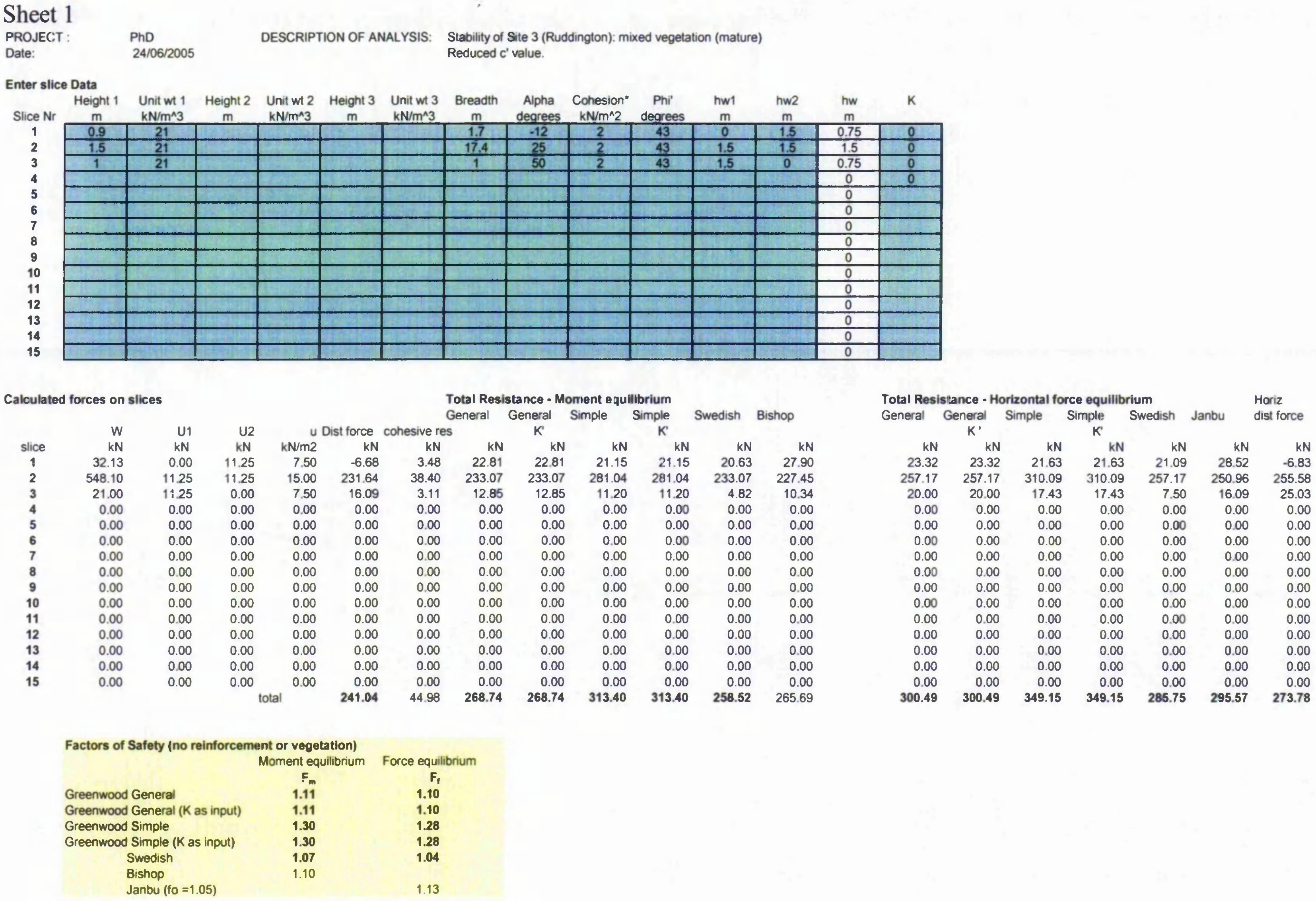
Calculated Reinforcement / Vegetation / Hydraulic effects

	Additional disturbing force (to reinf. and veg.)				Additional Restoring Forces									Total additional resistance		
slice	Veg.Weight kN	reinf dist fo kN	Wind dist f kN	Total add. dist force kN	add cohesion kN	add weight kN	add u kN	add U1 kN	add U2 kN	add 'U2-U1 Gen kN	add 'U2-U1 Simple kN	add wind kN	add T kN	General kN	Simple kN	Swedish kN
1	0.00	0.00	0.00	0.00	12.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.48	12.48	12.48
2	0.00	-13.56	0.00	-13.56	204.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.93	209.26	209.26	209.26
3	0.00	-0.83	0.00	-0.83	12.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	12.75	12.75	12.75
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	-14.38	0.00	**-14.38**	229.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.23	**234.49**	**234.49**	**234.49**

Factors of Safety with Reinforcement ,Vegetation and hydraulic changes included

		F_m
Greenwood General	No reinforcement/Veg	**0.53**
	with reinf /veg /water as input	**1.18**
Greenwood General (K as input)	No reinforcement/Veg	**0.53**
	With reinf /veg /water as input	**1.18**
Greenwood Simple	No reinforcement/veg	**0.60**
	With reinf/veg/water as input	**1.26**
Swedish	No reinforcement/veg	**0.52**
	With reinf/veg/water as input	**1.17**

Figure B9 (a) Spreadsheet showing modified soil input parameters for Site 3 - Case 3A – no wind loading.



Sheet 1

PROJECT : PhD DESCRIPTION OF ANALYSIS: Stability of Site 3 (Ruddington): mixed vegetation (mature)
Date: 24/06/2005 Reduced c' value.

Enter slice Data

Slice Nr	Height 1 m	Unit wt 1 kN/m^3	Height 2 m	Unit wt 2 kN/m^3	Height 3 m	Unit wt 3 kN/m^3	Breadth m	Alpha degrees	Cohesion* kN/m^2	Phi' degrees	hw1 m	hw2 m	hw m	K
1	0.9	21					1.7	-12	2	43	0	1.5	0.75	0
2	1.5	21					17.4	25	2	43	1.5	1.5	1.5	0
3	1	21					1	50	2	43	1.5	0	0.75	0
4													0	0
5													0	
6													0	
7													0	
8													0	
9													0	
10													0	
11													0	
12													0	
13													0	
14													0	
15													0	

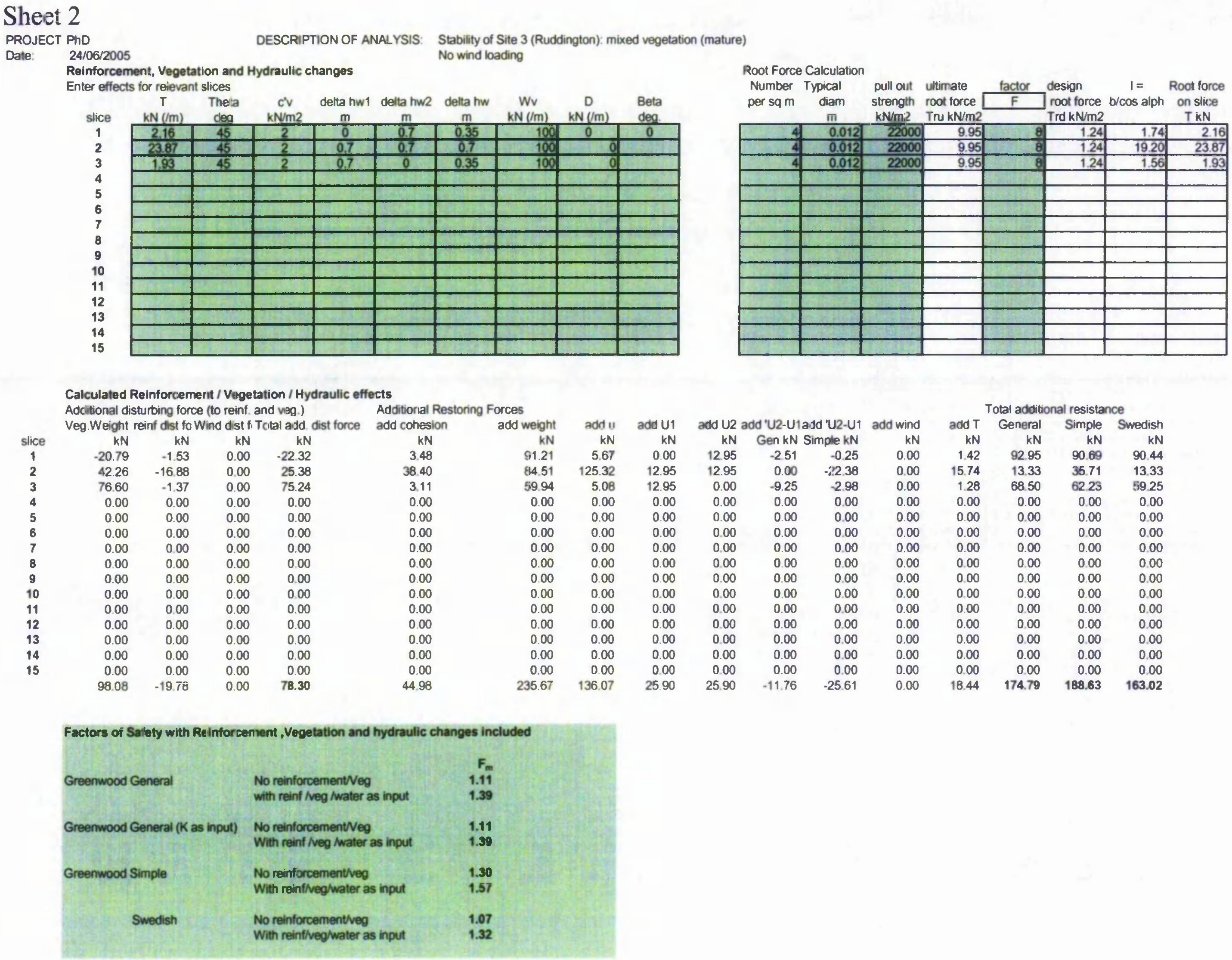
Calculated forces on slices

							Total Resistance - Moment equilibrium						Total Resistance - Horizontal force equilibrium						
	W	U1	U2	u	Dist force	cohesive res	General	General K'	Simple	Simple K'	Swedish	Bishop	General	General K'	Simple	Simple K'	Swedish	Janbu	Horiz dist force
slice	kN	kN	kN	kN/m2	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN
1	32.13	0.00	11.25	7.50	-6.68	3.48	22.81	22.81	21.15	21.15	20.63	27.90	23.32	23.32	21.63	21.63	21.09	28.52	-6.83
2	548.10	11.25	11.25	15.00	231.64	38.40	233.07	233.07	281.04	281.04	233.07	227.45	257.17	257.17	310.09	310.09	257.17	250.96	255.58
3	21.00	11.25	0.00	7.50	16.09	3.11	12.85	12.85	11.20	11.20	4.82	10.34	20.00	20.00	17.43	17.43	7.50	16.09	25.03
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				total	**241.04**	44.98	**268.74**	**268.74**	**313.40**	**313.40**	**258.52**	265.69	**300.49**	**300.49**	**349.15**	**349.15**	**285.75**	**295.57**	**273.78**

Factors of Safety (no reinforcement or vegetation)

	Moment equilibrium F_m	Force equilibrium F_f
Greenwood General	**1.11**	**1.10**
Greenwood General (K as input)	**1.11**	**1.10**
Greenwood Simple	**1.30**	**1.28**
Greenwood Simple (K as input)	**1.30**	**1.28**
Swedish	**1.07**	**1.04**
Bishop	1.10	
Janbu (fo =1.05)		1.13

Figure B9 (b) Spreadsheet showing vegetation input parameters for modified soil conditions for Site 3 - Case 3A – no wind loading.



Sheet 2

PROJECT PhD
Date: 24/06/2005

DESCRIPTION OF ANALYSIS: Stability of Site 3 (Ruddington): mixed vegetation (mature)
No wind loading

Reinforcement, Vegetation and Hydraulic changes
Enter effects for relevant slices

slice	T kN (/m)	Theta deg	c'v kN/m2	delta hw1 m	delta hw2 m	delta hw m	Wv kN (/m)	D kN (/m)	Beta deg.
1	2.16	45	2	0	0.7	0.35	100	0	0
2	23.87	45	2	0.7	0.7	0.7	100	0	
3	1.93	45	2	0.7	0	0.35	100	0	
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

Root Force Calculation

Number per sq m	Typical diam m	pull out strength kN/m2	ultimate root force Tru kN/m2	factor F	design root force Trd kN/m2	l = b/cos alph	Root force on slice T kN
4	0.012	22000	9.95	8	1.24	1.74	2.16
4	0.012	22000	9.95	8	1.24	19.20	23.87
4	0.012	22000	9.95	8	1.24	1.56	1.93

Calculated Reinforcement / Vegetation / Hydraulic effects

	Additional disturbing force (to reinf. and veg.)				Additional Restoring Forces									Total additional resistance		
slice	Veg.Weight kN	reinf dist fo kN	Wind dist f kN	Total add. dist force kN	add cohesion kN	add weight kN	add u kN	add U1 kN	add U2 kN	add 'U2-U1 Gen kN	add 'U2-U1 Simple kN	add wind kN	add T kN	General kN	Simple kN	Swedish kN
1	-20.79	-1.53	0.00	-22.32	3.48	91.21	5.67	0.00	12.95	-2.51	-0.25	0.00	1.42	92.95	90.69	90.44
2	42.26	-16.88	0.00	25.38	38.40	84.51	125.32	12.95	12.95	0.00	-22.38	0.00	15.74	13.33	35.71	13.33
3	76.60	-1.37	0.00	75.24	3.11	59.94	5.08	12.95	0.00	-9.25	-2.98	0.00	1.28	68.50	62.23	59.25
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	98.08	-19.78	0.00	**78.30**	44.98	235.67	136.07	25.90	25.90	-11.76	-25.61	0.00	18.44	**174.79**	**188.63**	**163.02**

Factors of Safety with Reinforcement ,Vegetation and hydraulic changes included

		F_m
Greenwood General	No reinforcement/Veg	**1.11**
	with reinf /veg /water as input	**1.39**
Greenwood General (K as input)	No reinforcement/Veg	**1.11**
	With reinf /veg /water as input	**1.39**
Greenwood Simple	No reinforcement/veg	**1.30**
	With reinf/veg/water as input	**1.57**
Swedish	No reinforcement/veg	**1.07**
	With reinf/veg/water as input	**1.32**

Figure B10 (a) Spreadsheet showing modified soil input parameters for Site 3 – Case 3B – wind loading.
Sheet 1

PROJECT : PhD
Date: 24/06/2005

DESCRIPTION OF ANALYSIS: Stability of Site 3 (Ruddington): mixed vegetation (mature)
Wind loading
Reduced c' value

Enter slice Data

Slice Nr	Height 1 m	Unit wt 1 kN/m^3	Height 2 m	Unit wt 2 kN/m^3	Height 3 m	Unit wt 3 kN/m^3	Breadth m	Alpha degrees	Cohesion' kN/m^2	Phi' degrees	hw1 m	hw2 m	hw m	K
1	0.9	21					1.7	-12	2	43	0	1.5	0.75	0
2	1.5	21					17.4	25	2	43	1.5	1.5	1.5	0
3	1	21					1	50	2	43	1.5	0	0.75	0
4													0	0
5													0	
6													0	
7													0	
8													0	
9													0	
10													0	
11													0	
12													0	
13													0	
14													0	
15													0	

Calculated forces on slices

							Total Resistance - Moment equilibrium					
							General	General	Simple	Simple	Swedish	Bishop
	W	U1	U2	u	Dist force	cohesive res		K'		K'		
slice	kN	kN	kN	kN/m2	kN	kN	kN	kN	kN	kN	kN	kN
1	32.13	0.00	11.25	7.50	-6.68	3.48	22.81	22.81	21.15	21.15	20.63	27.90
2	548.10	11.25	11.25	15.00	231.64	38.40	233.07	233.07	281.04	281.04	233.07	227.45
3	21.00	11.25	0.00	7.50	16.09	3.11	12.85	12.85	11.20	11.20	4.82	10.34
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				total	**241.04**	44.98	**268.74**	**268.74**	**313.40**	**313.40**	**258.52**	265.69

	Total Resistance - Horizontal force equilibrium						Horiz
	General	General	Simple	Simple	Swedish	Janbu	dist force
		K'		K'			
slice	kN	kN	kN	kN	kN	kN	kN
1	23.32	23.32	21.63	21.63	21.09	28.52	-6.83
2	257.17	257.17	310.09	310.09	257.17	250.96	255.58
3	20.00	20.00	17.43	17.43	7.50	16.09	25.03
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	300.49	**300.49**	**349.15**	**349.15**	**285.75**	**295.57**	**273.78**

Factors of Safety (no reinforcement or vegetation)

	Moment equilibrium F_m	Force equilibrium F_f
Greenwood General	**1.11**	**1.10**
Greenwood General (K as input)	**1.11**	**1.10**
Greenwood Simple	**1.30**	**1.28**
Greenwood Simple (K as input)	**1.30**	**1.28**
Swedish	**1.07**	**1.04**
Bishop	1.10	
Janbu (fo =1.05)		1.13

Figure B10 (b) Spreadsheet showing vegetation parameters for modified soil conditions for Site 3 – Case 3B – wind loading.
Sheet 2

PROJECT PhD
Date: 24/06/2005

DESCRIPTION OF ANALYSIS: Stability of Site 3 (Ruddington): mixed vegetation (mature)
Wind loading

Reinforcement, Vegetation and Hydraulic changes
Enter effects for relevant slices

slice	T kN (/m)	Theta deg	c'v kN/m2	delta hw1 m	delta hw2 m	delta hw m	Wv kN (/m)	D kN (/m)	Beta deg.
1	2.16	45	2	0	0.7	0.35	100	1	0
2	23.87	45	2	0.7	0.7	0.7	100	1	25
3	1.93	45	2	0.7	0	0.35	100	1	25
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

Root Force Calculation

Number per sq m	Typical diam m	pull out strength kN/m2	ultimate root force Tru kN/m2	factor F	design root force Trd kN/m2	l = b/cos alph
4	0.012	22000	9.95	8	1.24	1.74
4	0.012	22000	9.95	8	1.24	19.20
4	0.012	22000	9.95	8	1.24	1.56

Calculated Reinforcement / Vegetation / Hydraulic effects

	Additional disturbing force (to reinf. and veg.)				Additional Restoring Forces									Total additional resistance		
slice	Veg.Weight kN	reinf dist fc kN	Wind dist f kN	Total add. dist force kN	add cohesion kN	add weight kN	add u kN	add U1 kN	add U2 kN	add 'U2-U1 Gen kN	add 'U2-U1 Simple kN	add wind kN	add T kN	General kN	Simple kN	Swedish kN
1	-20.79	-1.53	0.98	-21.34	3.48	91.21	5.67	0.00	12.95	-2.51	-0.25	-0.19	1.42	93.15	90.88	90.64
2	42.26	-16.88	1.00	26.38	38.40	84.51	125.32	12.95	12.95	0.00	-22.38	0.00	15.74	13.33	35.71	13.33
3	76.60	-1.37	0.91	76.14	3.11	59.94	5.08	12.95	0.00	-9.25	-2.98	0.39	1.28	68.11	61.84	58.86
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	98.08	-19.78	2.88	**81.18**	44.98	235.67	136.07	25.90	25.90	-11.76	-25.61	0.20	18.44	**174.59**	**188.43**	**162.82**

Factors of Safety with Reinforcement ,Vegetation and hydraulic changes included

		F_m
Greenwood General	No reinforcement/Veg	**1.11**
	with reinf /veg /water as input	**1.38**
Greenwood General (K as input)	No reinforcement/Veg	**1.11**
	With reinf /veg /water as input	**1.38**
Greenwood Simple	No reinforcement/veg	**1.30**
	With reinf/veg/water as input	**1.56**
Swedish	No reinforcement/veg	**1.07**
	With reinf/veg/water as input	**1.31**

Appendix 3: SLIP4EX spreadsheets showing changes in Factor of Safety following removal of vegetation

Figure C1 (a) Spreadsheet showing soil input parameters for Site 3 before vegetation is removed.

Sheet 1

PROJECT : PhD
Date: 24/06/2005

DESCRIPTION OF ANALYSIS: Stability of Site 3 (Ruddington): mixed vegetation (mature)

Enter slice Data

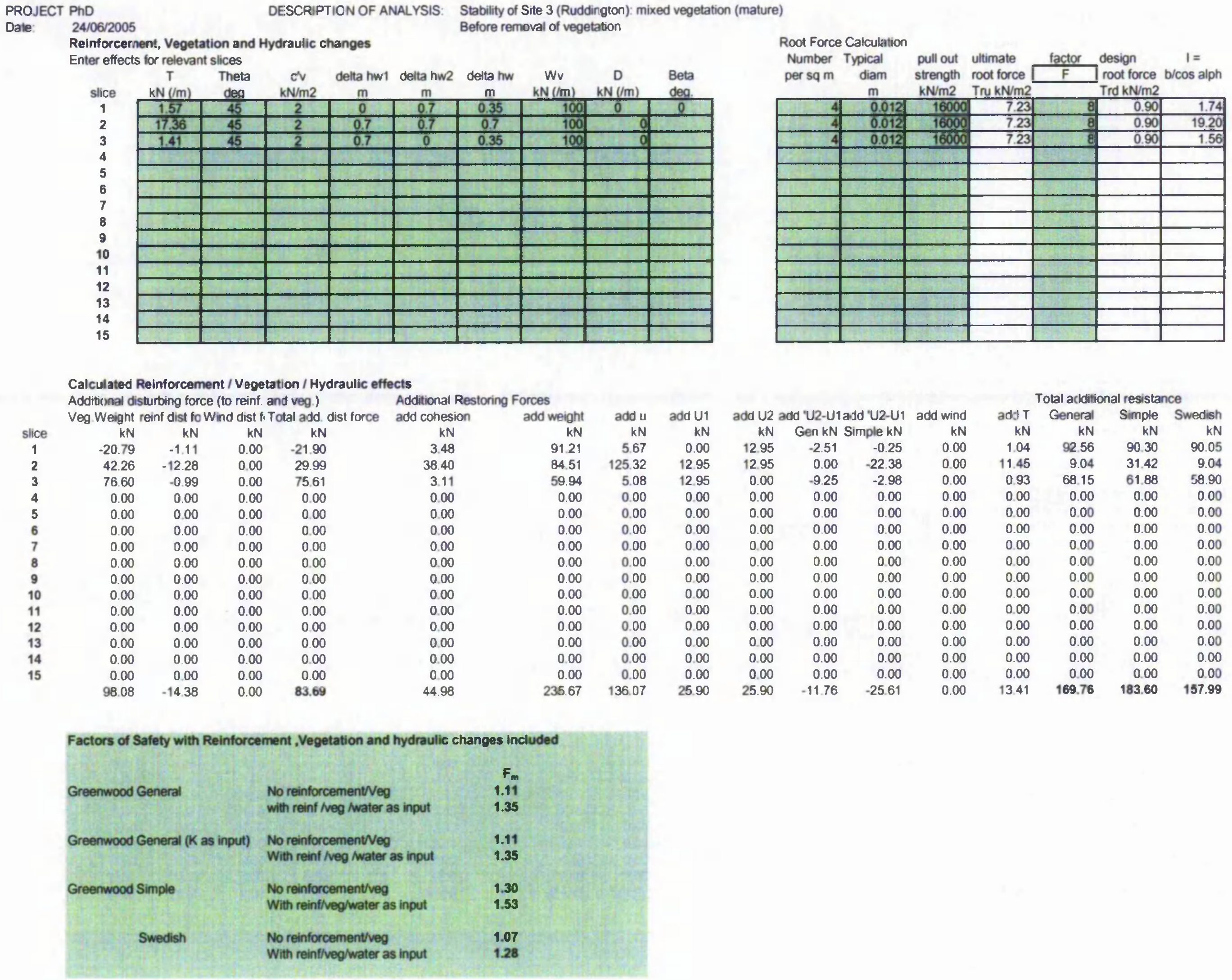
Slice Nr	Height 1 m	Unit wt 1 kN/m^3	Height 2 m	Unit wt 2 kN/m^3	Height 3 m	Unit wt 3 kN/m^3	Breadth m	Alpha degrees	Cohesion* kN/m^2	Phi' degrees	hw1 m	hw2 m	hw m	K
1	0.9	21					1.7	-12	2	43	0	1.5	0.75	0
2	1.5	21					17.4	25	2	43	1.5	1.5	1.5	0
3	1	21					1	50	2	43	1.5	0	0.75	0
4													0	0
5													0	
6													0	
7													0	
8													0	
9													0	
10													0	
11													0	
12													0	
13													0	
14													0	
15													0	

Calculated forces on slices							**Total Resistance - Moment equilibrium**						**Total Resistance - Horizontal force equilibrium**						Horiz
							General	General	Simple	Simple	Swedish	Bishop	General	General	Simple	Simple	Swedish	Janbu	dist force
	W	U1	U2	u	Dist force	cohesive res		K'		K'				K '		K'			
slice	kN	kN	kN	kN/m2	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN
1	32.13	0.00	11.25	7.50	-6.68	3.48	22.81	22.81	21.15	21.15	20.63	27.90	23.32	23.32	21.63	21.63	21.09	28.52	-6.83
2	548.10	11.25	11.25	15.00	231.64	38.40	233.07	233.07	281.04	281.04	233.07	227.45	257.17	257.17	310.09	310.09	257.17	250.96	255.58
3	21.00	11.25	0.00	7.50	16.09	3.11	12.85	12.85	11.20	11.20	4.82	10.34	20.00	20.00	17.43	17.43	7.50	16.09	25.03
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				total	**241.04**	44.98	**268.74**	**268.74**	**313.40**	**313.40**	**258.52**	265.69	**300.49**	**300.49**	**349.15**	**349.15**	**285.75**	**295.57**	**273.78**

Factors of Safety (no reinforcement or vegetation)

	Moment equilibrium F_m	Force equilibrium F_f
Greenwood General	**1.11**	**1.10**
Greenwood General (K as input)	**1.11**	**1.10**
Greenwood Simple	**1.30**	**1.28**
Greenwood Simple (K as input)	**1.30**	**1.28**
Swedish	**1.07**	**1.04**
Bishop	1.10	
Janbu (fo =1.05)		1.13

Figure C1 (b) Spreadsheet showing vegetation input parameters for Site 3 before vegetation is removed.
Sheet 2



PROJECT PhD DESCRIPTION OF ANALYSIS: Stability of Site 3 (Ruddington): mixed vegetation (mature)
Date: 24/06/2005 Before removal of vegetation

Reinforcement, Vegetation and Hydraulic changes
Enter effects for relevant slices

slice	T kN (/m)	Theta deg	c'v kN/m2	delta hw1 m	delta hw2 m	delta hw m	Wv kN (/m)	D kN (/m)	Beta deg.
1	1.57	45	2	0	0.7	0.35	100	0	0
2	17.36	45	2	0.7	0.7	0.7	100	0	
3	1.41	45	2	0.7	0	0.35	100	0	
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

Root Force Calculation

slice	Number per sq m	Typical diam m	pull out strength kN/m2	ultimate root force Tru kN/m2	factor F	design root force Trd kN/m2	l = b/cos alph
1	4	0.012	16000	7.23	8	0.90	1.74
2	4	0.012	16000	7.23	8	0.90	19.20
3	4	0.012	16000	7.23	8	0.90	1.56
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							

Calculated Reinforcement / Vegetation / Hydraulic effects

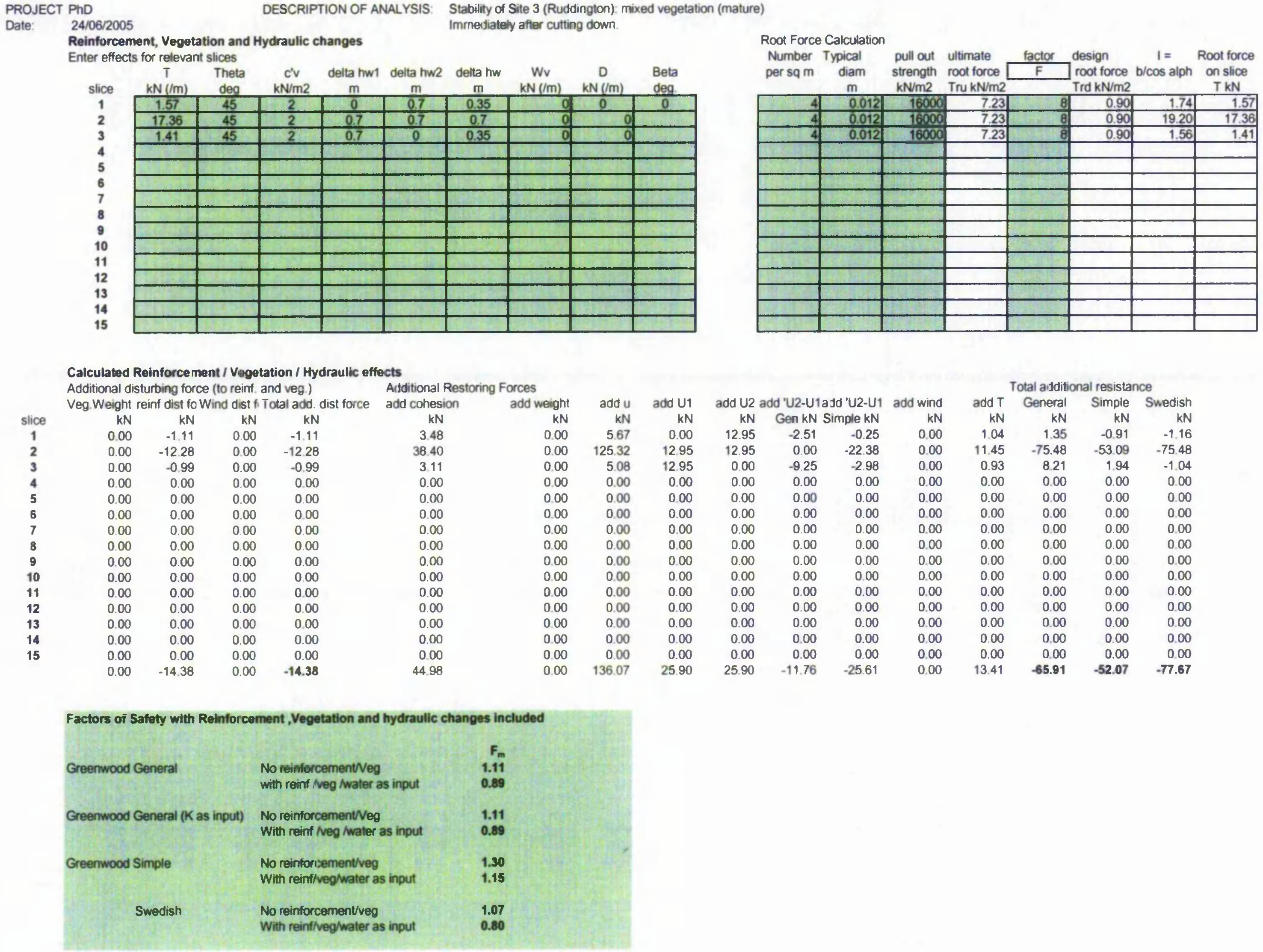
	Additional disturbing force (to reinf. and veg.)				Additional Restoring Forces			
slice	Veg Weight kN	reinf dist fo kN	Wind dist f kN	Total add. dist force kN	add cohesion kN	add weight kN	add u kN	add U1 kN
1	-20.79	-1.11	0.00	-21.90	3.48	91.21	5.67	0.00
2	42.26	-12.28	0.00	29.99	38.40	84.51	125.32	12.95
3	76.60	-0.99	0.00	75.61	3.11	59.94	5.08	12.95
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	98.08	-14.38	0.00	**83.69**	44.98	235.67	136.07	25.90

						Total additional resistance		
slice	add U2 kN	add 'U2-U1 Gen kN	add 'U2-U1 Simple kN	add wind kN	add T kN	General kN	Simple kN	Swedish kN
1	12.95	-2.51	-0.25	0.00	1.04	92.56	90.30	90.05
2	12.95	0.00	-22.38	0.00	11.45	9.04	31.42	9.04
3	0.00	-9.25	-2.98	0.00	0.93	68.15	61.88	58.90
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	25.90	-11.76	-25.61	0.00	13.41	**169.76**	**183.60**	**157.99**

Factors of Safety with Reinforcement ,Vegetation and hydraulic changes included

		F_m
Greenwood General	No reinforcement/Veg	**1.11**
	with reinf /veg /water as input	**1.35**
Greenwood General (K as input)	No reinforcement/Veg	**1.11**
	With reinf /veg /water as input	**1.35**
Greenwood Simple	No reinforcement/veg	**1.30**
	With reinf/veg/water as input	**1.53**
Swedish	No reinforcement/veg	**1.07**
	With reinf/veg/water as input	**1.28**

Figure C2. Spreadsheet showing vegetation input parameters for Site 3 immediately after the vegetation is removed.
Sheet 2



PROJECT PhD
Date: 24/06/2005

DESCRIPTION OF ANALYSIS: Stability of Site 3 (Ruddington): mixed vegetation (mature)
Immediately after cutting down.

Reinforcement, Vegetation and Hydraulic changes

Enter effects for relevant slices

slice	T kN (/m)	Theta deg	c'v kN/m2	delta hw1 m	delta hw2 m	delta hw m	Wv kN (/m)	D kN (/m)	Beta deg.
1	1.57	45	2	0	0.7	0.35	0	0	0
2	17.36	45	2	0.7	0.7	0.7	0	0	
3	1.41	45	2	0.7	0	0.35	0	0	
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

Root Force Calculation

slice	Number per sq m	Typical diam m	pull out strength kN/m2	ultimate root force Tru kN/m2	factor F	design root force Trd kN/m2	l = b/cos alph	Root force on slice T kN
1	4	0.012	16000	7.23	8	0.90	1.74	1.57
2	4	0.012	16000	7.23	8	0.90	19.20	17.36
3	4	0.012	16000	7.23	8	0.90	1.56	1.41
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								

Calculated Reinforcement / Vegetation / Hydraulic effects

	Additional disturbing force (to reinf. and veg.)				Additional Restoring Forces									Total additional resistance		
	Veg.Weight	reinf dist fo	Wind dist f	Total add. dist force	add cohesion	add weight	add u	add U1	add U2	add 'U2-U1	add 'U2-U1	add wind	add T	General	Simple	Swedish
slice	kN	kN	kN	kN	kN	kN	kN	kN	kN	Gen kN	Simple kN	kN	kN	kN	kN	kN
1	0.00	-1.11	0.00	-1.11	3.48	0.00	5.67	0.00	12.95	-2.51	-0.25	0.00	1.04	1.35	-0.91	-1.16
2	0.00	-12.28	0.00	-12.28	38.40	0.00	125.32	12.95	12.95	0.00	-22.38	0.00	11.45	-75.48	-53.09	-75.48
3	0.00	-0.99	0.00	-0.99	3.11	0.00	5.08	12.95	0.00	-9.25	-2.98	0.00	0.93	8.21	1.94	-1.04
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	-14.38	0.00	**-14.38**	44.98	0.00	136.07	25.90	25.90	-11.76	-25.61	0.00	13.41	**-65.91**	**-52.07**	**-77.67**

Factors of Safety with Reinforcement ,Vegetation and hydraulic changes included

		F_m
Greenwood General	No reinforcement/Veg	**1.11**
	with reinf /veg /water as input	**0.89**
Greenwood General (K as input)	No reinforcement/Veg	**1.11**
	With reinf /veg /water as input	**0.89**
Greenwood Simple	No reinforcement/veg	**1.30**
	With reinf/veg/water as input	**1.15**
Swedish	No reinforcement/veg	**1.07**
	With reinf/veg/water as input	**0.80**

Figure C3. Spreadsheet showing vegetation input parameters for Site 3 one month after the vegetation is removed.

Sheet 2

PROJECT PhD
Date: 24/06/2005

DESCRIPTION OF ANALYSIS: Stability of Site 3 (Ruddington): mixed vegetation (mature)
One month decay

Reinforcement, Vegetation and Hydraulic changes

Enter effects for relevant slices

slice	T kN (/m)	Theta deg	c'v kN/m2	delta hw1 m	delta hw2 m	delta hw m	Wv kN (/m)	D kN (/m)	Beta deg.
1	1.38	45	2	0	0.3	0.15	0	0	0
2	15.19	45	2	0.3	0.3	0.3	0	0	
3	1.23	45	2	0.3	0	0.15	0	0	
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

Root Force Calculation

Number per sq m	Typical diam m	pull out strength kN/m2	ultimate root force Tru kN/m2	factor F	design root force Trd kN/m2	l = b/cos alph	Root force on slice T kN
4	0.012	14000	6.33	8	0.79	1.74	1.38
4	0.012	14000	6.33	8	0.79	19.20	15.19
4	0.012	14000	6.33	8	0.79	1.56	1.23

Calculated Reinforcement / Vegetation / Hydraulic effects

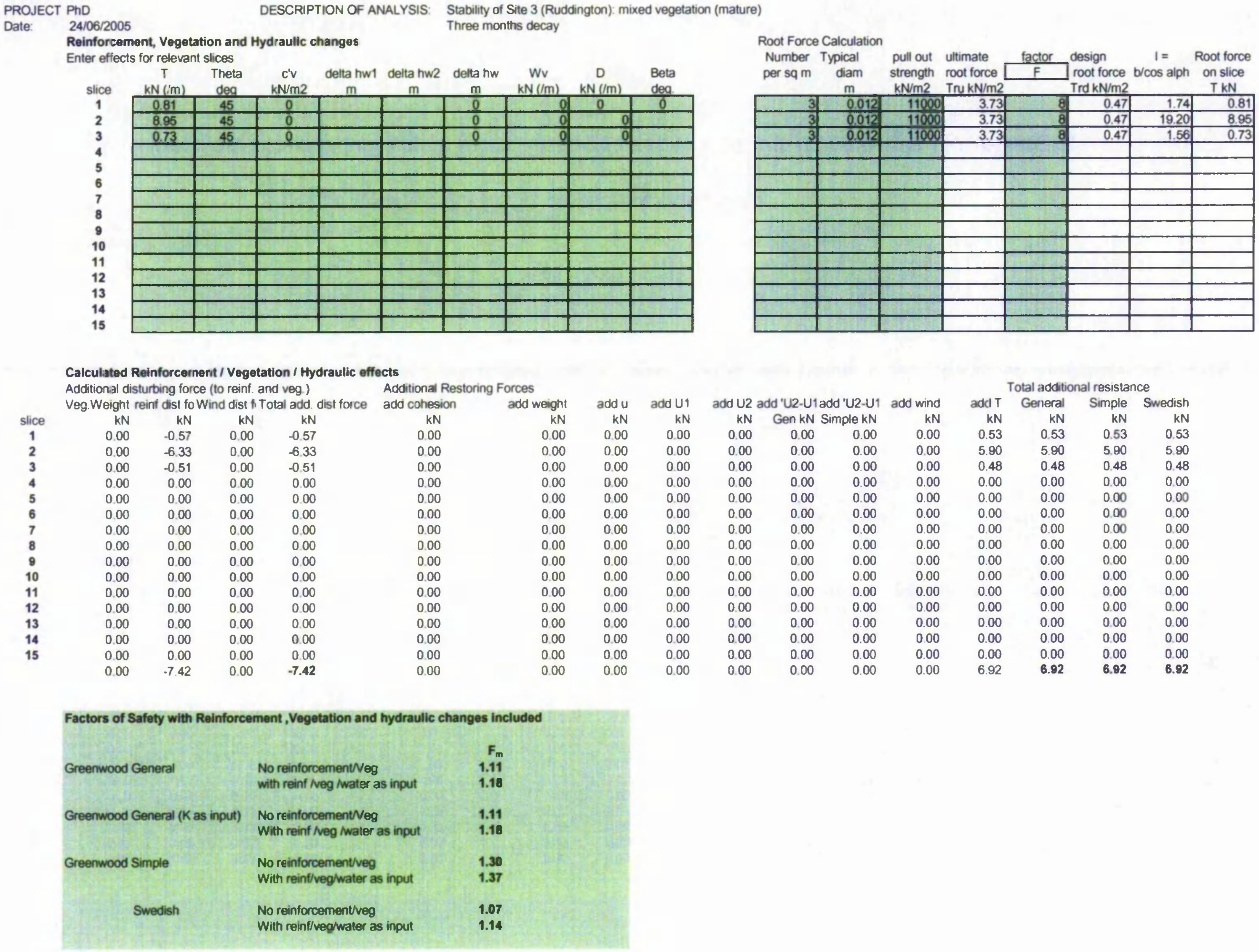
	Additional disturbing force (to reinf. and veg.)				Additional Restoring Forces									Total additional resistance		
	Veg.Weight	reinf dist fo	Wind dist f	Total add. dist force	add cohesion	add weight	add u	add U1	add U2	add 'U2-U1	add 'U2-U1	add wind	add T	General	Simple	Swedish
slice	kN	kN	kN	kN	kN	kN	kN	kN	kN	Gen kN	Simple kN	kN	kN	kN	kN	kN
1	0.00	-0.97	0.00	-0.97	3.48	0.00	2.43	0.00	4.95	-0.96	-0.11	0.00	0.91	2.91	2.06	1.95
2	0.00	-10.74	0.00	-10.74	38.40	0.00	53.71	4.95	4.95	0.00	-9.59	0.00	10.02	-5.29	4.30	-5.29
3	0.00	-0.87	0.00	-0.87	3.11	0.00	2.18	4.95	0.00	-3.54	-1.28	0.00	0.81	5.26	3.02	1.75
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	-12.58	0.00	**-12.58**	44.98	0.00	58.32	9.90	9.90	-4.50	-10.97	0.00	11.74	**2.90**	**9.38**	**-1.60**

Factors of Safety with Reinforcement ,Vegetation and hydraulic changes included

		F_m
Greenwood General	No reinforcement/Veg	**1.11**
	with reinf /veg /water as input	**1.19**
Greenwood General (K as input)	No reinforcement/Veg	**1.11**
	With reinf /veg /water as input	**1.19**
Greenwood Simple	No reinforcement/veg	**1.30**
	With reinf/veg/water as input	**1.41**
Swedish	No reinforcement/veg	**1.07**
	With reinf/veg/water as input	**1.12**

Figure C4. Spreadsheet showing vegetation input parameters for Site 3 three months after the vegetation was removed.

Sheet 2



PROJECT PhD DESCRIPTION OF ANALYSIS: Stability of Site 3 (Ruddington): mixed vegetation (mature)
Date: 24/06/2005 Three months decay

Reinforcement, Vegetation and Hydraulic changes

Enter effects for relevant slices

slice	T kN (/m)	Theta deg	c'v kN/m2	delta hw1 m	delta hw2 m	delta hw m	Wv kN (/m)	D kN (/m)	Beta deg.
1	0.81	45	0			0	0	0	0
2	8.95	45	0			0	0	0	
3	0.73	45	0			0	0	0	
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

Root Force Calculation

Number per sq m	Typical diam m	pull out strength kN/m2	ultimate root force Tru kN/m2	factor F	design root force Trd kN/m2	l = b/cos alph	Root force on slice T kN
3	0.012	11000	3.73	8	0.47	1.74	0.81
3	0.012	11000	3.73	8	0.47	19.20	8.95
3	0.012	11000	3.73	8	0.47	1.56	0.73

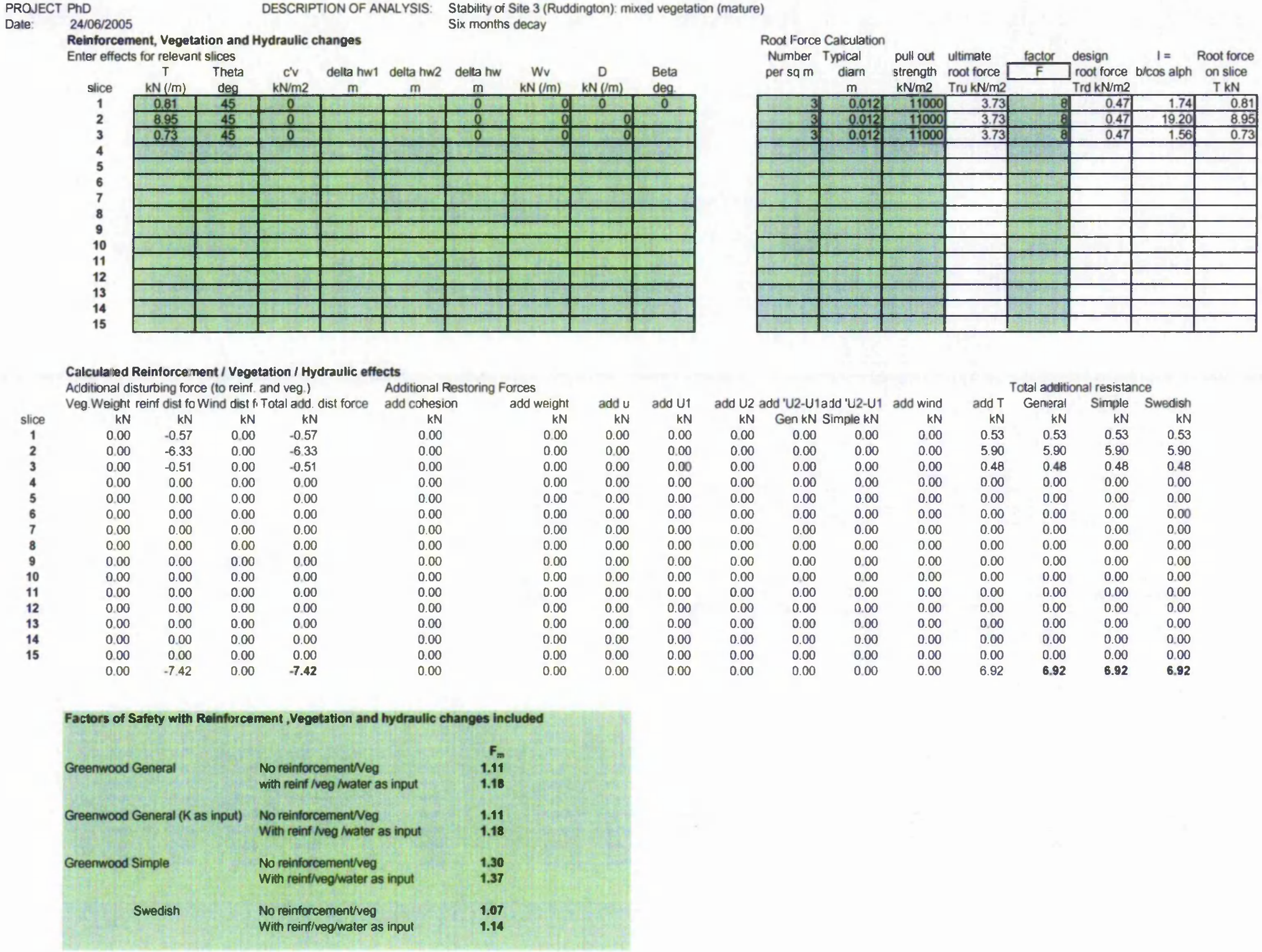
Calculated Reinforcement / Vegetation / Hydraulic effects

	Additional disturbing force (to reinf. and veg.)				Additional Restoring Forces									Total additional resistance		
slice	Veg.Weight kN	reinf dist fo kN	Wind dist f kN	Total add. dist force kN	add cohesion kN	add weight kN	add u kN	add U1 kN	add U2 kN	add 'U2-U1 Gen kN	add 'U2-U1 Simple kN	add wind kN	add T kN	General kN	Simple kN	Swedish kN
1	0.00	-0.57	0.00	-0.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.53	0.53	0.53
2	0.00	-6.33	0.00	-6.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.90	5.90	5.90	5.90
3	0.00	-0.51	0.00	-0.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.48	0.48	0.48	0.48
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	-7.42	0.00	**-7.42**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.92	**6.92**	**6.92**	**6.92**

Factors of Safety with Reinforcement ,Vegetation and hydraulic changes included

		F_m
Greenwood General	No reinforcement/Veg	**1.11**
	with reinf /veg /water as input	**1.18**
Greenwood General (K as input)	No reinforcement/Veg	**1.11**
	With reinf /veg /water as input	**1.18**
Greenwood Simple	No reinforcement/veg	**1.30**
	With reinf/veg/water as input	**1.37**
Swedish	No reinforcement/veg	**1.07**
	With reinf/veg/water as input	**1.14**

Figure C5. Spreadsheet showing vegetation input parameters for Site 3 six months after the vegetation was removed.
Sheet 2



PROJECT PhD DESCRIPTION OF ANALYSIS: Stability of Site 3 (Ruddington): mixed vegetation (mature)
Date: 24/06/2005 Six months decay

Reinforcement, Vegetation and Hydraulic changes
Enter effects for relevant slices

slice	T kN (/m)	Theta deg	c'v kN/m2	delta hw1 m	delta hw2 m	delta hw m	Wv kN (/m)	D kN (/m)	Beta deg
1	0.81	45	0			0	0	0	0
2	8.95	45	0			0	0	0	
3	0.73	45	0			0	0	0	
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

Root Force Calculation

Number per sq m	Typical diam m	pull out strength kN/m2	ultimate root force Tru kN/m2	factor F	design root force Trd kN/m2	l = b/cos alph	Root force on slice T kN
3	0.012	11000	3.73	8	0.47	1.74	0.81
3	0.012	11000	3.73	8	0.47	19.20	8.95
3	0.012	11000	3.73	8	0.47	1.56	0.73

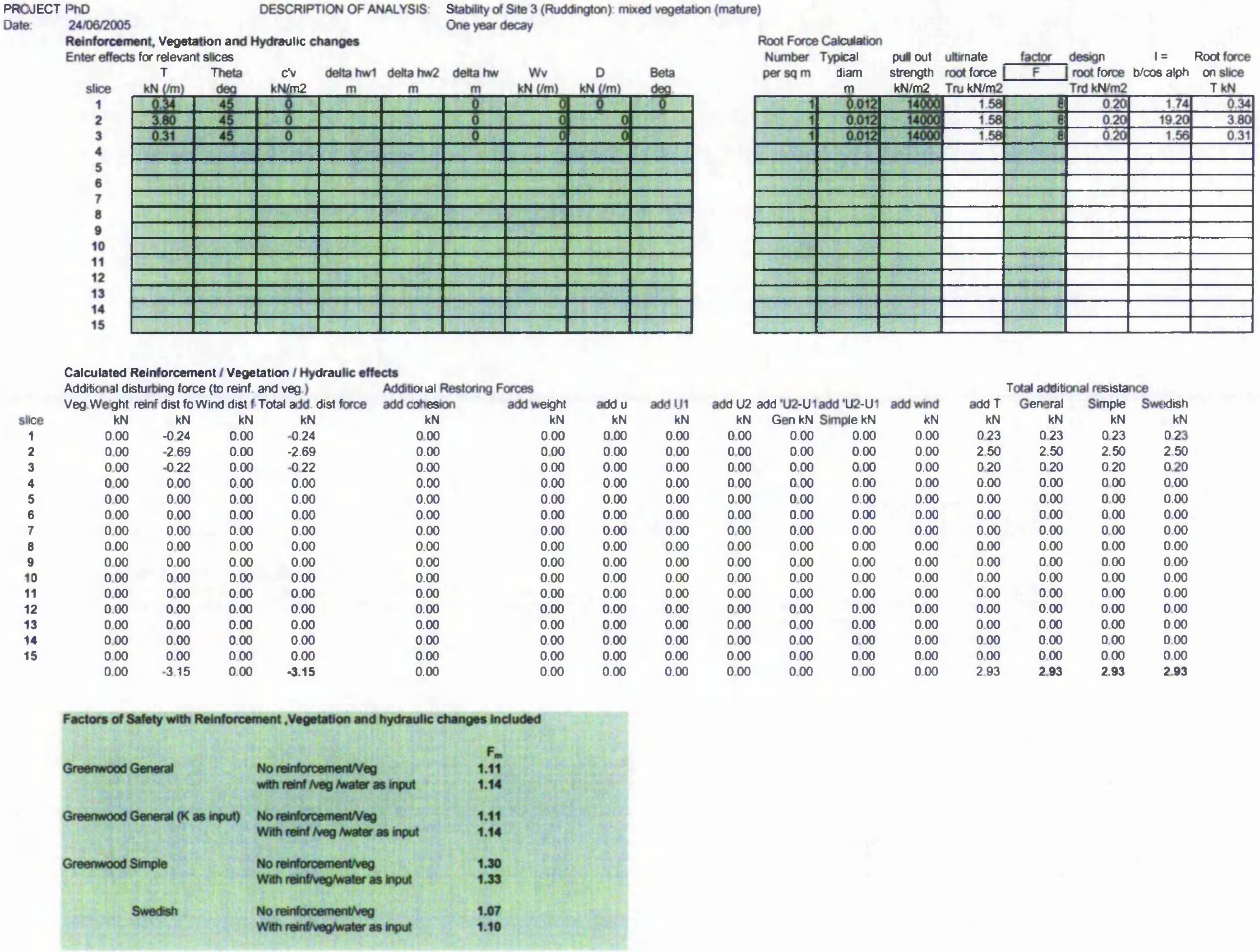
Calculated Reinforcement / Vegetation / Hydraulic effects

	Additional disturbing force (to reinf. and veg.)				Additional Restoring Forces									Total additional resistance			
	Veg.Weight	reinf dist fo	Wind dist f	Total add. dist force	add cohesion	add weight	add u	add U1	add U2	add 'U2-U1 Gen kN	add 'U2-U1 Simple kN	add wind	add T	General	Simple	Swedish
slice	kN	kN	kN	kN	kN	kN	kN	kN	kN			kN	kN	kN	kN	kN
1	0.00	-0.57	0.00	-0.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.53	0.53	0.53
2	0.00	-6.33	0.00	-6.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.90	5.90	5.90	5.90
3	0.00	-0.51	0.00	-0.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.48	0.48	0.48	0.48
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	-7.42	0.00	**-7.42**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.92	**6.92**	**6.92**	**6.92**

Factors of Safety with Reinforcement ,Vegetation and hydraulic changes included

		F_m
Greenwood General	No reinforcement/Veg	**1.11**
	with reinf /veg /water as input	**1.18**
Greenwood General (K as input)	No reinforcement/Veg	**1.11**
	With reinf /veg /water as input	**1.18**
Greenwood Simple	No reinforcement/veg	**1.30**
	With reinf/veg/water as input	**1.37**
Swedish	No reinforcement/veg	**1.07**
	With reinf/veg/water as input	**1.14**

Figure C6. Spreadsheet showing vegetation input parameters for Site 3 one year after the vegetation was removed.
Sheet 2



PROJECT PhD
Date: 24/06/2005

DESCRIPTION OF ANALYSIS: Stability of Site 3 (Ruddington): mixed vegetation (mature)
One year decay

Reinforcement, Vegetation and Hydraulic changes
Enter effects for relevant slices

Root Force Calculation

slice	T kN (/m)	Theta deg	c'v kN/m2	delta hw1 m	delta hw2 m	delta hw m	Wv kN (/m)	D kN (/m)	Beta deg.	Number per sq m	Typical diam m	pull out strength kN/m2	ultimate root force Tru kN/m2	factor F	design root force Trd kN/m2	I = b/cos alph	Root force on slice T kN
1	0.34	45	0			0	0	0	0	1	0.012	14000	1.58	8	0.20	1.74	0.34
2	3.80	45	0			0	0	0		1	0.012	14000	1.58	8	0.20	19.20	3.80
3	0.31	45	0			0	0	0		1	0.012	14000	1.58	8	0.20	1.56	0.31
4																	
5																	
6																	
7																	
8																	
9																	
10																	
11																	
12																	
13																	
14																	
15																	

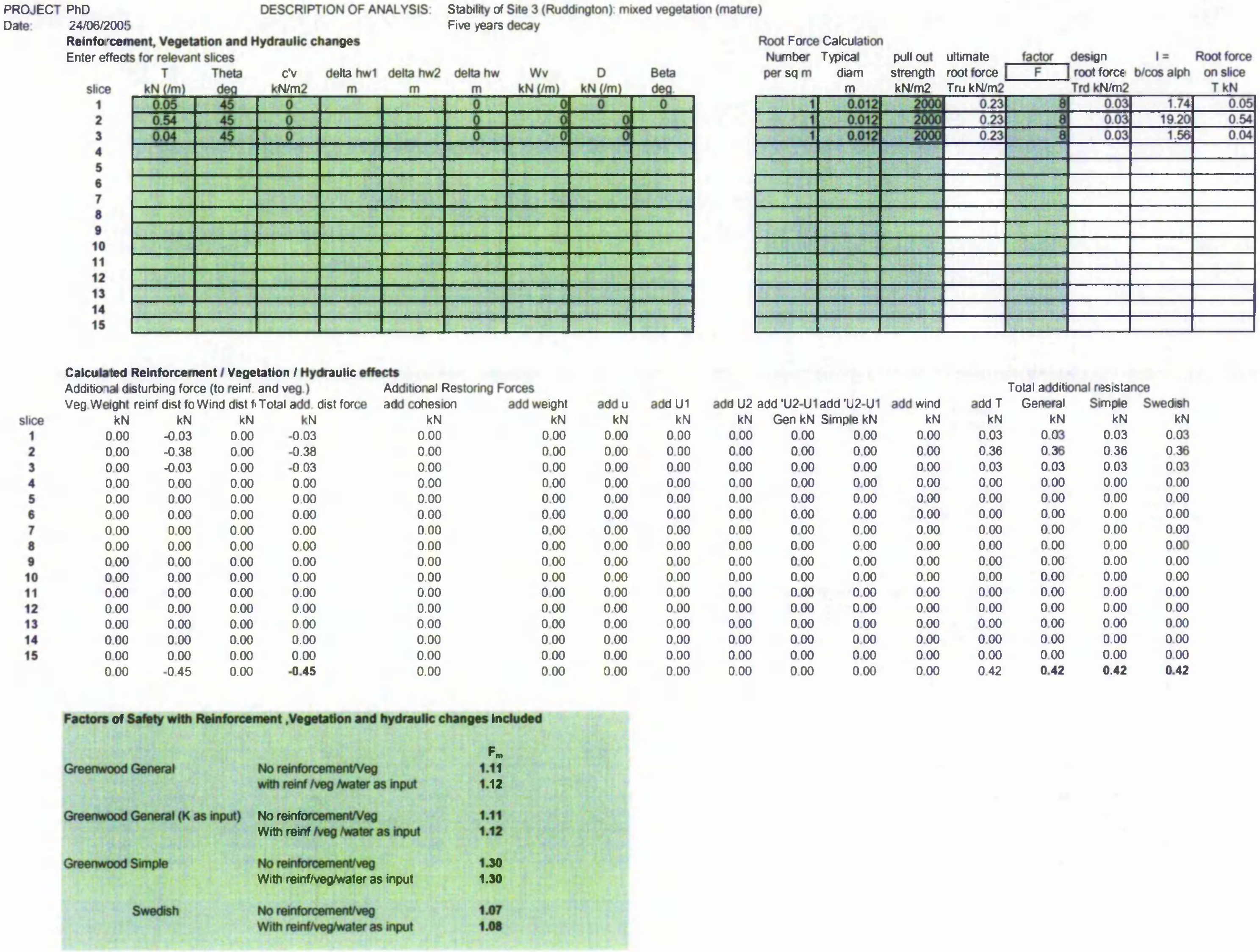
Calculated Reinforcement / Vegetation / Hydraulic effects

	Additional disturbing force (to reinf. and veg.)				Additional Restoring Forces									Total additional resistance			
slice	Veg.Weight kN	reinf dist fo kN	Wind dist f kN	Total add. dist force kN	add cohesion kN	add weight kN	add u kN	add U1 kN	add U2 kN	add 'U2-U1 Gen kN	add 'U2-U1 Simple kN	add wind kN	add T kN	General kN	Simple kN	Swedish kN
1	0.00	-0.24	0.00	-0.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23	0.23	0.23	0.23
2	0.00	-2.69	0.00	-2.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.50	2.50	2.50	2.50
3	0.00	-0.22	0.00	-0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.20	0.20	0.20
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	-3.15	0.00	**-3.15**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.93	**2.93**	**2.93**	**2.93**

Factors of Safety with Reinforcement ,Vegetation and hydraulic changes included

		F_m
Greenwood General	No reinforcement/Veg	**1.11**
	with reinf /veg /water as input	**1.14**
Greenwood General (K as input)	No reinforcement/Veg	**1.11**
	With reinf /veg /water as input	**1.14**
Greenwood Simple	No reinforcement/veg	**1.30**
	With reinf/veg/water as input	**1.33**
Swedish	No reinforcement/veg	**1.07**
	With reinf/veg/water as input	**1.10**

Figure C7. Spreadsheet showing vegetation input parameters for Site 3 five years after the vegetation was removed.



Sheet 2

PROJECT PhD
Date: 24/06/2005

DESCRIPTION OF ANALYSIS: Stability of Site 3 (Ruddington): mixed vegetation (mature)
Five years decay

Reinforcement, Vegetation and Hydraulic changes

Enter effects for relevant slices

slice	T kN (/m)	Theta deg	c'v kN/m2	delta hw1 m	delta hw2 m	delta hw m	Wv kN (/m)	D kN (/m)	Beta deg.
1	0.05	45	0			0	0	0	0
2	0.54	45	0			0	0	0	
3	0.04	45	0			0	0	0	
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

Root Force Calculation

Number per sq m	Typical diam m	pull out strength kN/m2	ultimate root force Tru kN/m2	factor F	design root force Trd kN/m2	l = b/cos alph	Root force on slice T kN
1	0.012	2000	0.23	8	0.03	1.74	0.05
1	0.012	2000	0.23	8	0.03	19.20	0.54
1	0.012	2000	0.23	8	0.03	1.56	0.04

Calculated Reinforcement / Vegetation / Hydraulic effects

	Additional disturbing force (to reinf. and veg.)				Additional Restoring Forces									Total additional resistance		
slice	Veg.Weight kN	reinf dist fo kN	Wind dist f kN	Total add. dist force kN	add cohesion kN	add weight kN	add u kN	add U1 kN	add U2 kN	add 'U2-U1 Gen kN	add 'U2-U1 Simple kN	add wind kN	add T kN	General kN	Simple kN	Swedish kN
1	0.00	-0.03	0.00	-0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.03	0.03
2	0.00	-0.38	0.00	-0.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.36	0.36	0.36	0.36
3	0.00	-0.03	0.00	-0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.03	0.03
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	-0.45	0.00	**-0.45**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.42	**0.42**	**0.42**	**0.42**

Factors of Safety with Reinforcement ,Vegetation and hydraulic changes included

		F_m
Greenwood General	No reinforcement/Veg	**1.11**
	with reinf /veg /water as input	**1.12**
Greenwood General (K as input)	No reinforcement/Veg	**1.11**
	With reinf /veg /water as input	**1.12**
Greenwood Simple	No reinforcement/veg	**1.30**
	With reinf/veg/water as input	**1.30**
Swedish	No reinforcement/veg	**1.07**
	With reinf/veg/water as input	**1.08**

Appendix 4: Published papers

Appendix 4 includes all published papers that have developed from aspects of this thesis. The first paper listed is included as the thesis built on this early work.

Norris, J. E. and Greenwood, J. R. 2000. Review of in situ shear tests on root reinforced soil. *In*: Stokes, A. (ed.). *The supporting roots of trees and woody plants: form, function and physiology*. Developments in Plant and Soil Sciences, Kluwer Academic Publishers. IUFRO International Conference The Supporting Roots, Structure and Function, Bordeaux, July 1998, 287-294.

Norris, J. E. and Greenwood, J. R. 2003a. Root reinforcement on unstable slopes in Northern Greece and Central Italy. International Conference on Problematic Soils, July 2003, Nottingham Trent University, Nottingham, UK, 411-418.

Norris, J. E. and Greenwood, J. R. 2003b. In-situ shear box and root pull-out apparatus for measuring the reinforcing effects of vegetation. *In*: Myrvoll, F. (ed.). *Field Measurements in Geomechanics*, Swets & Zeitlinger, Lisse, 593-597.

Greenwood, J. R., **Norris, J. E.**, Wint, J. and Barker, D. H. 2003. Bioengineering and the transportation infrastructure. *Transportation geotechnics*. Thomas Telford, London, 205-220.

Greenwood, J. R., **Norris, J. E.** and Wint, J. 2004. Assessing the contribution of vegetation to slope stability. *Journal of Geotechnical Engineering*, **157**, 199-208.

Norris, J. E. 2005. Root anchorage by Oak (*Quercus* sp.) and Hawthorn (*Crataegus monogyna*) trees on a London Clay motorway cutting in England. *Plant and Soil*, **278**, 43-53. [DOI: 10.1007/s11104-005-1301-0].

Greenwood, J. R., **Norris, J. E.** and Wint, J. 2006. Site investigation techniques to assess the effects of vegetation on slope stability. *Journal of Geotechnical and Geological Engineering*, in press.

A. Stokes (ed.), The Supporting Roots of Trees and Woody Plants: Form, Function and Physiology, 287–293.

Review of in situ shear tests on root reinforced soil

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Key words: in situ shear strength, root reinforced soil, shear box

Abstract

Bioengineering and the quantification of the effects of vegetation in civil engineering are still relatively new concepts in the United Kingdom. This paper reviews the development and use of in situ shear box techniques to measure the shear strength of root reinforced soil. Details of variation in design and the test procedures adapted by researchers are described and problems outlined. The review has led to the development of a 150 × 150 × 100 mm in situ shear box at Nottingham Trent University for testing root reinforced Gault Clay on a bioengineering demonstration site on the M20 motorway at Maidstone, UK.

Introduction

Bioengineering in the United Kingdom is a relatively new concept. Vegetation has been used in the past as a means of reducing the visual impact of civil engineering works and enhancing the quality of the landscape. It has been recognised that vegetation has contributed to slope stability but to an unquantifiable degree.

Recent work in Europe (Coppin and Richards, 1990; Mulder, 1991; Tobias, 1995), New Zealand (Phillips and Watson, 1994), Japan (Endo, 1980) and North America (Ziemer, 1981) has provided information on the engineering benefits of vegetation which must now be further developed and applied.

In this paper, previous work on in situ shear testing of root reinforced soil is reviewed to assist in the development of suitable apparatus for use on a Gault Clay bioengineering demonstration slope in the United Kingdom (Greenwood et al., 1996).

Review of in situ shear testing methods

The principle of in situ shear testing is described in BS5930. The sample of ground is subjected to direct shear using a stress system similar to the laboratory shear box (BS1377). However, this system has mainly been developed for testing in situ rock but not root-reinforced soil. A number of researchers have therefore devised and developed in situ shear testing apparatus for this purpose.

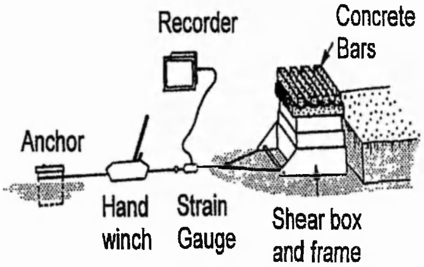

Figure 1. Schematic illustration of the in situ shear apparatus used by Endo and Tsuruta (1969) and Endo (1980) (modified from Endo 1980).

The first reference to testing of root reinforced soil was Endo and Tsuruta in 1969 who designed apparatus to measure the contribution of small *Alnus glutinosa* roots to the strength of homogeneous nursery soil in Japan. O'Loughlin (1972) later used a slightly modified design for the study of old-growth forests of coastal British Columbia, Canada. Endo reused his shear apparatus in 1980 to measure the strength of *Betula japonica* Sieb. and *Alnus japonica* Steud. tree roots.

The design of Endo and Tsuruta (1969) shearing apparatus (Figure 1) comprises a 500 mm wide × 500 mm long × 300–600 mm adjustable height shearing case made from 3-mm thick iron plates, in which the soil block is fully enclosed on all four sides; an outer frame to hold the shearing case and to act as a carrier; a wooden load stand; concrete bars for additional load; a hand winch of 2.5 tons capacity and a set of strain gauges and recorder attached by 10-mm wire ropes. The apparatus measures the in situ shear strength by pulling the shear case and surcharge load by continually levering the hand winch. The pulling force generated is monitored continuously using the strain gauge and recorder.

In 1981, Ziemer developed a shear box to measure the strength of mature *Pinus contorta* on coastal sands in California. Ziemer's shear box apparatus differed markedly from Endo and Tsuruta's original design in that instead of enclosing the soil block on four sides, two of the sides of the box remained open to allow for the continuous nature of horizontal roots through the soil block and into the surrounding soil. A base plate was also used. In this instance, shearing is along two vertical parallel planes and not along the base of the shear box and the shear box is pushed as opposed to being pulled as in Endo and Tsuruta's shear apparatus. Ziemer's apparatus consists of an open sided shear box made of steel plates bolted together on the top, bottom, front and back of the soil block. A mechanical jack extends at a rate of 12.7 mm/min for approximately 7 min and a proving ring mounted between the mechanical jack and the shear box is used to measure the shearing force.

Wu et al. (1988) successfully used Ziemers design for their study of soil–root systems in tree species Western hemlock, Alaska cedar and Silver maple at four test sites in Oregon, Alaska (× 2) and Ohio. The particular tree species used in this study were found to have many horizontally aligned roots so Ziemers design and test method proved fruitful although Wu et al. modified the dimensions of the shear box to suit their particular needs.

O'Loughlin (1981) adapted Ziemers design to test Beech forest in New Zealand. The shear box remained open on two sides but the base plate was removed so that the base of the soil block was kept in continuity with the surrounding soil (Figure 2). O'Loughlin reduced the dimensions of the shear box to 300 mm wide × 300 mm long × 150 mm high. The shear box is powered by a horizontally mounted CBR (California Bearing Ratio) test jack, which is turned at a constant rate of 1 rps. The jacking mechanism forces the soil block forward at 13 mm/min. Shear stresses are recorded using a dial gauge and proving ring.

In 1986, Abe and Iwamoto designed a large scale apparatus to test *Cryptomeria japonica* D. DON (sugi) a widely planted tree in Japan. This large scale shear apparatus shows a combination of design features from Endo and Tsuruta and Ziemer's apparatuses. Abe and Iwamoto's shear apparatus was of a much larger scale to any of the other previous in situ shear boxes, being 1 m wide × 1 m long × 0.3–1 m adjustable height. The apparatus comprises the following parts (Figure 3): (1) shear box made of steel plates 3 mm thick capable of holding the soil block together during the test; (2) oil jack and pump used to produce the shear load with a maximum capacity of 20 tons and 500-mm long stroke; (3) a 5-ton capacity load cell to measure the shearing load; (4) displacement meters to 0.02 mm accuracy; (5) digital strain recorder; (6) a steel bar for additional load (50 kg in weight, 1 m in length).

The apparatus works by pushing the shear box forward. The shear method is incrementally stress controlled by increasing the shear load by 100 kgf every 20 min.

Reported advantages of this system are: (i) whole live tree root systems could be sheared (shearing area 1 m^2); (ii) the displacement can be observed from the side of the block; (iii) both the acting forms of the roots in the soil and soil block movement can be observed by exposure after the test and the results can be expressed by the Coulomb equation (Abe and Iwamoto 1986).

Clark (1992) during research into the principles of bioengineering in East Nepal developed an in situ shear box to measure the root strength of Nepalese grasses. The design criteria required the shear box to be portable, for use on slopes steeper than 30° to the horizontal and to simulate shallow translational failures to a maximum depth of 300 mm. Initial design features included a large metal shear box, 500 mm wide × 750 mm long × 70 mm high, which was pulled by a hand winch to apply the strain. Sand bags were used as additional normal load. This design bears some resemblance to Endo and Tsuruta's original shear apparatus. This first design encountered problems during strain application. The back edge of the shear box created a passive failure with the shear plane, which penetrated the surface forcing the box to ride up and tilt. To overcome this Clark attempted to divide the shear box into a series of three smaller units (250 × 500 mm) using vertical grouser plates. These in turn had their problems and were subsequently abandoned due to the plates reducing the effectiveness

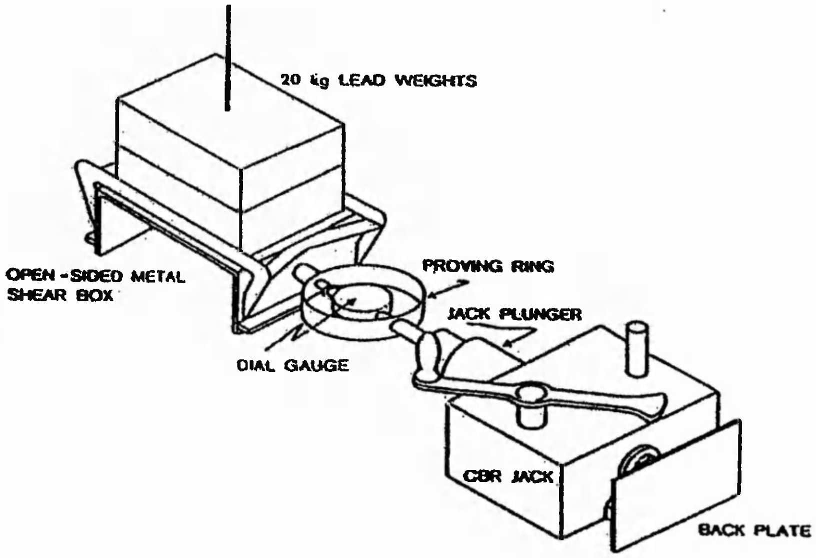

Figure 2. Field shear box testing equipment of O'Loughlin (1981).

of root reinforcement in the soil block as they cut the root mass/ball.

A revised design of a four-sided steel frame 250 mm wide × 250 mm long × 100 mm high pushed by a mechanical jack was finally used. The shear box was displaced at a rate of 1 mm/s. This design works in much the same way as Abe and Iwamoto's large scale direct shear apparatus although on a much smaller scale. This shear box was not without its limitations as the maximum displacement of the apparatus was 35 mm and an estimated 100 mm displacement was required to pull or break the roots and the front edge of the shear box lifted off the ground during jacking. Clark also felt that having digital recorders to measure and record displacement, shear force and time would have greatly improved the operators ability to observe the movements within the shear box.

Tobias (1995) also used the same principle method as Endo and Tsuruta to measure the shear strength of grassland (Table 1) in Switzerland. The shear box had dimensions of 500 mm wide × 500 mm long × 150 mm high. These dimensions reduced marginal effects such as roots being cut by the pushing of the metallic shear frame and also kept the whole apparatus reasonably manageable.

Yatabe et al. (1996) briefly discusses in situ direct shear tests on weathered granite soil with roots of Chinese cedar, fir shrub, bamboo and grass. Their apparatus reflects the BS 5930 in situ shear apparatus as it uses jacking systems for both normal and shear stress.

The main features of each of the referenced in situ shear box tests on root reinforced soil are summarised in Table 1.

Discussion

As described above only a few researchers have reported attempts to use an in situ shear box to determine the contribution of roots to soil strength. This may be due to the lack of standard commercially available in situ shear testing apparatus and the difficulties in preparing the soil block and setting up of the apparatus prior to testing.

The problems in the design of an in situ shear box may have been partly alleviated in more recent work through researchers highlighting the problems of their apparatus for example Clark (1992) encountered problems with tilting of the shear box during shearing, limited displacement of the shear box and difficulties in observing the test. Tobias (1995) stated that "it is indispensable to watch carefully what is happening during the test . . . ".

The two distinct shear box designs of Endo and Tsuruta (1969) and Ziemer (1981) measure the shear resistance of root reinforced soil in quite different ways. Ziemer in his open sided shear box provided for horizontally aligned roots normal to the shear plane,

Table 1. Review of in situ shear box testing relating to root reinforced soil

Author	Location	Vegetation type tested	Shear box dimensions ($w \times l \times h$	Comments
Endo and Tsuruta (1969)	Japan	*Alnus glutinosa*	500 × 500 × 300–600 mm (adjustable height) (Figure 1)	Roots 1–2 mm diameter pulled from the soil block during shearing.
O'Loughlin (1972) in Ziemer (1981)	British Columbia, Canada	*Pseudotsuga menziesii* *Thuja plicata* *Tsuga heterophylla*	Modified design of Endo and Tsuruta (1969)	Roots 5 mm in diameter pulled out of the soil block instead of shearing along the shear plane.
Endo (1980)	Japan	*Betula japonica* Sieb. *Alnus japonica* Steud.	500 × 500 × 300–600 mm (Figure 1)	A simple design but made possibly impractical by the addition of two kinds of concrete sticks to provide additional load. Vertically aligned roots may pull out or break.
Ziemer (1981)	California	*Pinus contorta*	Open sided shear box 600 × 300 × 300 mm. Open side is 300 mm^2.	Designed so that the shear box shears along two parallel vertical planes. Shear rate 1.27 cm/min. Roots lying horizontally and aligned normal to the shear planes are undisturbed by the shear box and continue into the soil either side of the box.
O'Loughlin (1981), O'Loughlin et al. (1982)	Maimai experimental catchment, New Zealand	Beach forest	Open sided and base shear box 300 × 300 × 150 mm (Figure 2)	Similar design to Ziemer (1981) although on a reduced scale. Shear rate 1.3 cm/min. During shearing, shear surfaces develop at the sides and base of the soil block; roots either stretch and break or pull out at these surfaces. Reviewed by Phillips and Watson (1994).
Abe and Iwamoto (1986)	Chiyda Experimental Branch Station nursery, Forestry and Forest Products Research Institute, Ibaraki Prefecture.	*Cryptomeria japonica* D. DON (sugi)	Large-scale direct shear box 1 × 1 × 0.3–1 m (adjustable height) (Figure 3)	Shear loading rate 100 kgf per 20 min. A large tree root present in the soil can easily be sheared by the oil jack with a uniform pressure.

Table 1. Continued

Author	Location	Vegetation type tested	Shear box dimensions ($w \times l \times h$	Comments
Wu et al. (1988)	Siuslaw National Forest Mapleton, Oregon	Western hemlock	Undrained or quick direct shear tests	Apparatus designed by Ziemer (1981). The dimensions of this box represent a compromise
	Tongass National Forest Alvin Bay, Alaska	Western hemlock Alaska cedar	300 × 600 × 300 mm	since increasing the length of the box would increase the number of roots that would be cut off
	Tongass National Forest Peterson Cr., Alaska	Western hemlock		and reducing the length would reduce the resistance developed by the root inside the box.
Clark (1992)	Ohio State University Columbus, Ohio	Silver maple		
	Ghopa Camp, Nepal	*Pennisetum Purpeneum* (Napier grass)	250 × 250 × 100 mm	It was noted that the four sided shear box had tilting problems during shearing.
	Karkichap, Nepal	*Seteria anceps* (local Nepalese fodder grass)		
	Ambote, Nepal	*Themeda* sp., *Neyraudia* sp., *Cymbopogan Microtheca*		
	Dhankuta, Nepal	*Cymbopogan Microtheca*, Imperata.		
Tobias (1995)	Zurich, Switzerland	Grasses (*Alopecurus geniculatus, Poa pratensis Agrostis stolonifera, Festuca rubra, Lolium multiflorum, Festuca pratensis*	500 × 500 × 150 mm	Marginal effects of roots cut by pushing in the metallic frame are minimised with these dimensions. Tests interpreted as unconsolidated and undrained.
Yatabe et al. (1996)	Japan	Chinese cedar, fir, shrub, bamboo, grass	Direct shear apparatus 300 × 300 × 120 mm	Normal stress applied by air cylinder, shear stress applied with a hydraulic jack.

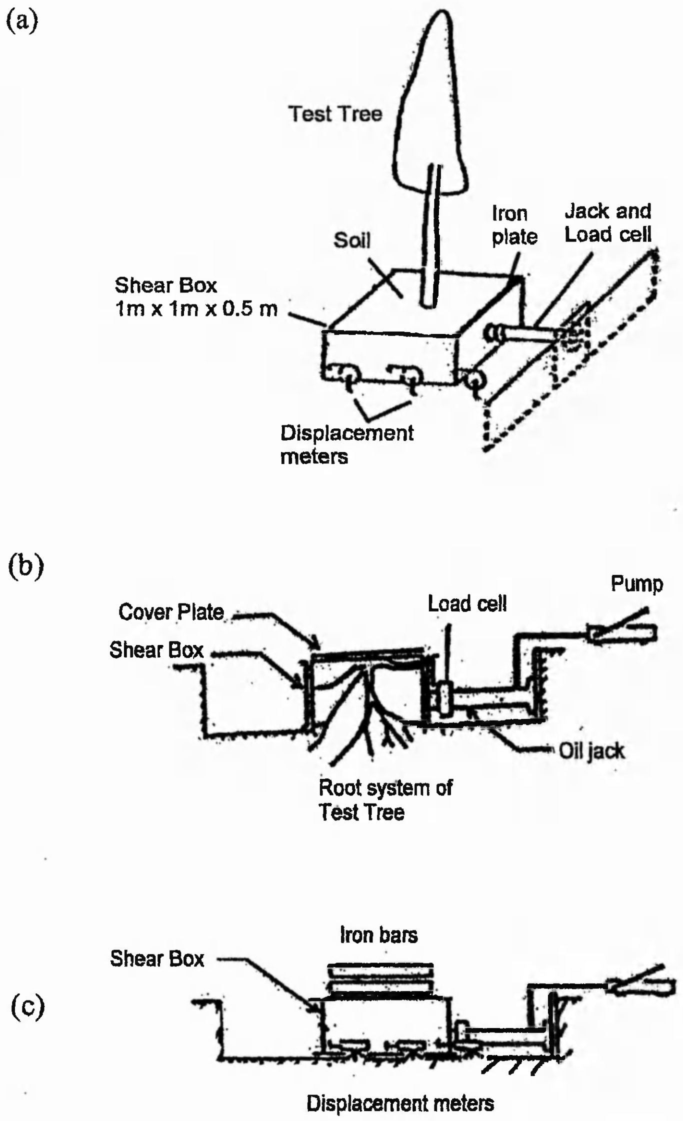

Figure 3. Large-scale direct-shear apparatus (modified from Abe and Iwamoto 1986).

which protrude undisturbed through the soil block and into the soil on either side of the shear box. Hence, these roots can only break when shearing takes place. However, Endo and Tsuruta's closed shear box roots can only extend undisturbed in the vertical direction, therefore these roots are able to break or pull out of the soil. When O'Loughlin (1981) removed the base plate of Ziemers shear apparatus roots could then be sheared in all directions (both horizontally and vertically) – although this probably creates more unknowns in the analysis.

As each author has used slightly different dimensions for the shear box and also used either a push or pull method of shearing the soil block this raises questions about repeatability between methods.

With more experimental work being carried out the results of these tests will gain credibility for application in geotechnical engineering and in the future, a database of root strength, should evolve for major plant species planted in particular soil types.

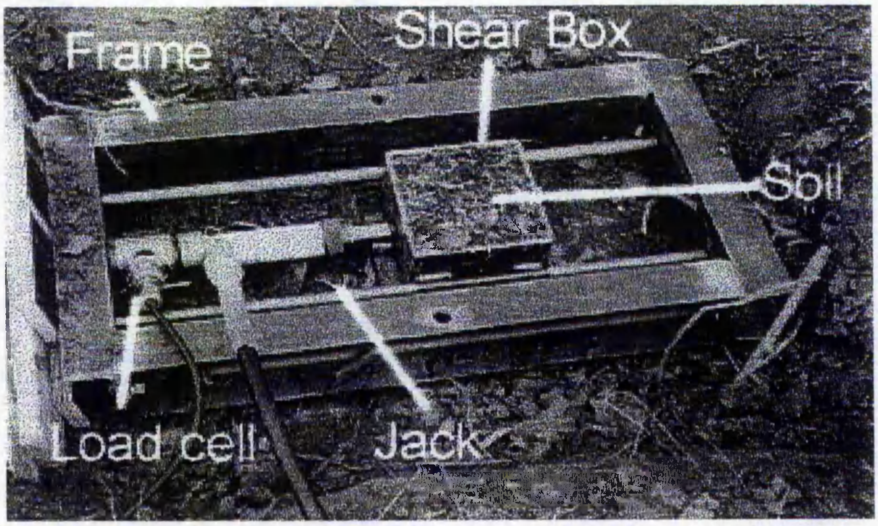

Figure 4. In situ shear box apparatus, developed by Nottingham Trent University, in operation on the bioengineering demonstration site, M20 motorway, Maidstone, UK.

Nottingham Trent University's in situ shear apparatus

This review of in situ shear boxes has assisted in the development of an in situ shear box at Nottingham Trent University. Whilst large shear boxes are desirable to overcome the local discontinuities effects with a soil/root system. It was recognised that the large shear boxes introduced more problems in terms of control and handling of equipment and the actual testing procedure. It was therefore concluded that a relatively small (150 × 150 mm) portable shear box apparatus is most appropriate, as it permits a greater number of tests. It is also hoped to include a means of anchoring larger roots within the shear box to obtain an indication of the pull out forces generated during shear.

A push jacking mechanism is favoured as opposed to the pulling mechanism of Endo and Tsuruta, for reasons outlined by Clark (1992). Clark also had tilting problems with the push method so to prevent tilting the shear box is designed inside a steel frame that sits on two runners. The steel frame also enables vertical roots protruding out of the ground to be clamped in position therefore simulating the trees resistance to shearing and also to measure the tensile force required to pull the root out of the ground.

The shear box is 150 mm wide × 150 mm long × 100 mm high made of steel plates. A hydraulic jack and pump provide the shearing force, which in turn is measured by a 10 kN load cell. Figure 4 shows the in situ shear box apparatus in operation on the bioengineering demonstration site on the M20 motorway Maidstone UK.

More information and results of the in situ shear testing and bioengineering trial are provided in Greenwood et al. (1999).

Acknowledgements

This work is funded by a Research Enhancement Fund grant from The Nottingham Trent University. CIRIA (the Construction Industry Research and Information Association) is thanked for providing a suitable field site and for supporting bioengineering research in the UK.

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ROOT REINFORCEMENT ON UNSTABLE SLOPES IN NORTHERN GREECE AND CENTRAL ITALY

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Abstract

The instability of natural and manmade soil slopes is a frequent problem throughout the world. One technique of stabilising soil slopes is by using naturally occurring vegetation. The potential of roots to stabilise soil slopes which suffer from soil erosion and from shallow landslides has been investigated at field sites in Northern Greece and Central Italy. In Northern Greece and other Mediterranean countries, soil erosion following forest fires and heavy winter-spring precipitation is a common problem. In Central Italy, the steep sided valleys of Tertiary age marls and flysch deposits frequently fail due to triggering by earthquakes or periods of heavy precipitation.

This paper presents two case studies, which review the stabilising potential of vegetation for two different scenarios, (1) preventing soil erosion and (2) preventing shallow landslides. In both case studies, a series of in-situ direct shear tests were carried out on root reinforced and root-free soil and a number of shrubs were tested for root pull-out resistance. Analysis of these tests shows that in both case studies roots provide additional reinforcement to the soil slope. The data obtained from these tests is included in slope stability analysis to show that vegetation can increase the factor of safety of soil slopes.

Keywords: in-situ shear strength, root reinforcement, slope stability analysis

1. Introduction

Previous work by the authors [1, 2] on in-situ shear box testing and root reinforcement has shown that roots contribute to the strength of soil and in turn enhance soil stability. In-situ shear and root pull-out testing was therefore applied to two sites which suffer from soil erosion and landslipping. This work formed part of a Fifth Framework European research project called "Ecoslopes".

2. Methodology

Six in-situ shear tests in Northern Greece and three in-situ shear tests in Central Italy were carried out on soil with and without vegetation. A small number of shrubs on each site were selected for root pull-out tests. These tests provide shear and pull-out resistance values for inclusion in slope stability analysis. The number of tests carried out on each site was restricted because of time, poor weather conditions and technical problems.

The in-situ shear box designed by Nottingham Trent University [1, 3] was further developed and modified for this project. The apparatus consists of a 150 mm square by 100 mm deep shear box, displacement meter, datalogger and hydraulic jacking system. The apparatus is described further in [4]. The root pull-out apparatus uses an original root clamp design [5] and the same pulling and measuring apparatus as the shear box.

3. Case Study 1: Soil Erosion In Northern Greece

3.1 Site Description

The site is located 100 km southeast of Thessaloniki, near the small town of Metamorfosi in the Halkidiki region of Greece (Lat. 40°15' N, Long. 23 °37' E). The site is in a natural forest, dominated by Pine trees (*Pinus halepensis*), with an understorey vegetation system of Oak (*Quercus coccifera*), *Phillyrea latifolia* and *Pistacia lentiscus*. The forest stand is approximately 50 years old, the wood volume is 95 m^3/ha and the annual wood growth is 5.8 m^3/ha [6]. The site climate is Mediterranean with a mean annual temperature of 15°C and an annual rainfall of 500 mm. The rainfall in this area is irregular, distributed mainly in spring and autumn, with peaks in March and November. The altitude range is 60-200 m, and the main aspects of the slopes are East and West. The slope gradient varies from 1:10 at the top of the hillslopes to over 1:2 at the lower parts in both the main aspects. The soil is a red-brown very clayey sand of low plasticity with occasional fine-medium sized angular gravel (0.5 m thick) overlain by a thin layer of black ash and organic matter (15 mm thick), with a mean moisture content of approximately 16%.

Figure 1. Burnt forest test site, Metamorfosi, Thessaloniki, Northern Greece.

The forest was deliberately set alight on 6 September 2001 and 185 ha of mature forest were destroyed. Most of the burnt forest was deforested by logging during Spring 2002, except a test plot (figure 1) which was left unlogged so that the amount of soil erosion following the fire could be calculated on a regular basis. Three in-situ shear tests were carried out on the unlogged burnt test plot and three on an unlogged partially burnt test plot. The partially burnt forest test plot consisted of scorched pine trees and understorey vegetation whereas the burnt forest test plot had no understorey vegetation and the pine trees had only burnt trunk remains. The tests were conducted with and without the presence of roots (ref: veg and non-veg in figures 2 and 3). All tests were carried out at approximately 100 mm depth and at the same angle as the slope. Shear strength readings were also taken using a hand vane for comparison. Soil moisture contents were recorded for each test. Two small shrubs of *Phillyrea latifola and Quercus coccitera* were tested for root pull-out resistance on the partially burnt test plot.

3.2 Results

The results of the in-situ shear testing are presented in figures 2 and 3. In figure 2, the peak shear strength of the non-vegetated test was 7.35 kN/m^2, whereas the peak shear strengths of the two vegetated tests were 26 and 24 kN/m^2 respectively. The residual shear strength of the non-vegetated test was 2 kN/m^2, whereas the residual shear strength of the vegetated tests were 13 kN/m^2 and 3 kN/m^2 respectively. The reinforcement effect of the vegetation in the above three tests is clearly apparent. Hand vane tests conducted on the soil showed a shear strength of 40-76 kN/m^2. There was no apparent difference between the vegetated and non-vegetated tests. Soil moisture contents for the three tests varied between 14 and 18%.

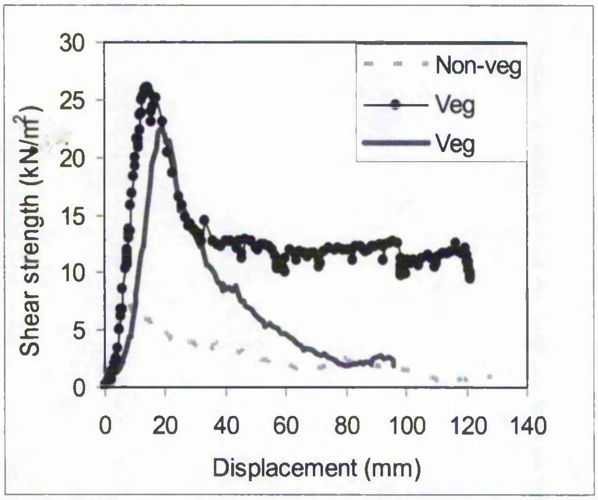

Figure 2. In-situ shear tests on vegetated and non-vegetated soil from the partially burnt forest test plot.

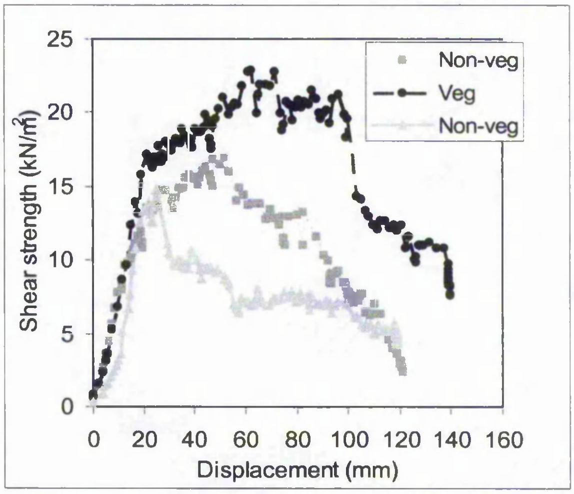

Figure 3. In-situ shear tests on vegetated and non-vegetated soil from the burnt forest test plot.

Figure 3 shows the in-situ shear strength of the soil in the burnt forest plot. The vegetated test showed a sharp rise to 17 kN/m^2 before peaking at 23 kN/m^2; this plateau is due to the reinforcing effect of an 8 mm thick root system enhancing the shear strength of the soil. This reinforcing effect lasts up to 100 mm displacement when the root fails and the soil strength reduces to its residual strength value. On dissection of the soil following the test, the two non-vegetated tests showed a mass of fine roots. These fine roots, as can be seen from figure 2, provide some reinforcement to the soil during shearing. These roots caused a delay in peak shear strength being reached and contributed to a higher residual strength than that observed for the non-vegetated test in the partially burnt test plot. All three test locations showed similar hand vane shear strength readings between 38-70 kN/m^2. The moisture content varied between 14 and 19% for these tests.

The results of the root pull-out tests are summarised in Table 1. The maximum pull-out stress of the roots of *Phillyrea latifolia* was between 9 and 15 MN/m^2 for a range of root diameters (2 - 7 mm). The roots show a slight correlation between decreasing root diameter and increasing pull-out stress. The roots of *Quercus coccitera* have maximum pull-out stress of 1-40 MN/m^2; the root diameters vary from 2 – 20 mm. It was observed that the smaller root diameters tended to show higher pull-out stress values.

Table 1. Root pull-out data for Northern Greece.

Plant ID	Plant name	Plant height (m)	Root diam at clamp, d (mm)	Root diam at break point, d_f (mm)	Root length to break point, ℓ (mm)	Max. pull-out force, F_{max} (N)	Max. pull-out stress (at clamp), $F_{max}/(\pi d^2/4)$ (MN/m^2)
Pl	*Phillyrea latifolia*	0.26					
PlA			2.23	1.73	180	44	11.31
PlB			2.72	1.79	240	74	12.67
PlC			3.49	1.26	412	137	14.36
PlD			6.75	1.7	103	294	8.23
Qc	*Quercus coccitera*	0.95					
QcA			5.55	1.66	154	39	1.62
QcC			3.04	2.71	159	294	40.57
QcE			2.38	2.24	79	88	19.86
QcF			2.14	1.92	110	69	19.10
QcG			1.83	1.92	115	39	14.93
QcH			3.9	4.0	50	44	3.70
QcI			2.36	1.81	63	39	8.98
QcJ			13.15	13.61	105	648	4.78
QcK			19.3	14.55	510	2399	8.20

3.3 Discussion

The in-situ shear box tests give some indication of the amount of root reinforcement provided by the vegetation in preventing soil erosion. Even in the completely burnt forest area, roots of the burnt shrubs and trees still contribute to soil reinforcement.

Although only two shrubs were investigated by the root pull-out technique, the results obtained add to the knowledge base for these plants and also give some indication of the reinforcement value of these species at shallow soil depths, i.e. trapping soil/organic matter at the ground surface and thus preventing erosion during high rainfall.

The presence of roots following forest fires helps to maintain soil stabilisation and slope stability. The roots provide additional reinforcement and increase soil strength preventing the soil from being eroded by storm and flash flood events.

4.0 Case Study 2: Shallow slip landslides in Central Italy

4.1 Site description

The site is located near Salcito Village, Molise, Italy (Lat. 41°71′ N, Long. 14°55′ E) in the catchment of the River Trigno. The area is managed by the "Comunità Montana Trigno Medio Biferno". The site (2700 m^2) is situated at 600 m a.s.l., on a north-facing slope of which the base is formed by a channel at 575 m. It is part of a complex of landslides with a varying degree of activity. The formation date of the complex or its history is unknown but recent activity is manifest at the base of the complex where it is undercut by the stream. This active part encompasses two small, secondary landslides that form the main components of the site. The site (fig 4) has a dominant vegetation cover composed of grasses and herbs with Oak shrubs (*Quercus cerris* and *Quercus pubescens*). Very few mature trees were present.

Figure 4. In-situ shear testing apparatus and typical vegetation cover of Oak shrubs and grasses, in the Molise region of Central Italy.

The geological succession in the region consists of Tertiary marls and flysch deposits of the Molise sequence [7]. The alternating marls and flysch deposits leads to an alternation of weak and more competent strata. Consequently, parts of the slope are highly susceptible to weathering and erosion resulting in slopes that have a high relative relief and several breaks of slope.

The study area is part of the Apennine orogenic belt. The geological structures of this orogeny complicate the lithological sequence in the area even further. Moreover, the orogeny is still active which is witnessed by the continued uplift and the incidence of earthquakes. As a result of the continued uplift, the Trigno and its tributaries have incised the Pleistocene glacial deposits. Along the incised valleys, the valley walls are much steeper and subject to widespread landsliding. Retrogressive failure leads to the formation of landslide complexes of associated flows and slides. These landslide complexes may develop into sub-catchments. In that case, the erosive power of the lower order stream is insufficient to remove the mobilised material and slope decline will occur. However, retreat is the predominant process of slope evolution where the material is effectively removed by the channel system. The undercutting of these slopes could be an important preparatory factor for landslide occurrence.

Seismic events and rainfall, in conjunction or not, are the most likely triggers for the landslide activity in the area. The climate in the region is Mediterranean with most of the rainfall occurring between the late fall and early spring. Thus, the antecedent conditions are more favourable for landslide triggering during the wet season, regardless of seismic events or accumulated rainfall as principal triggers.

The soil tested for its in-situ shear strength was a brown-grey clay of high plasticity, with fine-medium sized roots and rootlets, overlain by a thin layer (10 mm) of organic matter. Three in-situ shear tests were carried out on soil with and without vegetation. The tests were carried out at approximately 100 mm depth and at the same angle as the slope. Shear strength readings were also taken using a hand vane for comparison. Soil moisture contents were recorded for each test. One Oak shrub (*Quercus pubescens*) and seven Spartium (*Genestra*) shrubs were tested for root pull-out resistance. The younger, less established shrubs were pulled out as whole plants whereas the more established larger shrubs were subjected to pull-outs of individual roots.

4.2 Results and Discussion

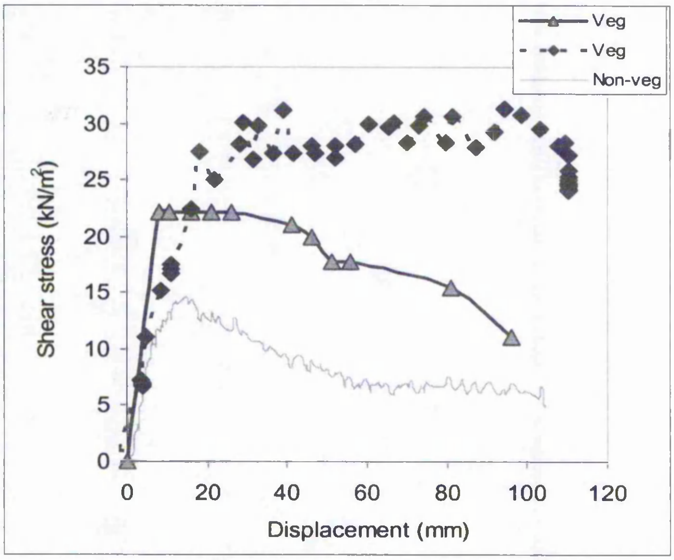

Figure 5. In-situ shear test on vegetated and non-vegetated soil from Central Italy.

Figure 5 shows the in-situ shear tests on vegetated and non-vegetated soils. The two vegetated tests were carried out on *Prunus spinosa* shrubs. A clear reinforcing effect of the vegetation is seen between the non-vegetated and vegetated tests. The shear strength recorded by the hand vane varied between 32 and 53 kN/m^2 for each of the three tests. The soil moisture content was between 24-45%. The clay soil had high moisture content values due to a period of heavy rainfall prior to and during testing and perched water tables were experienced in the clay at 300 mm depth.

The results of the root pull-out resistance tests are presented in Table 2. The maximum root pull-out stress of the *Quercus pubescens* roots range from 0.2 – 15 MN/m^2 for root diameters at the clamp of 2 – 24 mm. The maximum pull-out stress of the whole Spartium plants (G1-G6) varies from 2 – 14 MN/m^2, root diameters varied from 6 – 12 mm. The maximum root pull-out stress of the more established Spartium shrub roots (G7) were between 6 – 59 MN/m^2 and their individual root diameters varied from 0.8 – 22 mm. It was observed that in both species higher pull-out stress values occur in roots of small diameters and large diameter roots have low pull-out stress values. All roots exhibited a break point at failure.

5.0 Slope stability analysis

Whilst the shear box results are indicative of the dramatic increase in shear resistance available in the vicinity of particular roots their interpretation in terms of drained or undrained conditions and their application in stability analysis is not straightforward.

Table 2. Root-pull out data for Central Italy.

Plant ID	Plant name	Plant height (m)	Root diam at clamp, d (mm)	Root diam at break point, d_f (mm)	Root length to break point, ℓ (mm)	Max. pull-out force, F_{max} (N)	Max. pull-out stress (at clamp), $F_{max}/(\pi d^2/4)$ (MN/m²)
G1	*Genestra,* Spartium	0.64	6.3	2.1	132	118	3.78
G2		0.69	7.3	5	990	589	14.07
G4		0.36	11.3	12.8	328	491	4.90
G5		0.39	8.12	11.8	NR	216	4.17
G6		0.68	11.2	5.7	NR	206	2.09
G7		0.13					
G7A			11.6	NR	NR	932	8.82
G7B			0.8	NR	NR	29	58.58
G7C			2.2	1.4	230	39	10.33
G7D			4.6	2.4	295	177	9.76
G7E			4.4	0.96	515	177	11.62
G7F			3.1	1.6	500	98	13.0
G7G			2	1.2	230	69	21.87
G7H			4	3.5	NR	235	18.75
G7I			22.4	3.3	750	3728	6.3
Qp	*Quercus pubescens,* Oak	1.52					
Qp1			13.7	6	510	1118	7.62
Qp2			13.44	NR	NR	1678	11.7
Q1A			5.12	1.08	701	137	6.67
Q1B			3.5	2.33	135	137	14.28
Q1C			2.61	2.66	109	78	14.68
Q1D			6.28	0.71	312	226	7.29
Q1E			5.89	1.01	620	206	7.56
Q1F			7.41	0.6	565	128	2.96
Q1G			2.2	1.51	201	39	10.33
Q1H			3.34	1.89	255	78	8.96
Q1I			4.4	4.68	100	29	1.94
Q1J			6.58	1.75	590	157	4.62
Q1K			7.45	2.16	295	108	2.48
Q1L			16.21	0.76	750	1874	9.27
Q1M			23.68	5.94	3335	3365	7.65
Q1N			18.44	18.44	150	49	0.18
Q1O			2.26	NR	NR	59	14.68

NR – not recorded data.

The root pull-out tests provide an indication of root pull-out resistance, which is more readily applied to routine stability analysis. The various effects of vegetation may be included in routine stability analysis as described by Greenwood [1, 8]. In particular, the effect of root resistance, T, on the stability of a slope may be assessed by the Greenwood General equation (1) [9, 10]

$$F = \frac{\sum[(c'\ell + (W\cos\propto - u\ell - (U_2 - U_1)\sin\propto + T\sin\theta)\tan\phi' + T\cos\theta]}{\sum W\sin\propto} \qquad (1)$$

Terms are standard as used in stability analysis as follows:

Term	Units	Description
ℓ	m	Length (chord) along base of slice
c'	kN/m²	Effective cohesion at base of slice
ϕ'	degrees	Effective angle of friction at base of slice
W	kN	Total weight of soil in slice
α	degrees	Inclination of base of soil slice to horizontal (negative at toe)
U_1	kN	Water force on left hand side of slice (from flow net, seepage calculations or hydrostatic conditions)
U_2	kN	Water force on right hand side of slice (from flow net, seepage calculations or hydrostatic conditions)
u	kN/m²	Average water pressure on base of slice
T	kN	Tensile root or reinforcement force on slice
θ	degrees	Angle between direction of T and base of slip surface

For a planar slide on a continuous slope with seepage parallel to the slope, i.e. where $U_2 = U_1$, equation 1 simplifies to:

$$F = \frac{\sum\left[(c'\ell + (W\cos\propto - u\ell + T\sin\theta)\tan\phi' + T\cos\theta\right]}{\sum W\sin\propto} \qquad (2)$$

(It is noted that the tangential root reinforcement force, $T\cos\theta$, should strictly be deducted from the denominator as it is a negative disturbing (shear) force. The calculated values would be identical for a value of factor of safety, F = 1.)

The available benefit of the roots may be estimated by introducing the term T_r, the available root force per square metre across a particular plane, for example the slip surface.

$$T_r = \text{effective root area x available root strength} \qquad (3)$$

The force, T, applicable to the slice of the stability analysis is given by

$$T = T_r \times \ell \qquad (4)$$

where ℓ is equal to the length of slip surface affected by the roots, assuming a unit width of slope. Further details are given in [1].

Using equations (2) and (4), an estimate of the contribution the roots might make to the safety of the slope is given in Table 3 for the two case studies. It is assumed that a limited number of roots cross the potential slip plane at a given depth; in this case we have assumed 6 roots per square metre for the first case study i.e. more roots available at shallow depths, and 4 roots per square metre of slip surface for the second case study. A Factor of Safety of 8 is applied to the root strength [1] and θ is assumed to be 45°; this value is not critical to the calculation. Typical soil parameters and slope angles for each site have been used. The ultimate root strength and root diameters are based on the root pull-out resistance results given above. It has been assumed that roots are present at the depth of the slip surface with adequate bond length to generate the tensile strength. This has not been confirmed by deeper ground investigation.

Table 3. Possible effects of the presence of roots on the Factor of Safety for the two case studies.

Case Study	Slope angle, α	Assumed soil parameters			Depth of slip surface m	Assumed water table (depth)	Typical ultimate root strength MN/m^2	Assumed available root strength = ult/8 MN/m^2	Typical root diam mm	Typical no. roots per sq.m	T_r kN/m^2	F (no roots)	F (with roots)
		c' kN/m^2	Φ' °	γ kN/m^3									
1A. N. Greece	20°	0	35	18	0.5	Surface	12	12/8	8	6	0.45	0.71	0.89
1B. N. Greece	20°	0	35	18	0.5	Dry	12	12/8	8	6	0.45	1.92	2.25
2. Central Italy	27°	2.6	25	18	1.0	0.5 m	10	10/8	12	4	0.57	0.95	1.04

From Table 3, it can be seen that with the presence of roots a significant increase (>10%) in the Factor of Safety can be achieved.

6.0 Conclusions

In-situ shear box testing and root pull-out testing was carried out on two sites in Europe to assess the contribution of roots to slope stabilisation.

It was shown that the presence of vegetation could help to prevent soil erosion after forest fire in Northern Greece and assist stabilisation of shallow landslides in Northern Greece and Central Italy.

The inclusion of in-situ shear strength values provides valuable information on the increased shear resistance that can be obtained by the presence of roots. More research is needed to incorporate this data into slope stability analysis.

The root pull-out resistance values have been included in simple slope stability analysis, although many assumptions are made and the parameters applied with caution, it can be shown that root reinforcement can increase the Factor of Safety on slopes prone to soil erosion and shallow landslides. More work is needed to assess the depth distribution of roots for particular species in the local climate and soil conditions.

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In-situ shear box and root pull-out apparatus for measuring the reinforcing effects of vegetation

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ABSTRACT: The engineering role of vegetation is being investigated by civil and geotechnical engineers in the United Kingdom. At Nottingham Trent University, research in this field has led to the design and development of a 150 mm square shear box and apparatus to measure the in-situ shear strength of soil reinforced with roots of plants, shrubs and trees. The apparatus can also be adapted for root pull-out experiments. This paper describes the in-situ shear box and root pull-out apparatus. The testing procedure and methodology are explained. Typical failure curves as observed during field tests are presented.

1 INTRODUCTION

The use of vegetation as reinforcement (i.e. soil bioengineering techniques) has become established as a means of helping to stabilise soil slopes particularly on riverbanks and highways (Sotir 1998, Sotir et al. 2002). However, in some cases, engineers are reluctant to maintain the natural vegetation or to use these soil bioengineering techniques because the contribution made by the plants (woody vegetation) to the soil in increasing its shear resistance and stability is largely unknown. The contribution the plants provide to the soil strength depends to a large extent on the tensile strength of the roots involved and their ability to develop that tensile strength by resisting pull-out over their embedded lengths.

The in-situ tensile strength of the roots and the combined shear resistance the roots add to the soil has been investigated during a number of projects at Nottingham Trent University. The investigations have led to the design and manufacture of an in-situ shear apparatus (mark 1) to measure the combined root and soil strength. The mark 1 apparatus was trialled during field experiments on the M20 motorway, United Kingdom in 1998 (Greenwood et al. 2001). The mark 1 apparatus consisted of a 150 mm square by 100 mm high steel plated shear box, a hydraulic jack and pump and a 10 kN load cell (Norris & Greenwood 2000a). The background to the development of in-situ shear testing and a more detailed description of the mark 1 apparatus is given in Norris & Greenwood (2000a, b).

During field experiments on a subsequent project, the mark 1 apparatus was redesigned to facilitate the field set up and to enable electronic recording of the force and displacement measurements (mark 2). Automation of the apparatus is the ultimate goal but with limited time available a manually operated hydraulic system was chosen. This had also been proven in the mark 1 trials.

The in-situ tensile strength or pull-out resistance of the roots of woody vegetation has been measured by adapting the mark 2 apparatus by detaching the shear box and replacing with a suitable root clamp. The mark 2 apparatus with its modifications is described in this paper.

2 METHODOLOGY

2.1 *Description of mark 2 apparatus*

2.1.1 *In-situ shear box apparatus*

The in-situ shear box apparatus is shown in Figure 1. It consists of a 150 mm by 150 mm by 100 mm steel plated shear box. The shear box is attached to an aluminium frame, which contains running tracks. These

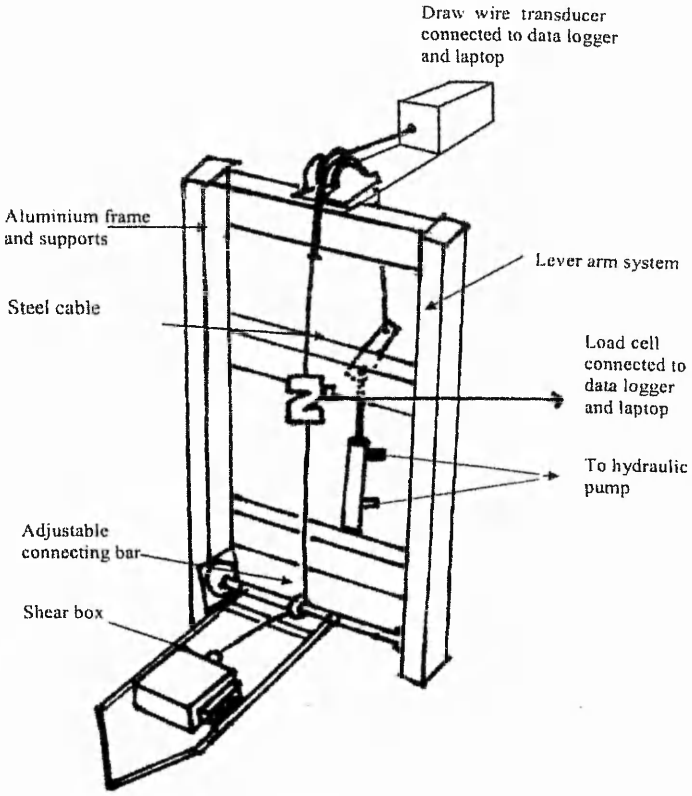

Figure 1. Field set up and lay out of the in-situ shear box apparatus.

tracks control the movement of the shear box during testing. The shear box is connected to a 250 kg Z-type load cell by a steel cable. The load cell measures tensile force. Force is applied through a hydraulic cylinder having a pulling force of 8.79 kN and capable of 100 mm displacement. The cylinder is fully extended prior to the test.

In order to measure the displacement of the shear box, a draw wire transducer (type DWT-20-06-CR-1-E) is fixed to the top of the frame and the draw wire is clipped to the steel cable. Both the load cell and the draw wire transducer are electronically connected to an IOTech Data Acquisition System (USB 56) where the data is logged and recorded as an ASCII file. Prior calibration of the draw wire transducer and the load cell enables the data to be logged in real time values of mm's and kN's, respectively. The data is scanned at 140 Hz per second. This gives an unmanageable number of data points, therefore the data acquisition system can be set to block average the number of scans. This was set at one reading per second. The logged data is easily imported into Microsoft Excel, where it can be analysed.

2.1.2 *Root clamp adaptation*

The in-situ shear apparatus is readily adapted to measure the pull-out resistance of roots of woody vegetation. The shear box and running track frame are detached from the main frame containing the load cell and hydraulic cylinder. The root is clamped using a specifically designed clamping tool (Fig. 2). The clamped root is attached to the load cell with strong steel cable. High strength values are recorded when measuring the pull-out resistance, therefore it is necessary to use a 500 kg load cell and a hydraulic cylinder which has a larger effective pulling force and length of travel. The apparatus is set up in a similar way as before and the data is logged in the same manner.

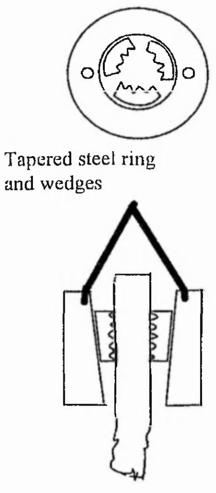

Figure 2. Root clamp (for roots up to 20 mm diameter).

2.2 *Test procedure to measure the combined root-soil strength*

A description of the general site details (soil, slope angle, slope height, vegetation cover, location) and weather conditions are recorded. The site is assessed for suitable test plot areas for the unreinforced and reinforced in-situ shear tests i.e. an area with a combination of bare ground or grasses, shrubs and trees. An area of approximately 3 m long by 1 m wide is marked out with pegs. The type, density cover, height and spread of the vegetation within the test plot is recorded on a data sheet. The top growth of all the vegetation present within the plot is removed, as this may become a hazard during the testing procedure.

The shear box is positioned on the ground above the area of soil that is to be tested. The soil is carefully excavated around all four sides of the box maintaining an intact soil block inside the box, some pressure may need to be exerted on the box during emplacement. Note, when testing a reinforced sample some roots protruding from the sides of the soil sample may need to be removed with sharp secateurs. Once the shear box is in place i.e. at the required shearing depth from the ground surface, the soil surrounding the box can be removed to allow the shearing apparatus and frame to be assembled. The hydraulic pumping system and laptop are set up once the apparatus is assembled. The test is conducted at a constant rate of shearing. It is necessary during the shear test, to observe the mode of shear and to record any unusual events that may occur, for example, the presence of stones preventing the shear box from moving will cause a false peak in the failure curve.

On completion of the test, the soil in the shear box is explored and the number, locations and diameters of the roots (if present) are recorded. The moisture content of the soil in the shear box and below the shear plane is recorded. Any features present on the shear plane are also recorded.

2.3 *Test procedure to measure root pull-out resistance*

A description of the general site details and weather conditions are recorded as before. An appropriate plant specimen is chosen for testing. The diameter at breast height (normally 1.3 m above ground level), height, spread and the condition of the plant is recorded on a data sheet. The top growth of the plant is removed at 50 mm above ground level. The stem diameter, age of tree and mass of above ground vegetation is recorded. The soil is excavated from around the plants' stump, to an approximate distance of 200 mm from the stump, leaving all roots greater than 2 mm intact. Some fine roots may be damaged during this process. Each individual root is labelled with a suitable tag and identity number. All root diameters, root orientations and inclinations are measured and recorded on a data sheet. The stump can now be removed, so that the roots are free to be pulled.

Each successive root is attached to the root clamp, as shown in Figure 2. The clamped root is pulled at a constant rate until failure occurs and the root is pulled out of the ground. The maximum pull-out

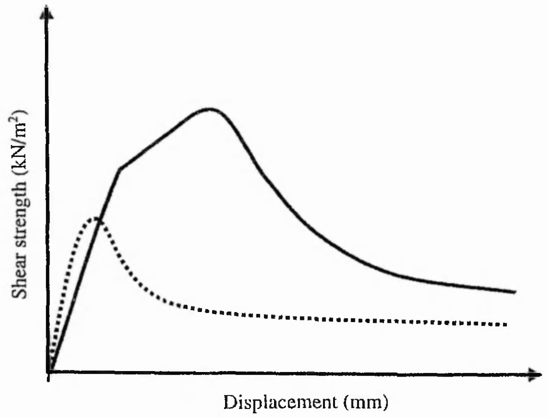

Figure 3. Typical failure curves of reinforced and unreinforced soil. The reinforced soil is represented by a solid black line. The unreinforced soil by a broken line.

resistance (force) and root displacement is recorded by the datalogger. After each test, the root is sketched and its morphology (sinuosity, branching, tapering) is described. The type of failure is recorded. The root length and diameters of the break point or tip are measured and recorded. The mass of the root is recorded and a portion of the root is used to determine the root moisture content. The detailed procedure for the root pull-out test is described by Greenwood et al., in preparation.

3 ANALYSIS OF RESULTS

3.1 *Analysing the in-situ shear tests*

The in-situ soil shear strength is calculated from the load cell readings recorded by the data logger and divided by the area of the shear box. The shear strength of the reinforced or unreinforced soil can be plotted on an x-y graph, with shear strength (measured in kN/m^2) against displacement (measured in mm). A typical failure curve for an unreinforced and reinforced soil sample is given in Figure 3. The unreinforced soil failure curve attains a peak strength value, and then gradually decreases until a residual strength is maintained. The reinforced soil shows a somewhat different character, with a gradual rise in strength, before a prolonged peak where the plant roots are increasing the soils strength. At the end of this "peak" or when the roots are no longer adding any reinforcement to the soil, there is a decrease in the strength value, which is approximately equal to the residual strength of the soil without reinforcement. The difference between the two peak values in the two curves gives the added strength value of the roots to the soil.

3.2 *Analysing the root pull-out tests*

The root pull-out resistance value (F) is obtained from the load cell readings recorded by the data logger. These values can be plotted against displacement as shown in Figure 4.

A number of different failure curves have been observed during the testing, depending on the size (diameter) and morphology of the roots. For example, a single straight root of diameter 8 mm may break at a node in the root and produce the failure curve as seen in Figure 4a. The root reaches a maximum resistance then fails suddenly so subsequently has no further bond with the surrounding soil. Alternatively, a root may have multiple branches and during pull-out, the branches fail at different times producing a failure curve as shown in Figure 4b. In some cases, when the root is of a sinusoidal nature and has many small diameter rootlets along its length, it may fail as shown in Figure 4c. The root reaches its maximum pull-out resistance on straightening and fails at its weakest point, however in this case, it does not fail suddenly and pull straight out of the ground, it adheres and interacts with the soil producing a residual strength (flat portion of graph). In this case, if the pulling was stopped at this point, the root would provide

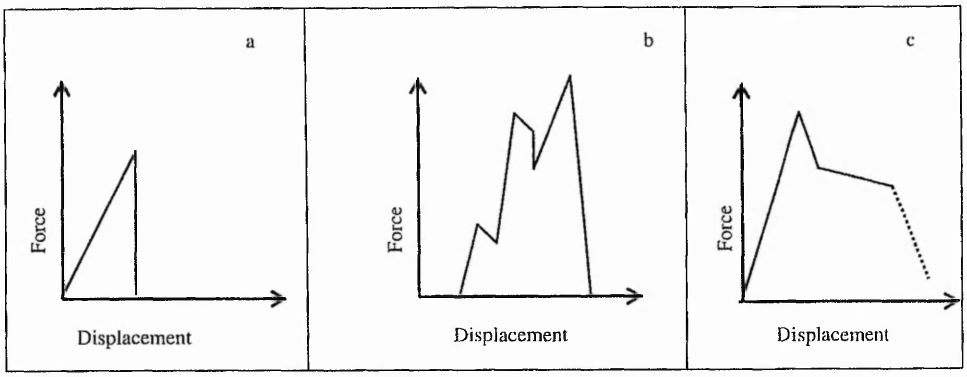

Figure 4. Typical failure curves observed during root pull-out tests. (a) Single root with no root-soil interaction. (b) Multi-branched root. (c) Root-soil interaction.

additional strength to the soil. Since, the root is pulled completely out of the ground, there is no further pull-out resistance available (dotted portion of graph).

An indication of the available tensile strength of the root is obtained by dividing the measured maximum force (F_{max}) by the effective cross sectional area of the root at the clamp (A_e). This value may be compared with laboratory measured tensile strengths. The root pull-out values obtained can be used in slope stability analysis calculations. This is further described in Norris & Greenwood, in press.

4 CONCLUSION

The mechanics of an in-situ shear box, root pull-out test and the associated apparatus are presented and described for testing soil reinforced with woody vegetation. Future developments of the apparatus would be to design a fully automated portable testing machine that could be used by a two-person team.

ACKNOWLEDGEMENTS

This work has been funded and supported by CIRIA, Nottingham Trent University Research Enhancement Fund, and the European Union 5th Framework "Ecoslopes" project. Nottingham Trent University Technical Staff, Steve Goodman and Mark Flanagan, are thanked for their assistance in the design and manufacture of the apparatus and with the field testing. Colleagues Ken O'Hara-Dhand and Joanne Wint are thanked for assistance with the electronic mechanisation and field testing.

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Bioengineering and the transportation infrastructure

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Introduction

Vegetation will generally establish itself naturally over time even on relatively barren soils provided some nutrients and water are available. In the United Kingdom most soil slopes will support an array of vegetation types. Grasses, shrubs and trees will initially self-seed as 'pioneer' vegetation and evolve into a consistent pattern of coverage referred to as 'climax' vegetation.

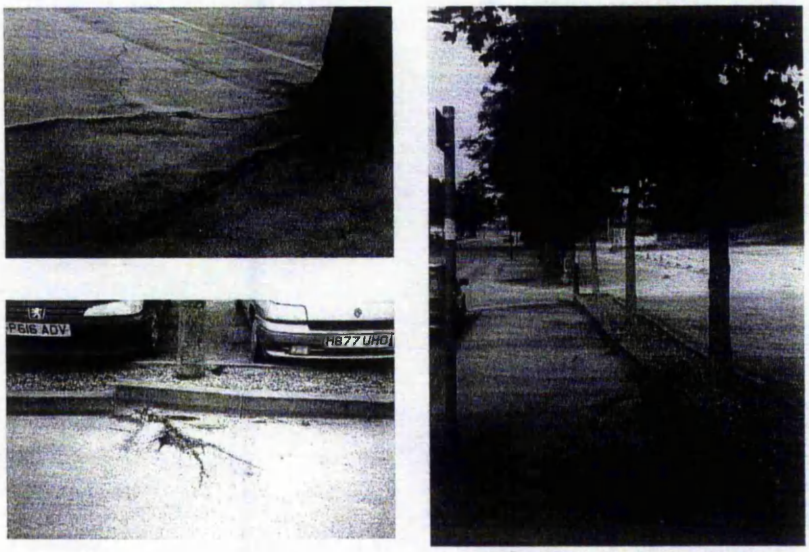
Embankment and cutting slopes formed as part of the UK transportation infrastructure are generally seeded with grasses in accordance with the Specification for Highway Works (Design Manual for Roads and Bridges and Manual of Contract Documents for Highway Works) and selected shrubs and trees planted in accordance with locally agreed landscaping criteria. Whilst it is recognised that the grass, once established, will prevent surface erosion, the vegetation is not intended for any purpose other than landscaping aesthetics.

Many of the embankments and cutting slopes in the UK, particularly in the South East of England, are constructed of or within stiff over-consolidated clays which are prone to softening with time leading to shallow slope failures (Greenwood et al, 1985). It is becoming increasingly important, as the need for more eco-friendly solutions arises, for engineers to explore how vegetation might be selected and maintained, to help enhance the soil strength and reduce the risk of shallow slope failure.

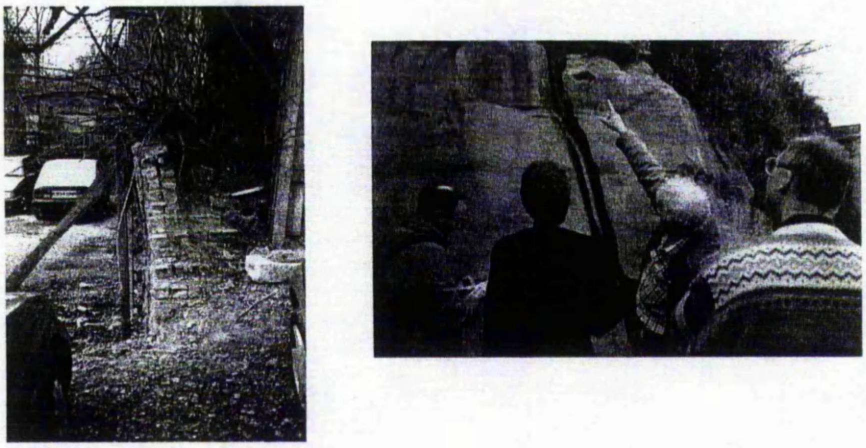
However, the detrimental effects of vegetation cannot be ignored. Figure 1 indicates some of the problems frequently encountered due to vegetation when it exists in the 'wrong' locations in relation to engineering constructions. The detrimental effects on foundations located too close to certain trees leading to ground movements of a seasonal and permanent nature has been extensively studied by the Building Research Establishment (1987) and others (Biddle, 1998).

On the other hand, vegetation can often be seen 'holding together' slopes that would otherwise degrade very rapidly. Examples are shown in Figures 2. There is a general awareness and perception by the public that tree roots bind the soil

Transportation geotechnics. Thomas Telford, London, 2003



a). Damage to pavements due to tree roots, Nottingham Trent University car park



b). Retaining wall damage due to roots at Nottingham Trent University

c). Wedging apart of sandstone blocks due to roots in fissures at Nottingham Castle

Figure 1, Examples of detrimental effects of vegetation

a) Water Lane, Kent. Vegetation root network permits steeper slopes in Greensands

b) and c) Dune grasses resisting erosion and local instability on the Wash

Figure 2, Examples of vegetation assisting stability together as indicated by the following report from the Daily Telegraph following a minor train derailment near Merstham tunnel on the Brighton line on 2nd January 2003:-

'Passengers rescued as train hits mudslide'.

...Sam Livermore, whose home is beside the track, said: "Since they uprooted trees about 10 months ago the banks have become increasingly unstable as there are no longer any roots to keep the ground in place."

A resident whose home overlooks the cutting said: "Last year work was carried out to supposedly prevent land-slips. But workers missed a 40 yard section when they were putting wire netting and reinforcing materials on the bank. It is this exact spot where the landslip has happened. It is on a bend so the train driver would have been on top of it before he realised."

A spokesman for Network Rail said the trains had been ordered to travel at 5 mph because of the heavy rainfall over the previous 24 hours. He said almost an inch of rain had fallen during that time. "The trees were taken out because of the risk of them falling on to the tracks," he added. "They presented more of a risk than landslides and contrary to popular belief they do not make the embankments more stable."

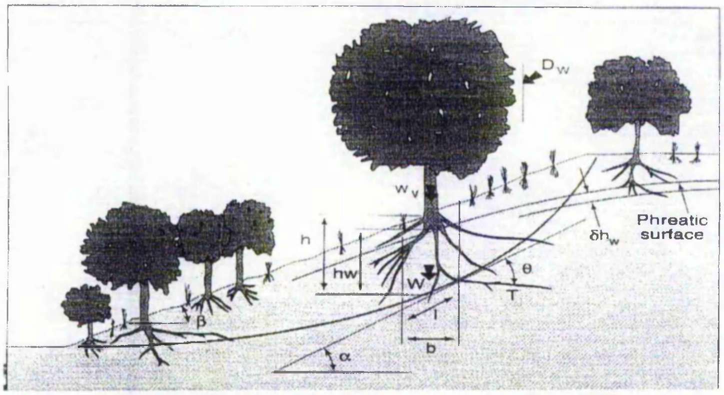
It is interesting to note that the Network Rail 'spokesman' was rather dogmatic that the trees were not helping stability but the danger of them falling on to the track was high. The contribution and problems associated with presence of vegetation on the London Underground cutting and embankment slopes was more positively discussed by Gellatley et al, (1995). There is an obvious need to quantify the potential benefits (and dis-benefits) that vegetation can bring to the stability of slopes.

This paper summarises the work relating to Soil Bioengineering carried out at Nottingham Trent University and assesses the various influences that vegetation will have on the stability of slopes.

CIRIA vegetation trials

The publication by CIRIA of the text 'Use of Vegetation in Civil Engineering' (Coppin and Richards, 1990) formed a major landmark in introducing to engineers the concepts of enhancing soil properties with appropriate vegetation. This was followed up by further guidance relating specifically to highway slopes (Barker, 1996, 1997) and CIRIA sponsored field trials of specific vegetation on the M20 motorway at Longham Wood, near Maidstone, Kent (Greenwood et al, 2001).

The main influences of vegetation are given in Figure 3, based on Coppin and Richards (1990). The M20 trials set out to assess the relative importance of these influences on the geotechnical parameters and stability of a slope (Greenwood et al, 2001). The Longham Wood site was monitored for a period of 5 years after which it had to be destroyed as the new Channel Tunnel Rail link was constructed immediately adjacent to the M20 passing through the trial site.



Basic parameters and dimensions used in stability analysis by method of slices

Term	Units	Description
H	m	Average height of slice
B	m	Width of slice
ℓ	m	Length (chord) along base of slice
c'	kN/m^2	Effective cohesion at base of slice
ϕ'	degrees	Effective angle of friction at base of slice
γ	kN/m^3	Bulk Unit weight of soil in slice
γ_w	kN/m^3	Unit weight of water (usually taken as 10 kN/m^3)
W	kN	Total weight of soil in slice (for layered soils, 1,2,3 etc $W = (\gamma_1 h_1 + \gamma_2 h_2 + \gamma_3 h_3 + \text{etc}) \times b$)
α	degrees	Inclination of base of soil slice to horizontal (may be negative at toe)
h_{w1}	m	Height of free water surface at left hand side of slice
h_{w2}	m	Height of free water surface at right hand side of slice
U_1	kN	Water force on left hand side of slice (from flow net, seepage calcs or based on h_{w1})
U_2	kN	Water force on right hand side of slice (from flow net, seepage calcs or based on h_{w2})
h_w	m	Average piezometric head at the base of the slice. For hydrostatic $h_w = (h_{w1} + h_{w2})/2$
U	kN/m^2	Average water pressure on base of slice ($= \gamma_w \times h_w$)
F	ratio	Factor of Safety (usually shear strength/ shear force on slip plane)
F_m	ratio	Factor of Safety in terms of moment equilibrium
F_f	ratio	Facto of safety in terms of horizontal force equilibrium
Vegetation, Reinforcement and Hydrological effects		
c'_v	kN/m^2	Additional effective cohesion at base of slice (due to vegetation etc.)
W_v	kN	Increase in weight of slice due to vegetation (or surcharge)
T	kN	Tensile root or reinforcement force on slice
θ	degrees	Angle between direction of T and base of slip surface
Dw	kN	Windthrow force (downslope)
β	degrees	Angle between wind direction and horizontal (often assume equal to slope angle)
Δh_{w1}	m	Increase in height of free water surface at left side of slice
Δh_{w2}	m	Increase in height of free water surface at right side of slice
ΔU_1	kN	Increase in water force on left hand side of slice
ΔU_2	kN	Increase in water force on right hand side of slice
Δh_w	m	Increase in average piezometric head at base of slice (due to vegetation)
Δu_v	kN/m^2	Increase in average water pressure at the base of the slice, $= \gamma_w \times \Delta h_w$

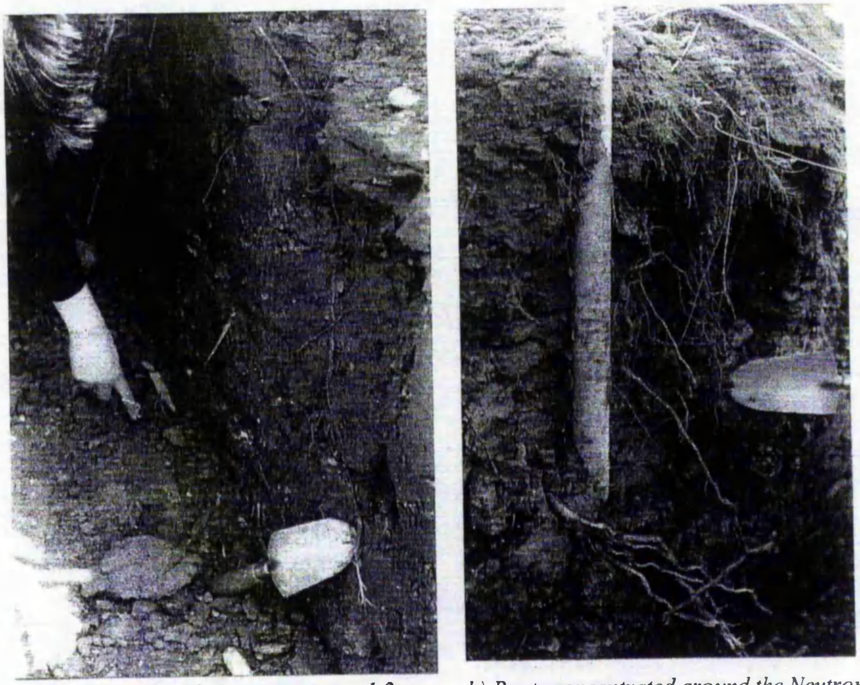
Figure 3, The various influences of vegetation (developed from Coppin and Richards, 1990) and notation used for routine stability analysis by the method of slices (Greenwood, 1989).

During the final 'destructive' testing of the site, trenches were excavated to provide more detail of the ground and root growth conditions (Figures 4a–4b). Apparatus was developed to assess the in situ shear strength of the root reinforced Gault Clay and to determine the resistance of selected roots to pulling out of the ground.

The main conclusions from the Longham Wood trials were (Greenwood et al, 2001):-

- Willow and alder trees became established over the five year trial period and developed a substantial root network extending to 1.2 m depth.
- The instrumentation used, particularly that for determining soil water pressure, detected changes in the state of the slope produced by the vegetation and root systems.
- Seasonal changes in ground conditions were clearly indicated by the Mackintosh probe testing but this testing was not sensitive to the smaller changes due to the vegetation.
- The counterfort slope drains had no apparent effect on the vegetation or the soil and groundwater conditions in the upper 1.2 m of the slope.
- Of the possible influences of the vegetation, the tensile root force was found to be most effective in increasing the resistance to slope failure.
- The study recommended that further monitoring is carried out on other sites to examine the effects of the vegetation in the medium - long term and to quantify the strength contribution available from different root systems.

Moisture content changes during the trials were monitored by use of a neutron probe inserted down access tubes at specific locations (Vickers and Morgan, 1999). During the final 'destructive' testing physical moisture contents were taken and the 'moisture in the bag' technique Greenwood and Norris (1999a).



a) Final trench with roots present to 1.2m

b) Roots concentrated around the Neutron Probe access tube

Figure 4, Trenching at the end of the M20 trials to check on root growth with depth.

The ECOSLOPES 5th framework project

The award of a £1.6m research grant under the 5th Framework of the European Community enabled Nottingham Trent University, as a partner in the ECO-SLOPES project, to further develop the in situ shear apparatus and to link the work done in the UK with related work in other European countries. The project is broad-based with the partners focusing on the many related aspects of vegetation as listed in Table 1. Current details of the project are available on the Website, www.ecoslopes.com.

It is intended that the final outcome of the project will be a reference data base and a manual or computer-aided decision support system to help the slope engineer to select, specify and maintain appropriate vegetation to enhance slope stability in the various regions of Europe.

Table 1, The EU funded ECOSLOPE partners and research activities (Contract period 2001–2004)

ECOSLOPES PARTNER	PARTICULAR ACTIVITY
NTU (Nottingham Trent University)	Root investigations -shear and pull out testing; Stability analysis; Vegetated slope data base; Decision support system.
INRA (University of Bordeaux)	Project coordination; Root architecture; Tree winching; Numerical modelling (with Wilde and Partners).
Cemagref (France)	Dynamic effects – vegetation to resist rockfalls.
Forest Research, Scotland	Forest Stand stability.
University of Molise, Italy	Root architecture.
Geostructures, UK (joined NTU)	Modelling; Decision support system.
NAGREF, Forest Research, Greece	Effects of fires on vegetation and erosion.
IBED, University of Amsterdam	Site characterisation; Modelling.
CIDE, Spain	Desertification; Forest fires; Vegetation recovery.
End User Group (UK reps Alex Kidd, Neil Bayfield)	Comments and guidance to research contractors.

The influences of vegetation (and how they may be modelled)

In this section each of the possible influences of vegetation on a slope (Figure 3) is reviewed in the light of the M20 trials, the ECOSLOPES project and reference to other work.

Enhanced cohesion, c'_v.

The concept of effective cohesion in soils has received considerable attention with some researchers advocating that no true cohesion exists in clay soils. However back analysis of slope failures has generally indicated an operational effective shear strength which is best represented by a small cohesion intercept in the order of $c' = 1$ to $2\ kN/m^2$. The actual value can have considerable influence on the calculated factor of safety, F, hence the interest of geotechnical engineers in defining the value.

It would be expected that a fine root network would act to provide an enhanced cohesion much in the same way that geosynthetic mesh elements have been demonstrated to enhance the soil strength properties (Andrawes et al, 1996).

Values of c'_v have been measured by researchers often based on shear tests (Coppin and Richards, 1990, Table 3.4).

The use of enhanced c′ values will be appropriate for grassed areas or areas of uniform vegetation where fine root distribution with depth is consistent and easily defined (see later and Figure 6).

In general the reliable benefit of an enhanced c′ value will be limited to shallow depths. Just as it is difficult to measure accurate values of c′ which are appropriate for stability analysis it will be equally difficult to measure the additional contribution, c'_v, due to the vegetation. Field tests will tend to give an indicative undrained strength increase due to the presence of fine roots but, for clay soils, the true effective parameters are probably best obtained by back analysis or more sophisticated effective stress laboratory testing.

The role of fine roots in resisting surface erosion is well documented (Morgan and Rickson, 1995). Whilst fine roots are the major root components in garnering nutrients and moisture from the soil, their role in more general slope stability is less certain with perhaps a minor contribution as they help to maintain the integrity of the surface layers.

The Mass of Vegetation, W_v.

The mass of vegetation is only likely to have a major influence on slope stability when larger trees are present. The loading due to a well stocked forest of 30 to 50m tree height is in the order of 0.5 to 2 kN/m^2 (Coppin and Richards, 1990, Figure 3.17). A 30m high tree having a base trunk diameter of around 0.8m is likely to have a weight of around 100 to 150 kN. Such trees located at the toe of a potential slip could add 10% to the factor of safety. (See Coppin and Richards, 1990, Figure 3.18). Equally if located at the top of a potential slip the factor of safety could be reduced by 10%. Each situation must be individually assessed for the mass of vegetation involved. It should be borne in mind that plant evapo-transpiration will reduce the weight of soil as moisture is lost. This can be important on slopes of marginal stability.

When larger trees are removed from the toe area of a slope, in addition to the gradual reduction in soil strength due to the loss of evapotranspiration effects, the reduction in applied loading could result in temporary suctions in clay soils which may lead to softening as available water is drawn in to satisfy the suction forces. This is of course akin to the recognised softening of overconsolidated clays due to relaxation of overburden pressures when placed in the top layers of an embankment from deep cutting (Greenwood et al, 1985).

Windthrow loading, D_w.

Windthrow loading is particularly relevant when considering the stability of individual trees but of lesser significance for general slope stability where the wind forces involved represent a much smaller proportion of the potential disturbing forces and trees within a group (stand) are sheltered to some extent by those at the edge.

Windthrow forces on single trees may be estimated from Brown and Sheu (1975), and windthrow on forested slopes may be calculated (Hsi and Nath, 1970). (Both approaches given in Coppin and Richards, 1990).

Soil strength increase due to moisture removal by roots.

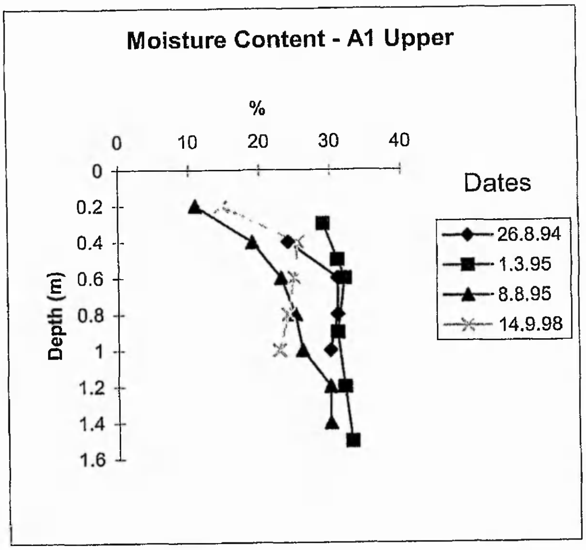
There have been various well documented observations of moisture deficit around trees (Biddle, 1998) due to the effects of evapotranspiration and the problems this has caused for buildings (Hunt et al, 1991). However when it comes to relying on tree and shrub roots to remove water and hence strengthen the soil it is not quite so straightforward.

Observations on the M20 at the Longham Wood trial site indicated huge seasonal variation in the moisture content (and hence the undrained soil strength) of the south facing trial area (Figure 5). These large variations masked any effects due to the vegetation over the 5 year period of the trials (Greenwood et al, 2001).

More work is needed to compare the moisture contents of slopes with particular types of vegetation with adjacent slopes in the same soil type without vegetation (or with grass alone). The availability of Time Domain Reflectometry and Theta probe technology to assist in non destructive moisture content determinations should enable data to be accumulated on the actual influences of the vegetation on moisture content.

During particularly wet periods, the ability of the roots to influence the seasonal moisture content will be curtailed and therefore any enhanced soil strength gained previously by evapotranspiration will be reduced or lost entirely to an extent difficult to quantify. Hence this effect cannot be taken into account at such critical times. However, it can be assumed that there is a narrowing of the window of risk of failure due to soil saturation by storm events or periods of prolonged rainfall. Furthermore, whilst moisture content changes influence the undrained shear strength (c_u) the effective stress parameters ($c'$and ϕ') as generally used in routine stability analysis are not directly influenced by the changing moisture content, although the water pressures (suctions) used in the analysis may well be.

It should be borne in mind that desiccation cracks, possibly extended during dry periods by the presence of certain vegetation, will encourage a deeper penetration of water and water pressures into the soil during wet periods. However, these cracks will subsequently provide pathways for roots to extend deeper into the soil in their search for moisture and nutrients.



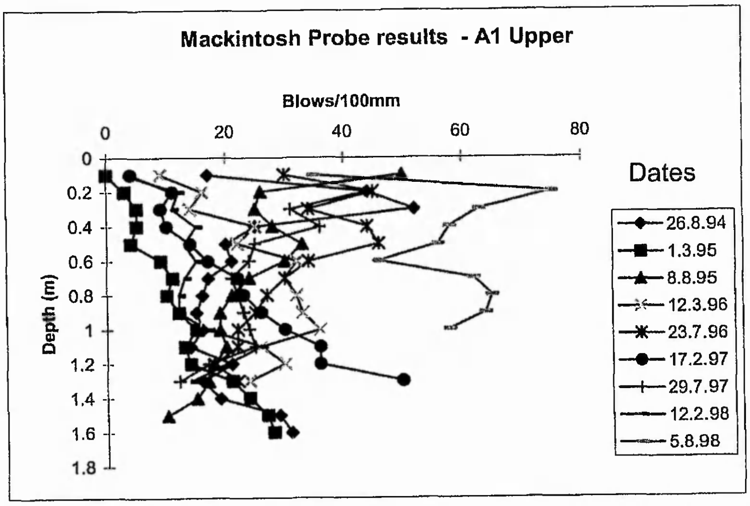


Figure 5, Typical moisture content and Mackintosh probe results from M20 vegetation trial site indicating extreme seasonal variations in moisture content and soil strength (Greenwood and Norris, 1999b).

Suctions and changes in pore water pressure due to vegetation (u_v).

As discussed in the previous section, the moisture content and soil water pressures are related. On the M20, seasonal fluctuations in the water table, as measured by standpipes, were not significantly modified by the effects of the newly established vegetation. Tensiometers installed on the M20 project (Vickers and Morgan, 1999) and on other slopes have proved much more worthwhile in recording the detailed response of the ground suctions to rainfall events and periods of wet or dry weather.

The soil scientist and agriculturalist has tended to view soil suctions and moisture contents rather differently from the civil and geotechnical engineering approach. It is recognised that there is some merit in relating the geotechnical engineering parameters to the terminology of the soil scientist. Some terms which are relevant to the consideration of the effects of vegetation are described below with their relationship to conventional geotechnical terms.

- *Soil moisture characteristic curve* – this relationship between the moisture content and the suction pressures is particularly relevant to the geotechnical engineer (Fredlund and Xing, 1984).
- *Field Capacity* – the moisture content after saturation and after free drainage has practically ceased. Typical suctions are -5 to -10 kNm^2 at field capacity.
- *Moisture deficiency* – the difference between the measured moisture content and the field capacity.
- *Gravimetric (engineering) moisture content* = mass of water / mass of solids (dry soil).
- *Volumetric moisture content* (as used by soil scientists and measured by indirect tests such as Theta probe) = Volume of water / Total volume of soil.
- The gravimetric and volumetric moisture contents are related by:-
- Gravimetric moisture content = Volumetric moisture content x density of water / dry density of the soil.

Tensile root strength contribution, T.

The tensile strengths of roots of various diameters from different species have been measured in the laboratory and found to be typically in the order of 5 - 60 MN/m^2 (Coppin and Richards, 1990).

In the field, to make use of the available tensile strength to enhance slope stability the root must have sufficient embedment and adhesion with the soil. The biological growth patterns and interaction between the root and soil are complex (Greenwood et al, 2003 in preparation) but for engineering purposes the available force contribution from the roots may be measured by in situ pull out tests.

Measurement of the root pullout resistance has been carried out by various methods ranging from hand pull to screw and hydraulic jacks. The method depends very much on the size of root and the convenience of available equipment and a reaction frame. A constant rate of strain is required, typically 1% per minute, and a means of measuring the resistance by spring balance or load cell at defined displacements. Procedures for the root pull out test are given in Greenwood et al, (2003 in preparation).

Design of the clamp to grip the root requires particular attention. Many species of root, particularly when fresh, demonstrate a tendency for the bark to separate and slide over the core wood during tensile testing. It is therefore often necessary to strip the bark at the clamp and to grip directly on to the core wood. The tensile strength is then calculated based on the diameter of the core wood assuming that the bark is making little contribution to the strength of the root. However it is the bark which is in contact with the soil and generating the adhesion resistance so the full root diameter must be considered in the pull out assessment. These issues are discussed by Greenwood et al, (2003 in preparation).

Modelling of vegetation influences

The various influences of vegetation on the factor of safety of a slope are conveniently assessed by routine limit equilibrium stability analysis. Various methods of stability analysis are available. The Greenwood General Equation (equation 1) (Greenwood, 1989; Morrison and Greenwood, 1989) is considered particularly appropriate because it takes full account of hydrological (seepage) forces to give a realistic estimate of the factor of safety for all types of slopes and slip surfaces.

$$\mathrm{F} = \frac{\sum\left[c'\ell + \left(W\cos\propto - u\ell - \left(U_2 - U_1\right)\sin\propto\right)\tan\phi'\right]}{\sum W\sin\propto} \qquad (1)$$

The mathematically 'simple' form of the equation and the factor of safety defined in terms of restoring and disturbing forces means that it is straightforward to add the various vegetation influences (equation 2)

$$\mathrm{F} = \frac{\sum\left[(c'+c'_v)\ell + \left((W+W_v)\cos\propto - (u+\Delta u_v)\ell - \left((U_2+\Delta U_{2v}) - (U_1+\Delta U_{1v})\right)\sin\propto - D_w\sin(\alpha-\beta) + T\sin\theta\right)\tan\phi'\right]}{\sum\left[(W+W_v)\sin\propto + D_w\cos(\alpha-\beta) - T\cos\theta\right]} \qquad (2)$$

A procedure for estimating the available tensile root reinforcement force, T, based on observation of the number of roots of a given diameter present at a particular depth is given in Norris and Greenwood (2000). A factor of safety of 8 is applied to the measured pull out resistance to allow for the large strain needed to generate the peak measured root pull out force and for other uncertain factors relating to root distribution.

An EXCEL spreadsheet, known as 'SLIP4EX', has been developed at Nottingham Trent University to compare routine methods of analysis for a given slip surface and to quantify the changes to the factor of safety due to the influences of the vegetation.

The tensile root force available and other changed parameters due to the vegetation may be assessed by considering the typical distribution of roots below a vegetated area.

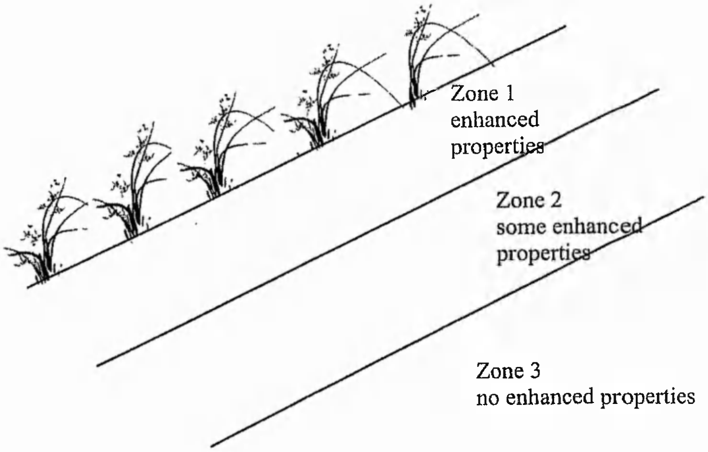


Figure 6, Zones of enhanced soil properties for regular vegetation cover

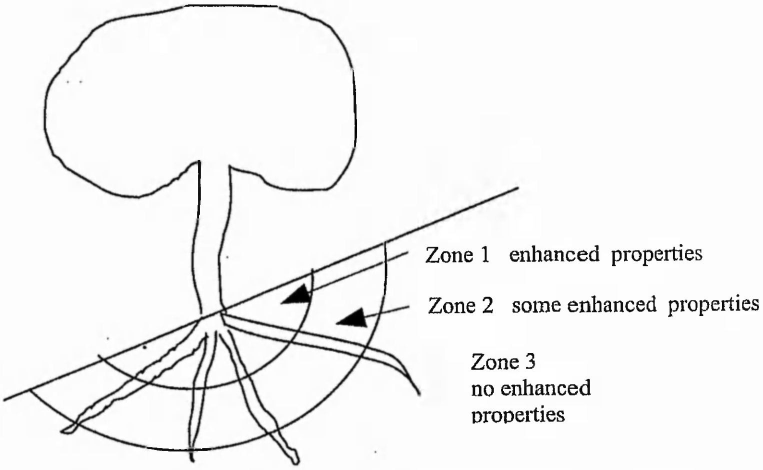


Figure 7, Saucer shaped zones of enhanced parameters beneath a single tree.

If the coverage is consistent over the area, enhanced parameter zones may be represented as zones parallel to the slope (Figure 6). For isolated larger trees and shrubs a distribution such as that shown in Figure 7 might be considered as being typical of the saucer shaped root network frequently encountered.

Finite element modelling of the vegetation influences is also helpful particularly where strain compatibility is to be considered. The application of finite element programs such as PLAXIS to vegetated slopes is being assessed within the ECOSLOPES project.

Conclusions

The presence of vegetation may be sufficient to maintain stability of certain marginally stable slopes. A framework of modelling by limit equilibrium and finite element methods already exists and data are being acquired to help quantify the enhancement that vegetation can provide.

Of the various influences, the physical presence of roots and the tensile reinforcement they can provide appears to be the most significant based on observations to date.

The on–going development of field monitoring and analytical techniques with engineers working alongside the plant specialists, soil scientists and foresters to determine characteristic growth patterns and resulting changes in geotechnical parameters should lead to the necessary guidance on selection and maintenance of the vegetation to assist slope stability.

Future research should address the implications of climate change affecting the long term stability of vegetated slopes. The establishment of a ‘controlled climate’ test bed on a purpose built embankment of known soil properties will provide the necessary facilities for longer term modelling/monitoring of how vegetation on slopes reacts to changes in climatic conditions.

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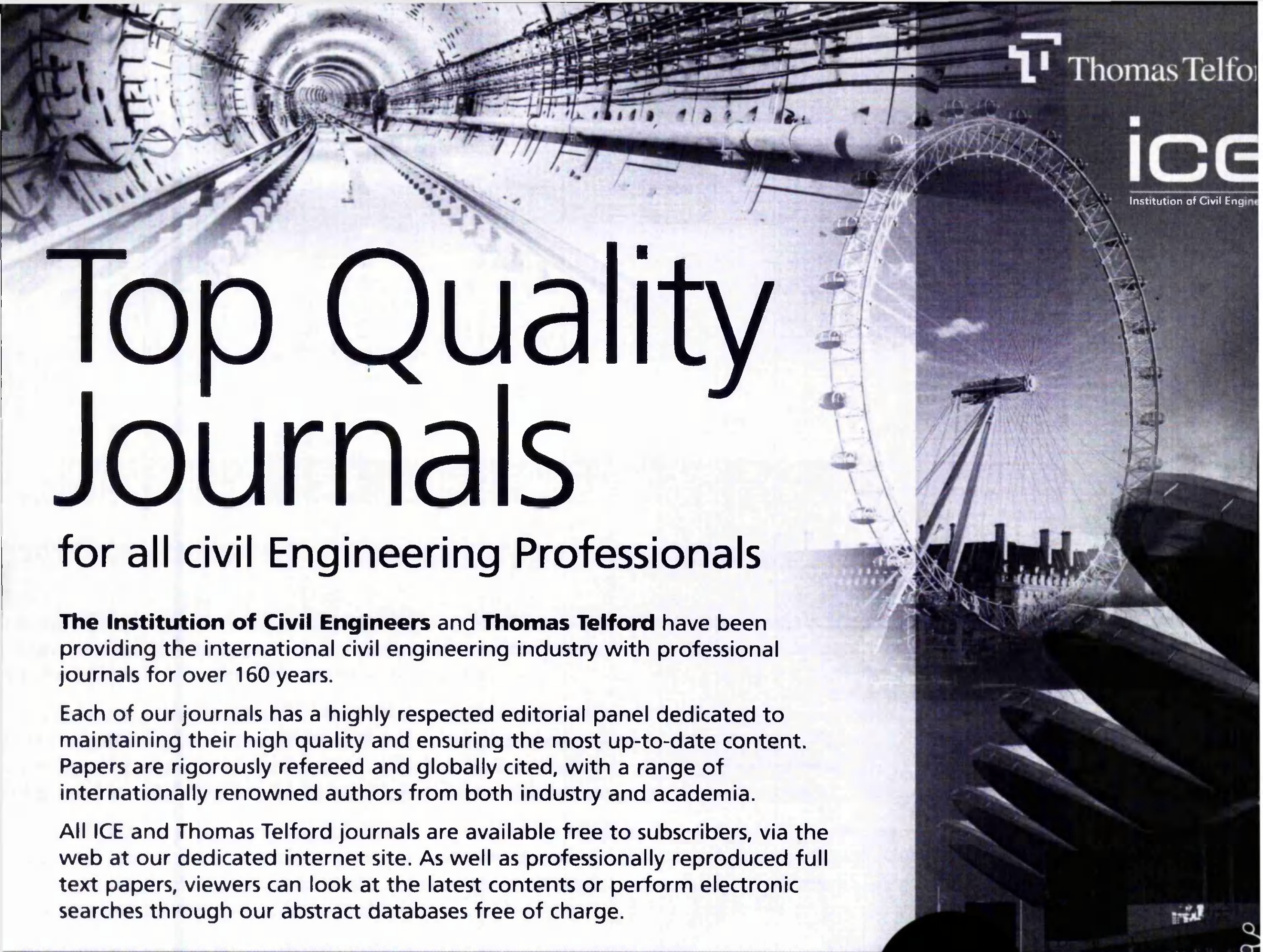

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Assessing the contribution of vegetation to slope stability

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Many embankments and cuttings associated with the transportation infrastructure in the UK are only marginally stable. Engineering techniques such as soil nailing, geosynthetic reinforcement, improved drainage and ground improvement by stabilisation are available to improve stability, but the cost can be high. A lower-cost solution may be to utilise vegetation, either self-seeded or planted. The benefits and drawbacks associated with vegetation have been the subject of some debate. The problems caused by vegetation in relation to building foundations are well documented, and confirm that vegetation can have very significant influences on geotechnical parameters. Appropriate properly maintained vegetation can have the same significant influence to help provide additional stability to soil slopes. This paper considers the potential engineering influences of vegetation and how it can be characterised on site within a geotechnical framework for stability assessments. The direct reinforcement available from the roots of trees and shrubs is identified as providing one of the most significant contributions to slope stability. Case studies in the UK, Greece and Italy demonstrate how results from in-situ root pull-out tests may be used to estimate the potential reinforcement forces available from the roots. A scheme is presented to designate zones of influence within the soil according to the size and nature of the vegetation.

NOTATION

Basic parameters and dimensions used in stability analysis by method of slices

b	width of slice (m)
c'	effective cohesion at base of slice (kN/m^2)
F	factor of safety (usually shear strength/shear force on slip plane) (ratio)
F_f	factor of safety in terms of horizontal force equilibrium (ratio)
F_m	factor of safety in terms of moment equilibrium (ratio)
h	average height of slice (m)
h_w	average piezometric head at base of slice. For hydrostatic $h_w = (h_{w1} + h_{w2})/2$ (m)
h_{w1}	height of free water surface at left-hand side of slice (m)
h_{w2}	height of free water surface at right-hand side of slice (m)
l	length (chord) along base of slice (m)
u	average water pressure on base of slice ($= \gamma_w \times h_w$) (kN/m^2)
U_1	water force on left-hand side of slice (from flow net, seepage calculations or based on h_{w1}) (kN)
U_2	water force on right-hand side of slice (from flow net, seepage calculations or based on h_{w2}) (kN)
W	total weight of soil in slice (for layered soils 1, 2, 3... $W = (\gamma_1 h_1 + \gamma_2 h_2 + \gamma_3 h_3 + \ldots) \times b$) (kN)
α	inclination of base of soil slice to horizontal (may be negative at toe) (degrees)
γ	bulk unit weight of soil in slice (kN/m^3)
γ_w	unit weight of water (usually taken as 10 kN/m^3) (kN/m^3)
ϕ'	effective angle of friction at base of slice (degrees)

Vegetation, reinforcement and hydrological effects

c'_v	additional effective cohesion at base of slice (due to vegetation etc.) (kN/m^2)
δh_w	increase in average piezometric head at base of slice (due to vegetation) (m)
δh_{w1}	increase in height of free water surface at left-hand side of slice (m)
δh_{w2}	increase in height of free water surface at right-hand side of slice (m)
δU_1	increase in water force on left-hand side of slice (kN)
δU_2	increase in water force on right-hand side of slice (kN)
δu_v	increase in average water pressure at base of slice, $= \gamma_w \times \delta h_w$ (kN/m^2)
D_w	windthrow force (downslope) (kN)
F_r	factor of safety applied to ultimate root force to reflect uncertainty in root distributions and assumptions made
T	tensile root or reinforcement force on base of slice (kN)
T_{rd}	available (design) root force per square metre of soil on a particular plane (for example the slip surface) (kN/m^2)
T_{ru}	ultimate root force per square metre of soil (kN/m^2)
W_v	increase in weight of slice due to vegetation (or surcharge) (kN)
β	angle between wind direction and horizontal (often assumed equal to slope angle) (degrees)
θ	angle between direction of T and base of slip surface (degrees)

1. INTRODUCTION

Shallow slope instability is a common problem in embankments and cutting slopes, particularly in the overconsolidated clay soils frequently encountered in the United Kingdom. The excavation and placement processes during earthworks result in a reduction in overburden stresses, and the stiff overconsolidated clays are consequently susceptible to swelling and softening as they gain access to water. Zones of instability form typically at depths of 0·75 to 1·5 m below the slope surface.[1,2] In the more sandy soils, and after placement of topsoil, erosion and washout can be a problem for newly constructed embankment and cutting slopes in the period before low vegetation (grass cover) becomes established.[3]

Vegetation will generally establish itself naturally over time, even on relatively barren soils such as colliery spoil heaps, provided some nutrients and water are available. In the United Kingdom most soil slopes will support an array of vegetation types. Grasses, shrubs and trees will initially self-seed as *pioneer* vegetation and eventually evolve into a consistent pattern of coverage referred to as *climax* vegetation.

Embankment and cutting slopes formed as part of the UK transportation infrastructure are generally seeded with grasses in accordance with the Specification for Highway Works,[4,5] and selected shrubs and trees are planted in accordance with locally agreed landscaping criteria. Although it is recognised that grass, once established, will prevent surface erosion, the vegetation is not intended for any purpose other than landscaping aesthetics.

It is becoming increasingly important, as the need for more eco-friendly solutions arises, for engineers to explore how vegetation might be selected and maintained to help enhance the soil strength and thereby reduce the risk of shallow slope failure.

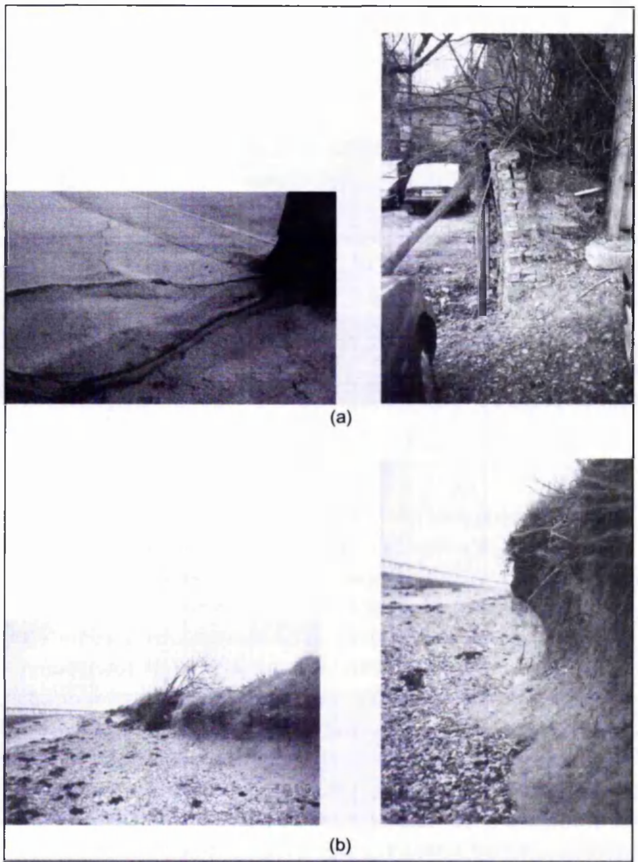

Fig. 1. Detrimental and positive effects of vegetation: (a) damage to pavements and retaining walls due to tree roots at Nottingham Trent University car park; (b) dune grasses stabilising beach sediments, The Wash

When vegetation exists in the 'wrong' locations in relation to engineering constructions, problems are frequently encountered (Fig. 1(a)). Poorly managed vegetation can cause problems due to amassing of fallen leaves and debris, blocking of drainage channels, and the danger of windblown trees during storms affecting the safety of transportation operations. The detrimental effects on foundations located too close to certain trees leading to ground movements of a seasonal and permanent nature have been studied by the Building Research Establishment[6] and others, e.g. Biddle.[7]

Vegetation can often be seen 'holding together' slopes that would otherwise degrade very rapidly (Fig. 1(b)). There is a general awareness and perception by engineers and the public that tree roots bind the soil together to resist ground erosion and movement. References 8 and 9 provide extensive information on the advantages and detrimental aspects of using vegetation for slope stabilisation.

This paper considers the potential engineering influences of vegetation and how it can be characterised on site within a geotechnical framework for slope stability assessments.

2. BACKGROUND

The publication by CIRIA of the book *Use of Vegetation in Civil Engineering*[9] formed a major landmark in introducing the concepts of enhancing soil properties with appropriate vegetation. This was followed up by a CIRIA-sponsored field trial of specific vegetation on the M20 motorway at Longham Wood, near Maidstone, Kent.

The M20 trial set out to assess the relative importance of the influence of grass, shrubs and trees on the geotechnical parameters and stability of a 1 in 3 cutting slope in Gault Clay.[10] The site, at Longham Wood, was monitored for a period of five years, after which it was lost as the new Channel Tunnel Rail link was constructed immediately adjacent to the M20 passing through the trial site. During the final 'destructive' testing of the site, trenches were excavated to provide more detail of the ground and root growth conditions. Apparatus was developed to assess the in-situ shear strength of the root reinforced Gault Clay and to determine the resistance of selected roots to pulling out of the ground.[10, 11] Moisture content changes during the trials were monitored by use of a neutron probe inserted down access tubes at specific locations.[10, 12]

The M20 trial confirmed that

(*a*) willow and alder trees became established over the five-year trial period and developed a substantial root network extending to 1·2 m depth

(*b*) the instrumentation used, particularly that for determining soil-water pressure, detected seasonal changes in the state of the slope and to some extent that produced by the root systems of the vegetation

(*c*) seasonal changes in ground conditions were clearly indicated by the Mackintosh probe testing, but this testing was not sensitive to the smaller changes due to the vegetation

(*d*) the counterfort slope drains had no apparent effect on the vegetation or the soil and groundwater conditions in the upper 1·2 m of the slope

(*e*) of the possible influences of the vegetation, the potential tensile root force appeared to be most effective in increasing the resistance to slope failure.

The report on the trial recommended that further monitoring be carried out on other sites to examine the effects of the vegetation in the medium to long term, and to quantify the strength contribution available from different root systems.[10]

The opportunity for further research was provided by the award of a £1·6 million research grant under the European Community Fifth Framework Programme. This enabled Nottingham Trent University, as a partner in the ECOSLOPES project, to further develop the in-situ shear and root pull-out apparatus, and to link the work done in the UK with related work in other European countries. The project is broad based, with the partners focusing on the many related aspects of vegetation (current website www.ecoslopes.com). The final outcome of the project will be a reference database and a guidance manual with a computer-aided decision support system to help the geotechnical engineer to select, specify and maintain appropriate vegetation to enhance slope stability in the various regions of Europe.[13,14]

3. THE INFLUENCES OF VEGETATION

The main influences of vegetation on the stability of a slope are shown in Fig. 2, developed from Coppin.[9] The parameters relating to the vegetation influences and the notation used for routine stability analysis by the method of slices are listed above. The parameters reflecting the effects of vegetation in stability analysis are: an additional effective cohesion; an increase in weight of slice due to the vegetation; a tensile reinforcement force by the roots present on the base of each slice; wind force; possible changes in undrained soil strength due to moisture removal by the vegetation; and changes in pore water pressure. These parameters are further explained and a description of the method of characterising each parameter within a geotechnical framework is discussed.

3.1. Enhanced cohesion, c'_v

The concept of effective cohesion in soils has received considerable attention, with some researchers advocating that no true cohesion exists in clay soils. However, back-analysis of slope failures has generally indicated an operational effective shear strength, which is conveniently represented by a small cohesion intercept of the order of $c' = 1$ to $2\ \text{kN/m}^2$. The value adopted can have considerable influence on the calculated factor of safety, F.

The role of fine roots in resisting surface erosion is well documented.[15] Fine roots are the major root components in garnering nutrients and moisture from the soil, but their role in more general slope stability is less certain, with perhaps a minor contribution as they help to maintain the integrity of the surface layers and prevent surface erosion. It would be expected that a fine root network would act to provide an apparent enhanced cohesion much in the same way that geosynthetic mesh elements have been demonstrated to enhance the soil strength properties.[16] The use of c' values enhanced by c'_v would therefore be appropriate for grass and shrub areas where fine root distribution with depth is consistent and easily defined.

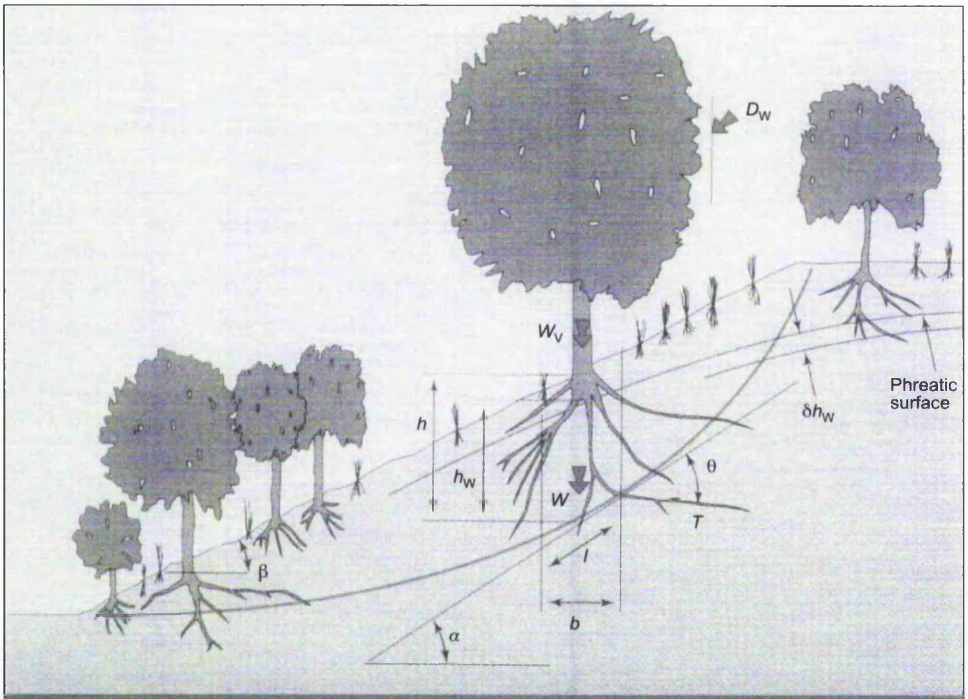

Fig. 2. The influences of vegetation on slope stability[9]

The reliable benefit of an enhanced c' value is limited to shallow depths, as root distribution is concentrated mainly within 1 m of the ground surface. As accurate values of c' are difficult to measure, it is equally difficult to measure the additional contribution, c'_v, due to the vegetation. Values of c' and c'_v are often based on laboratory direct shear tests.[9] At Nottingham Trent University, ongoing development of an in-situ shear apparatus[10,11,17,18] has enabled the additional contribution of the vegetation to be more accurately assessed. A description of the apparatus (Fig. 3) and test procedure is available in Norris and Greenwood.[18] Tests carried out on a motorway cutting in London

Fig. 3. In-situ shear and root pull-out apparatus developed at Nottingham Trent University[18]

Clay soil give an indication of enhanced cohesion, as shown in Fig. 4.

Field shear tests tend to give an indicative undrained strength increase owing to the presence of fine roots, but for clay soils the true effective parameters are probably best obtained by back-analysis or more sophisticated effective stress laboratory testing.

3.2. The mass of vegetation, W_v

The mass of vegetation is likely to have a major influence on slope stability only when larger trees (dbh* of >0·3 m) are present. The loading due to a well-stocked forest of 30–50 m tree height is in the order of 0·5–2 kN/m^2.[9] A 30 m high tree having a dbh of approximately 0·8 m is likely to have a weight of 100–150 kN. Such trees located at the toe of a potential slip could add 10% to the factor of safety.[3,9] Equally, if located at the top of a potential slip the factor of safety could be reduced by 10%. Each situation must be individually assessed for the mass of vegetation involved. It should be borne in mind that plant evapotranspiration will reduce the weight of soil as moisture is lost. This can be important on slopes of marginal stability.

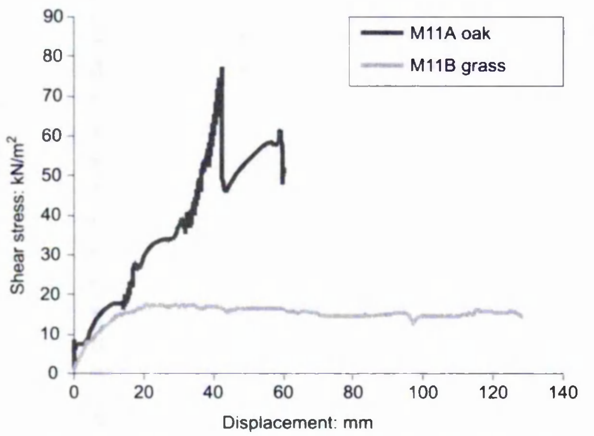

Fig. 4. Shear stress against displacement of two in-situ shear box tests: test 1, M11A, on a root ball of a small oak tree; test 2, M11B, grass roots

When larger trees are removed from the toe area of a slope, in addition to the gradual reduction in soil strength due to the loss of evapotranspiration effects, the reduction in applied loading could result in temporary suctions in clay soils, which may lead to softening as available water is drawn in to satisfy the suction forces. This is of course akin to the recognised softening of overconsolidated clays due to relaxation of overburden pressures when placed in the top layers of an embankment from deep cutting.[2]

The mass of the vegetation may be determined ideally by weighing complete trees where it is practical to do so, estimated from published in-situ densities of wood (Table 1), or from published data sources on typical biomass of trees (e.g. reference 20).

3.3. Wind loading, D_w

Wind loading is particularly relevant when considering the stability of individual trees, but is of lesser significance for general slope stability, where the wind forces involved represent a much smaller proportion of the potential disturbing forces, and trees within a cluster (stand) are sheltered to some extent by those at the edge.

Wind forces on single trees may be estimated from the method developed by Brown,[21] and wind forces on forested slopes may be calculated by Hsi and Nath;[22] both approaches are explained in reference 9.

3.4. Soil strength increase due to moisture removal by roots

There have been various well-documented observations of moisture deficit around trees[7] due to the effects of evapotranspiration and the problems this has caused for buildings.[23] However, reliance on tree and shrub roots to remove water on embankments/cuttings and hence strengthen the soil is not so straightforward.

Observations on the M20 at the Longham Wood trial site indicated large seasonal variation in the moisture content (and hence the undrained soil strength) of the south-facing trial area. Plots with and without vegetation showed similar large seasonal variations. These variations masked and dominated any effects due to the vegetation over the five-year period of the trial.[10]

Tree species	Density at 15% moisture content: Mg/m^3
Beech	0·720
Ash	0·710
Birch	0·670
Sycamore	0·630
Oak	0·720

Table 1. In-situ density of common tree species on the UK's transport infrastructure[19]

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*dbh = standard measurement of trunk diameter taken at breast height (1·3 m). On slopes, dbh is measured from the upslope side of the tree.

During particularly wet periods the ability of the roots to influence the seasonal moisture content will be curtailed, and therefore any enhanced soil strength gained previously by evapotranspiration will be reduced or lost entirely, to an extent difficult to quantify. Hence this effect cannot be taken into account at such critical times. However, it can be assumed that there is a narrowing of the window of risk of failure due to soil saturation by storm events or periods of prolonged rainfall. Furthermore, although moisture content changes influence the undrained shear strength (c_u), the effective stress parameters (c' and ϕ') as generally used in routine stability analysis are not directly influenced by the changing moisture content, although the water pressures (suctions) used in the analysis will change.

It should be borne in mind that desiccation cracks, possibly extended during dry periods by the presence of certain vegetation, will encourage a deeper penetration of water and water pressures into the soil during wet periods. However, these cracks will subsequently be exploited by roots extending deeper into the soil as they follow pathways of least resistance.

The actual influence of the vegetation on moisture content can be monitored by time domain reflectometry (TDR) and theta probe technology. These are non-destructive approaches to collecting moisture content data. TDR is currently being trialled on a vegetated slope at Newbury, Berkshire.[24]

3.5. Suctions and changes in pore water pressure due to vegetation (u_v)

As discussed in the previous section, the moisture content and soil-water pressures are related. On the M20, seasonal fluctuations in the water table, as measured by standpipes, were not significantly modified by the effects of the newly established vegetation. Tensiometers installed on the M20 project[12] and on other slopes have proved much more worthwhile in recording the detailed response of the ground suctions to rainfall events and periods of wet or dry weather. Seasonal pore water pressures and moisture changes are currently being monitored on a lightly vegetated (grass/shrub cover) slope at Newbury, Berkshire.[24]

3.6. Tensile root strength contribution, T

The tensile strengths of roots of various diameters from different species have been measured in the laboratory and found to be typically in the order of 5–60 MN/m^2 (Table 2).[9] In the field, to make use of the available tensile strength to enhance slope stability the root must have sufficient embedment and adhesion with the soil. The biological growth patterns and interaction between the root and soil are complex, but for engineering purposes the available force contribution from the roots may be measured by in-situ pull-out tests. Measurement of the root resistance to pull-out has been carried out by various methods, ranging from hand pull to screw and hydraulic jacks.[18, 27] The pull-out method depends very much on the size of root and the type of equipment and reaction frame available. A constant rate of strain is required, typically 1%/min, and a means of measuring the resistance by spring balance or load cell at defined displacements. Procedures for the root pull-out test are given in reference 18.

Design of the clamp to grip the root requires particular attention. Many species of root, particularly when fresh, demonstrate a tendency for the bark to separate and slide over the core wood during tensile testing. It is therefore often necessary to strip the bark at the clamp and to grip directly on to the core wood. In some cases, slipping of the clamp may be overcome by wrapping a piece of sandpaper around the root to improve grip. The tensile strength is then calculated based on the diameter of the core wood assuming that the bark is making little contribution to the strength of the root. However, it is the bark that is in contact with the soil and generating the adhesion resistance, so the full root diameter must be considered in the pull-out assessment.

Analysis of the pull-out testing on the M11 motorway site has revealed different types of root failure, depending on root morphology and branching.[18] Roots that have no branches tend to fail in tension and pull straight out of the ground with minimal resistance. Roots that have multiple branches fail in stages as each branch breaks within the soil. These types of roots can be divided into two categories: those that break with increasing applied force, and those that initially reach their maximum peak force and then maintain a high force that gradually reduces as the root branches fail after considerable strain. In some tests significant adhesion between a section of the root and the soil can be measured before the root finally slips out of the soil mass. Fig. 5 shows schematic examples of the types of

Common name	Latin name	Tensile strength:* MN/m^2	Pull-out resistance:† MN/m^2	Reference
Common alder	*Alnus glutinosa*		7	10
Alder	*Alnus incana*	32		9
Birch	*Betula pendula*	37		9
Broom	*Cytisus scoparius*	32		9
Elderberry	*Sambucus nigra*		0·1–2	25
Hawthorn	*Crataegus monogyna*	16–159		unpublished data
		0·6–21		unpublished data
			2–25	unpublished data
		7–90		29
Black Poplar	*Populus nigra*	5–12		9
Hybrid Poplar	*Populus euramericana*	32–46		9
Oak	*Quercus robur*	32		9
Sycamore maple	*Acer pseudoplatanus*		2	26
Willow	*Salix purpurea*	36		9
Sallow	*Salix cinerea*	11		9

*Tensile strength for live roots as tested in the laboratory.
†Pull-out resistance as measured from in-situ tests.

Table 2. Tensile strength and pull-out resistance of vegetation found on the UK's transport infrastructure

failure observed during root pull-out tests of hawthorn roots.

The maximum breaking force or pull-out resistance of the roots together with an assessment of the root size and distribution (root area ratio) is used to determine the appropriate root reinforcement values for inclusion in the stability analysis (further described below).

4. STABILITY ANALYSIS TO INCLUDE THE INFLUENCES OF VEGETATION

The influences of vegetation on the factor of safety of a slope are conveniently assessed by routine limit equilibrium stability analysis by the method of slices. Various methods of stability analysis are available. The Greenwood general equation[28, 29] is considered appropriate because it takes full account of hydrological (seepage) forces to give a realistic estimate of the factor of safety for all types of slope and slip surface:

$$F = \frac{\sum\{c'l + [W\cos\alpha - ul - (U_2 - U_1)\sin\alpha]\tan\phi'\}}{\sum W\sin\alpha} \tag{1}$$

The interslice water forces, U_1 and U_2, may be calculated based on assumed hydrostatic conditions below the phreatic surface, or derived from a flow net for more complex hydraulic situations. It should be noted that if the interslice forces U_1 and U_2 are equal the equation becomes

$$F = \frac{\sum[c'l + (W\cos\alpha - ul)\tan\phi']}{\sum W\sin\alpha} \tag{2}$$

This is the well-known Swedish (Fellenius) equation, which is appropriate to use for a planar, slab slide on a continuous slope with seepage parallel to the slope. However, the user should be cautious, as in practice the parallel seepage is often interrupted by less permeable layers, resulting in a local reduction in the factor of safety. The actual hydraulic conditions are therefore more correctly modelled using the general equation (1).[29]

The mathematically 'simple' form of the Greenwood general equation and the factor of safety defined in terms of restoring and disturbing forces allow straightforward inclusion of the various vegetation influences:

$$F = \frac{\begin{array}{l}\sum[(c' + c'_{\mathrm{v}})l + \{(W + W_{\mathrm{v}})\cos\alpha - (u + \Delta u_{\mathrm{v}})l \\ -[(U_2 + \Delta U_{2\mathrm{v}}) - (U_1 + \Delta U_{1\mathrm{v}})]\sin\alpha \\ -D_{\mathrm{w}}\sin(\alpha - \beta) + T\sin\theta\}\tan\phi']\end{array}}{\sum[(W + W_{\mathrm{v}})\sin\alpha + D_{\mathrm{w}}\cos(\alpha - \beta) - T\cos\theta]} \tag{3}$$

Note that in equation (3) the tangential component of the root reinforcement force, $T\cos\theta$, is correctly deducted from the denominator as it is a negative disturbing force. In practice the term is often assumed to be a positive restoring force and is added to the numerator. The differences in the calculated factor of safety by either approach are small, with identical values calculated when $F = 1$.

While the factor of safety in equation (3) is expressed as a traditional ratio of restoring to disturbing forces, the equation may be readily adapted to the inclusion of partial factors on each individual term in accordance with recommendations of more recent British Standards and European codes of practice.

An Excel spreadsheet, SLIP4EX, has been developed by the authors to compare the various routine methods of analysis for a given slip surface and to quantify the changes to the factor of safety due to the influences of the vegetation. A version, SLIP5EX, incorporating graphics and search routines for critical slip surfaces is being developed in association with the University of Amsterdam.

4.1. Zones of influence of vegetation

The changed soil parameters due to the influence of the vegetation may be assessed by considering typical distributions of roots below a vegetated area. If the vegetation coverage is consistent over the area, enhanced parameter zones may be represented as zones parallel to the slope (Fig. 6). For isolated larger trees and shrubs a distribution such as that shown in Fig. 7 might be considered as being typical of the saucer-shaped root network frequently observed. The suggested approximations of zones of root influence need to be assessed for individual species in particular soil and growing conditions.

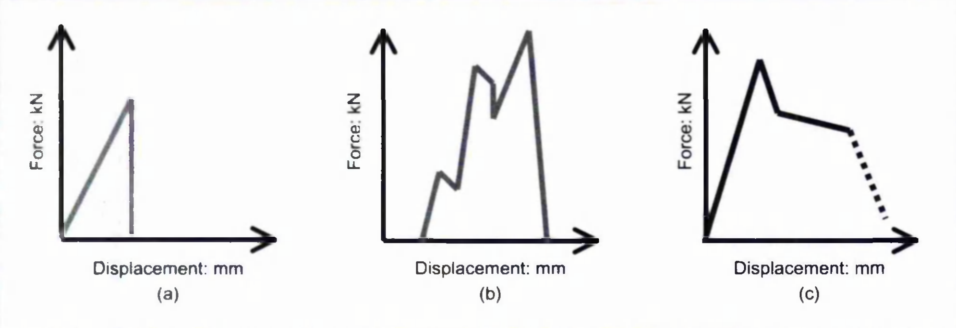

Fig. 5. Interaction of roots and soil during pull-out tests:[18] (a) single root with minimal root–soil interaction; (b) multi-branched root with some root–soil interaction; (c) full root–soil interaction

4.2 Estimation of available root reinforcement force

Observation and measurement in the field have indicated that the direct reinforcement forces available due to the presence of the roots are likely to be the main contribution of the vegetation to slope stability.[9, 10]

In order to estimate the value of *T*, the available root force

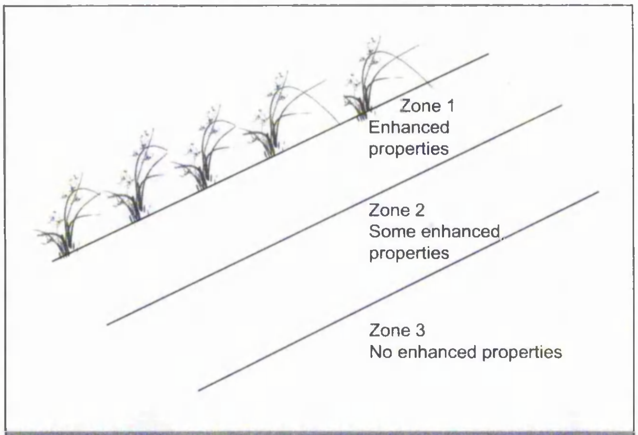

Fig. 6. Zones of enhanced soil properties for regular vegetation cover[30]

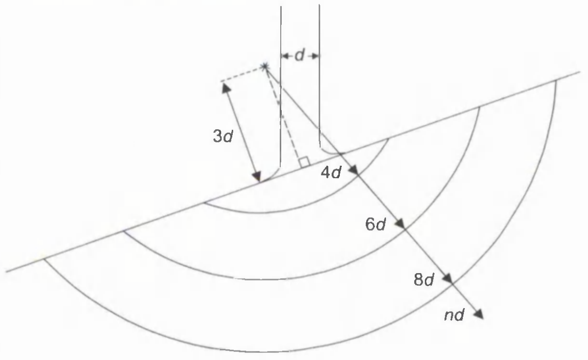

Fig. 7. Saucer-shaped zones of enhanced parameters beneath a single tree; d = diameter at breast height (dbh)

acting on the base of the slice of the analysis, for inclusion in the stability equation (3), the size and distribution, strength and pull-out resistance of the roots must be considered, together with an appropriate partial factor of safety to reflect the uncertainty in the assumptions made.

It is convenient to introduce the term T_{ru}, the ultimate root force per square metre across a given plane (for example the slip surface) within a particular soil zone. T_{ru} may be estimated based on the observed or assumed root distribution and determination of characteristic resisting forces for the roots of varying diameter by root pull-out and tensile strength testing. Values of T_{ru} may be assigned for particular root zones as illustrated in Figs 6 and 7.

The natural evolution of vegetation roots is such that they are generally just sufficient to serve their purpose of maintaining stability against gravitational and wind forces. It is observed that the pull-out resistance of a root is likely to be only slightly less than the measured tensile strength of the root. In the absence of specific pull-out data, the tensile strength of the root is therefore likely to be a reasonable indicator of the maximum pull-out resistance available.

T_{ru} may therefore be estimated based on the measured pull-out strengths or estimated as a proportion of the measured or assumed tensile strength of the roots crossing the soil plane.

$$T_{ru} = \text{assigned ultimate root resistance (strength)} \times \text{root area per square metre of soil} \tag{4}$$

The available (design) root force on that plane, T_{rd} per square metre of soil, is then derived by application of a suitable partial factor of safety, F_r:

$$T_{rd} = \frac{T_{ru}}{F_r} \tag{5}$$

There is much uncertainty about the root distribution in the ground and the resisting forces that are available for a particular slip surface geometry and soil conditions. For this reason a high value of F_r is recommended. Values of F_r of around 8 or 10 are currently used to reflect the uncertainties and to allow for the large strains, typically in the order of 20%, necessary to generate the ultimate root resistance to pull-out. It may be possible to reduce the factors of safety as the root zones around the vegetation are better characterised on a seasonal basis and more root pull-out information becomes available.

The force T applicable to a slice of the stability analysis is given by

$$T = T_{rd}\, l \tag{6}$$

where l is the length of slip surface affected by the roots (assuming unit width of slope).

The angle θ between the root direction and the slip surface is typically assumed to be 45°. The calculated factor of safety for the slope is not generally sensitive to the value of θ selected as the terms $T\cos\theta$ and $T\sin\theta\tan\phi'$ in the stability equation (3) tend to compensate for each other as θ changes. The assumption $\theta = 45°$ is conservative because, as shearing occurs and the roots distort, the value of θ is likely to decrease, thereby slightly increasing the available root resisting forces on the slip surface.

4.3 Examples of the influence of vegetation

The following examples illustrate the application of this approach to cases studied.

4.3.1. M20 trial: Longham Wood. On the M20 site it was observed that the willow roots extended down to 1·2 m or more. At 1 m depth (the typical depth of a shallow slope failure in overconsolidated clay), there may be say four roots of 12·5 mm diameter crossing each square metre of the potential slip plane and acting in a direction likely to be beneficial to resisting downslope movement. The ultimate tensile 'pull-out' strength of the roots measured by tests in the field was typically 8 MN/m^2 (based on the diameter at the clamp). By substituting these values into equations (4) and (5) and assuming $F_r = 8$, T_{rd} is approximately equal to 0·5 kN per square metre of slip surface. Assuming, for simplicity, a continuous 1 in 3 slope, and soil parameters $c' = 1{\cdot}5\ \mathrm{kN/m^2}$ and $\phi' = 23°$, the calculated factor of safety using equation (3) would increase from 0·90 without roots to 0·99 due to the effects of roots at 1 m depth (assuming $T_{rd} = 0{\cdot}5\ \mathrm{kN/m^2}$ and $\theta = 45°$). This represents a significant 10% increase in the factor of safety. This calculation is indicative of the benefits of root reinforcement. Closer to the ground surface, say 0·5 m depth, the value of T_{rd} may increase to 1 kN and equally at lower levels, below 1·5 m, reduce to 0.[11]

4.3.2. 'ECOSLOPES' Greece and Italy examples. An estimate of the contribution the roots might make to the safety of the slope is given in Table 3 for two case studies of a weathered metamorphic/sedimentary soil slope in Greece and a slope consisting of Tertiary marls, Molise sequence, in Italy.[31] Again, it is assumed that a limited number of roots cross the potential slip plane at a given depth; a partial factor of safety of 8 is applied to the root strength and θ is assumed to be 45°. The soil parameters and slope angles for each site are included in Table 3. The ultimate root strength and root diameters are based on root pull-out resistance results described in reference 31. It was assumed that roots are present at the depth of the slip surface with adequate bond length to generate the tensile strength. From Table 3, it can be seen that with the assumed presence of roots a significant increase (>10%) in the factor of safety can be achieved.

Case study	Slope angle, α: degrees	Soil parameters			Depth of slip surface: m	Assumed water table (depth)	Typical ultimate root strength: $\mathrm{MN/m^2}$	Assumed available root strength = ult/8: $\mathrm{MN/m^2}$	Typical root dia: mm	Typical no. roots per $\mathrm{m^2}$	T_{rd}: $\mathrm{kN/m^2}$	F (no roots)	F (with roots)
		c': $\mathrm{kN/m^2}$	ϕ': degrees	γ: $\mathrm{kN/m^3}$									
1A: N. Greece	20	0	35	18	0·5	Surface	12	12/8	8	6	0·45	0·71	0·89
1B: N. Greece	20	0	35	18	0·5	Dry	12	12/8	8	6	0·45	1·92	2·25
2: Central Italy	27	2·6	25	18	1·0	0·5 m	10	10/8	12	4	0·57	0·95	1·04

Table 3. Possible effects of the presence of roots on the factor of safety for two case studies in Greece and Italy[31]

5. CONCLUSIONS

A framework has been established for assessing the contribution of vegetation to slope stability. Methods are available to consider the likely influences of vegetation including its mass, effects on the groundwater regime, enhanced cohesion due to fine roots, wind forces and the anchoring effects of the larger roots. Of these influences the tensile anchoring contribution of the larger roots is considered to be the most positive and reliable factor. Techniques for measuring root tensile forces have been discussed.

Incorporation of the available root forces into routine stability analysis has been demonstrated. At this stage relatively high partial factors of safety (say $F_r = 8$ or more) are recommended when determining the available root force from the measured values of the ultimate root pull-out resistance. This allows for uncertainties and variability in the assumed or observed root distribution with depth and the availability of adequate root/soil adhesion throughout the seasons of the year. It also recognises that large strains are typically needed to generate the ultimate root pull-out forces.

Further work is required to improve the understanding of the soil–root interaction and potential for further development and control of vegetation and its root systems to help assist slope stability. It is important that appropriate vegetation maintenance programmes be defined to accompany planting proposals. The engineer must be realistic in the expectations of what can be achieved from a natural, growing product subject to the vagaries of nature.

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Root reinforcement by hawthorn and oak roots on a highway cut-slope in Southern England

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Key words: Pull-out resistance, root morphology, root tensile strength, soil reinforcement, soil–root interaction

Abstract

Highway embankments and cutting slopes in the United Kingdom, particularly in the South East of England, are often constructed of or within stiff over-consolidated clays. These clays are prone to softening with time leading to shallow slope failures and costly repairs. Reinforcement by natural vegetation is potentially a cost-effective method of stabilising these types of slopes over the medium–long term. However, there is a lack of information on how natural vegetation reinforces and stabilises clay slopes. To investigate this problem, the potential reinforcement of selected oak (*Quercus robur* L.) and hawthorn (*Crataegus monogyna* Jacq.) roots was assessed by conducting *in situ* root pull-out experiments on a London Clay cutting in south-east England. Pull-out tests were carried out using specifically designed clamps and either a hand pull system with a spring balance and manual recording of force for oak roots or a jacking system with electronic data logging of applied force and displacement for hawthorn roots. Oak roots had a mean pull-out resistance of 7 MPa and that of hawthorn roots was 8 MPa. The electronic data logging of applied force (pull-out resistance) and displacement of the hawthorn roots provided additional data on the failure of branched roots which could be correlated with variations in root morphology. The failure of the roots can be categorised into three modes: Type A: single root failure with rapid rise in pull-out resistance until failure occurs; Type B: double peak failure of a forked or branched root and Type C: stepped failure with multiple branches failing successively. The different types of root–soil bonds are described in relation to root anchorage and soil stability.

Introduction

Many of the highway embankments and cutting slopes in the United Kingdom, particularly in the South East of England, are constructed of or within stiff over-consolidated clays which are prone to softening with time leading to shallow slope failures at depths of 1–1.5 m (Greenwood et al., 1985; Perry et al., 2003a, b). These slopes are usually seeded with grasses or planted with selected shrubs and trees in accordance with locally agreed landscaping criteria and the Highways Agency advice notes (Highways Agency, 2003, 2004). Over time, these slopes become self seeded and natural regeneration starts to take place. It is the mid-long term stability of these slopes that is critical but very little knowledge exists on how this combination of seeded grass, planted shrubs and natural vegetation are contributing to the stabilisation of these over-consolidated clay slopes.

The potential benefits of using vegetation for highway slope reinforcement (bioengineering) has been considered in recent years (e.g., Barker et al., 2004; Coppin and Richards, 1990; Gray

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and Sotir, 1996; Greenwood et al., 2001; MacNeil et al., 2001). However, the quantification of *in situ* root reinforcement involves a detailed appreciation of root growth, development and decay with time, the roots' interaction with the soil and the seasonal effects on the geotechnical parameters which are relevant to slope stability.

In situ root strength can be determined by conducting *in situ* root–soil tests. *In situ* root–soil strength can be obtained by carrying out *in situ* shear box tests (Endo and Tsuruta, 1969; Norris and Greenwood, 2003a, b; O'Loughlin, 1981; Van Beek et al., 2005; Waldron and Dakessian, 1981; Wu et al., 1988), whereas *in situ* root strength can be determined by *in situ* root pull-out tests (e.g., Operstein and Frydman, 2000). The tensile strength or root pull-out strength is valuable information when assessing the stability of a slope and can be included in limit equilibrium stability analysis (Barneschi and Preti, 2005; Greenwood, 2005; Greenwood et al., 2004).

Assessing the pull-out resistance for quantification of root reinforcement and for slope stability analysis has received little attention, whereas the pull-out resistance of roots or whole plants for resistance to lodging by the wind (Bailey et al., 2002; Ennos, 1990, 2000; Ennos et al., 1993; Goodman et al., 2001), disease (Kevern and Hallauer, 1983), forest stand stability during severe gales and storms (Achim et al., 2003; Nicoll and Ray, 1996) and slope stability following clear-felling (Watson, 2000; Ziemer, 1981) is much more widely accepted. The uprooting resistance of trees by wind has been investigated through wind tunnel experiments on young trees (Stokes et al., 1995) and tree winching experiments (Cucchi et al., 2004; Stokes, 1999).

The pull-out resistance of simulated roots and their branching systems using wire models and computer-generated root systems by numerical models was attempted by Stokes et al. (1996) and Dupuy et al. (2004), respectively. Numerical models determined that the number of root branches and the diameter of roots were major components in affecting uprooting resistance.

A number of authors have carried out uprooting resistance tests on either plants or roots, but there are very few descriptions of the apparatus used to do this (Anderson et al., 1989; Denis et al., 2000; Norris and Greenwood, 2003b; Operstein and Frydman, 2000). The designs of the apparatus are based on a simple clamp, jack or pulley system to extract the ro the ability to record resistance to pull-out extraction force and displacement.

For the current study, the root reinforcem of natural vegetation growing on a highway slope in south-east England on the M11 mo way was investigated. A bio-geotechnical investigation was carried out to determine ground conditions and characteristics of the etation. From the wide variety of natur regenerated vegetation present, two common species were selected to investigate the interac of roots and soil. Selection of the tree spe was restricted by site accessibility, species ab dance and time to excavate the soil from the r system. The hawthorn (*Crataegus monog* Jacq.) was selected for its abundance on the and commonality on the UK's transportat infrastructure. This species also grows in a w range of soil and climate conditions and is to ant of all but the poorest acid soils. Hawthor a hardy and long lived tree (Flora for fa 2002). The oak (*Quercus robur* L.) was selec for its longevity. Both species chosen were tes for their potential suitablility to provide soil r forcement on over-consolidated clay slopes.

Materials and methods

Study area

The study area is situated on a road cutting o southbound slip road of the M11 motor between junctions 4 and 5, near Chigwell, Lou ton, Essex, UK (coordinates Lat: 51°37′45″ (51.6292°), Long: 0°04′ 14″ E (0.0704°)). The st area is a northwest facing slope having an ove slope angle of 20° and a height of 15 m. The c of the cutting is at 40 m above sea level. The g ogy of the cutting is predominantly London C with a thin cover of superficial deposits (Boyn Gravel and Boulder Clay) (BGS Sheet 257).

The soil profile consists of a surface top layer of a brown sandy clay with occasional to medium flint gravel and a varying abunda of roots and rootlets. It varies in thickn between 0.15 and 0.25 m. A weathered soft-f brown–grey mottled fissured (London) clay w occasional orange–brown silt partings and so roots lay beneath the topsoil layer.

The cut-slope contains a wide variety of plants, from grasses to shrubs and mature trees. Tree species present are silver birch, oak, hawthorn and pine. It was observed that natural regeneration of the vegetation was taking place as young oak trees (approximately 5 years old) were present. There seemed to be a marked change in vegetation type approximately half way up the cutting with predominantly grass, shrubs and young trees towards the lower half of the slope and the upper half of the slope consisting of mature trees. The marked difference in vegetation is probably due to reprofiling of the lower part of the slope during construction of the access road and motorway (A. Kidd, pers comm). The original motorway was constructed in 1976.

Root pull-out tests

Four hawthorn (*Crataegus monogyna* Jacq.) trees and one oak (*Quercus robur* L.) sapling were selected for root pull-out resistance tests. Mean characteristics of each species are given in Table 1. The oak sapling and two of the hawthorn trees were tested in September 2002 and the other two hawthorn trees were tested in the Spring of the following year (May 2003).

Soil from around the base of the trunk of each tree was carefully excavated by hand trowel to a distance of 0.3 m from the trunk. Soil was removed until the main lateral roots could be clearly seen. Each main lateral root was labelled using an alphabetical labelling system and their diameters, dips and orientations recorded. Photographs and sketch drawings were taken of each root system. The tree was carefully removed in sections, so that only the stump remained. Each root was successively cut from the stump to allow the stump to be removed. The above-ground mass (biomass) of each tree was recorded.

The labelled roots were clamped and pulled out of the ground in turn. Surface roots were pulled first to cause minimal soil disturbance to roots penetrating deeper into the ground. The manual and mechanical apparatus used to pull-out the roots was designed by Nottingham Trent University (Norris and Greenwood, 2003b). The mechanical apparatus automatically recorded measurements of applied load and displacement using a 20 kN load cell and draw-wire transducer connected to a datalogger. A constant

Table 1. Plant, root and soil characteristics of the hawthorn and oak trees

Tree	Ref No.	Slope angle (°)	dbh[a] (mm)	Height (m)	Biomass (kg)	Approximate age (years)	Mean soil shear strength (kPa)	Mean root diameter (at clamp) (mm)	Mean root length (m)
Oak[b]	MO1	18	5	1.45	–	8	47	5.4 ± 2.8	0.36 ± 0.08
Hawthorn[c]	H1/H2/ H3/H5	17.8 ± 0.4	84.8 ± 19.8	5.17 ± 2.6	32.8 ± 15.7	80	73 ± 17.3	21.6 ± 12.5	1.29 ± 1.49
Hawthorn[d]	HRA	14	113	6	95.5	80	61 ± 11.7	–	–

[a] dbh taken at 1.3 m above-ground level.
[b] only one tree tested.
[c] mean data of hawthorn trees tested for root pull-out resistance.
[d] characteristics of the hawthorn tree excavated for root morphology observations.

strain of 2 mm/s was applied. The hand-pull apparatus had manual recording of load and displacement using a spring balance and tape measure. The nature of the failure was recorded in both cases.

Curves of 'applied pull-out force' against 'displacement' were plotted for each root. The maximum applied force (pull-out resistance) did not necessarily correspond to the point when the root failed (broke).

Each root was sketched and/or photographed and a description of the roots sinuosity or straightness, tapering and number of branches recorded. The length of the root was determined by using a tape measure or ruler to the nearest millimetre. Root diameters at the clamp, all break points and/or root tips were measured using vernier callipers to an accuracy of 0.02 mm. Root diameter was measured by taking the average of the maximum and minimum diameter readings. The mass of the root was recorded and a portion of the root was used to determine the root moisture content by oven-drying at 80 °C for 24 h. Soil shear strength (or stiffness) was also determined as soon as possible after the tests by using a hand held shear vane (Clayton et al., 1995).

Plots were used to analyse the relationships between the maximum force (resistance) taken by the root, the failure stress and root parameters (diameter measured at the clamp, root length and number of branches). The failure stress was calculated based on the maximum applied force divided by the root diameter at the clamp (values are given as mean ± standard deviation). Regression analysis was carried out on the resultant plots. Root orientation was analysed using GeoOrient v 9.2 (Stereographic Projections and Rose Diagram Plots) software available on the web at http://www.earth.uq.edu.au/~rodh/software. Circular statistics (Fisher, 1993; Mardia and Jupp, 1999) were applied to the data to obtain the mean root growth direction.

Results

Pull-out resistance of hawthorn and oak roots

A total of 42 roots were tested using the mechanical pull-out apparatus from the four hawthorn trees, three tests were unsuccessful as the roots were too strong for the apparatus (force to p out exceeded the 20 kN load cell). Ten oak rc were pulled out by hand.

The maximum pull-out resistance for h thorn roots with diameters 7.1–61.8 mm (m 21.6 ± 12.5 mm) varied between 0.3 and 12 (mean 2.88 ± 2.6 kN) (Figure 1a) whereas oak roots had maximum pull-out resistar between 0.03 and 0.44 kN (mean 0.15 ± 0.14 for root diameters between 1.7 and 9.3 mm (m 5.4 ± 2.8 mm) (Figure 1b). A positive correlat exists between maximum root pull-out resista and root diameter for hawthorn and oak rc (Figure 1). Small root diameters have low pull- resistance and/or breaking force whereas lar diameter roots have a high resistance to pull- and/or high breaking forces. No signific

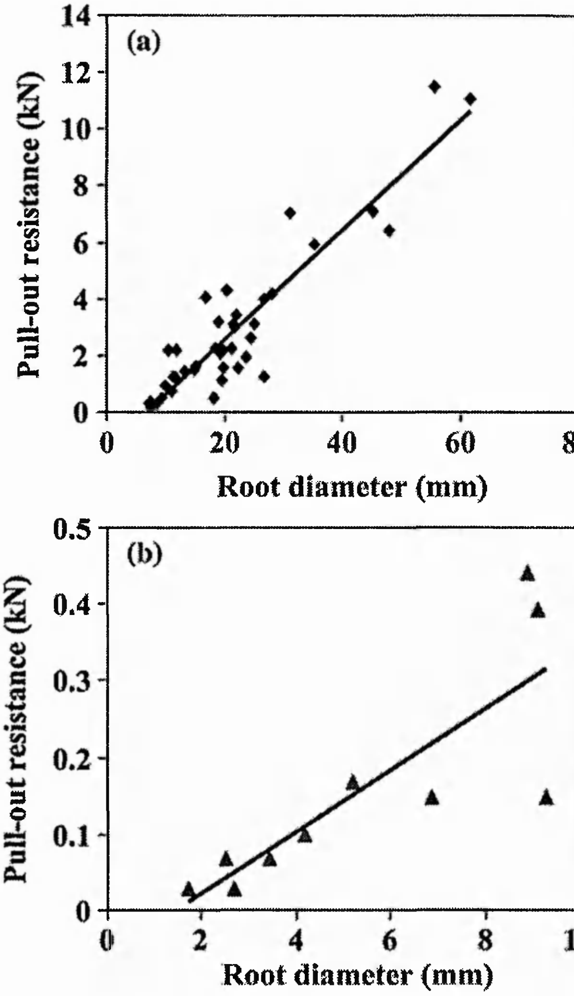


Figure 1. Root pull-out resistance was significantly correl with root diameter in (a) hawthorn ($y = 0.1929x{-}1.2$ $R^2 = 0.835$, $P = 0$) and (b) oak ($y = 0.0401x{-}0.0$ $R^2 = 0.666$, $P = 0.002$).

relationship existed between root breaking force and (recovered) root length for either hawthorn or oak roots.

About 70% of hawthorn roots broke in a tensile failure along their length, 8% pulled completely out of the ground with 22% exhibiting a combined tensile slippage failure pattern, whereby the roots reached a maximum peak load and partially failed but adhesion with the soil provided a residual resistance (Greenwood et al., 2004). The oak roots, had an 80% combined tensile and slippage failure pattern, 10% tensile failure and 10% pulled completely out of the ground.

Root pull-out failure stress

The failure stress of the hawthorn roots, based on the diameter at the clamp, ranged from approximately 5 MPa at 60 mm diameter to typically 3–15 MPa at diameters less than 30 mm (Figure 2), mean failure stress was 8.1 ± 4.6 MPa. Oak roots had failure stresses between 2 and 14 MPa, with a mean of 7.4 ± 3.5 MPa (Figure 2). When failure stress was correlated with number of branches a non-significant relationship existed.

Root morphology and orientation

The hawthorn and oak both show an asymmetric root growth pattern (Figure 3). The hawthorn had a mean root growth direction of 299° ± 2.2° whereas the oak was 124° ± 1.7°. The most frequent number of roots occur laterally across the slope in hawthorn (Figure 3a) whereas the oak shows a greater number of roots occurring in the upslope direction (Figure 3b).

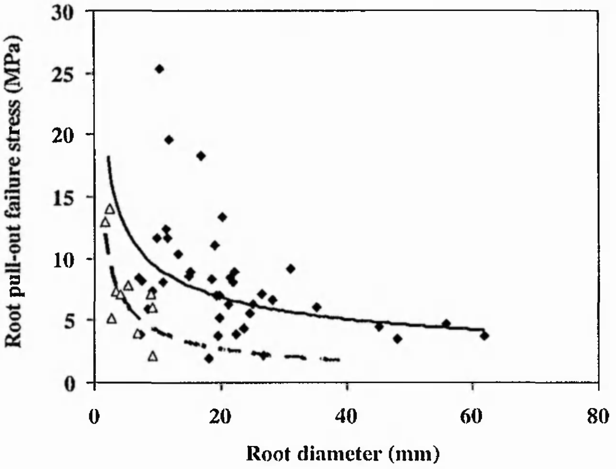


Figure 2. Root pull-out failure stress was significantly correlated with root diameter for hawthorn (solid diamonds, solid line $y = 24.919x{-}0.4322$, $R^2 = 0.188$, $P = 0.004$) and oak (open triangles, dotted line $y = 16.585x{-}0.6088$, $R^2 = 0.464$, $P = 0.018$).

Morphology of the pulled hawthorn roots

The majority of the hawthorn roots pulled out of the ground were either short or long thick straight roots, many forking into two or more branches near the top of the root. Some of the long roots showed marked curvatures to their form. The thinner roots were sinuous in nature. Roots were ellipsoidal in cross section and showed a gradual taper along their length. The outer cortex of the roots was a reddish-brown colour, the thicker roots had prominent ridges at regular intervals along the length of the root.

During root pull-out there was no separation of the cortex (bark) and stele (inner root core) and the root generally remained intact except, where lateral and forked branches had broken or snapped through tensile failure. The clay soil was observed to be smeared along many of the roots.

Hawthorn root morphology as observed from excavating the root system of one tree

To appreciate the nature of the roots in the ground and how they were resisting pull-out, a further hawthorn tree was excavated using an airspade to a distance of 1.5 m from the centre of the trunk. This hawthorn tree had a shallow rooting depth of 0.5 m below-ground level, and had other characteristics similar to the four hawthorn trees used for root pull-out tests (HRA in Table 1). The root plate showed no obvious tap-root directly below the trunk, but had many lateral roots which radiated from the base of the trunk. Roots were ellipsoidal in cross section and tapered gradually. Some lateral roots divided into multiple branches along their length.

Morphology of the pulled oak roots

The majority of the oak roots pulled out of the ground were long straight roots with many short

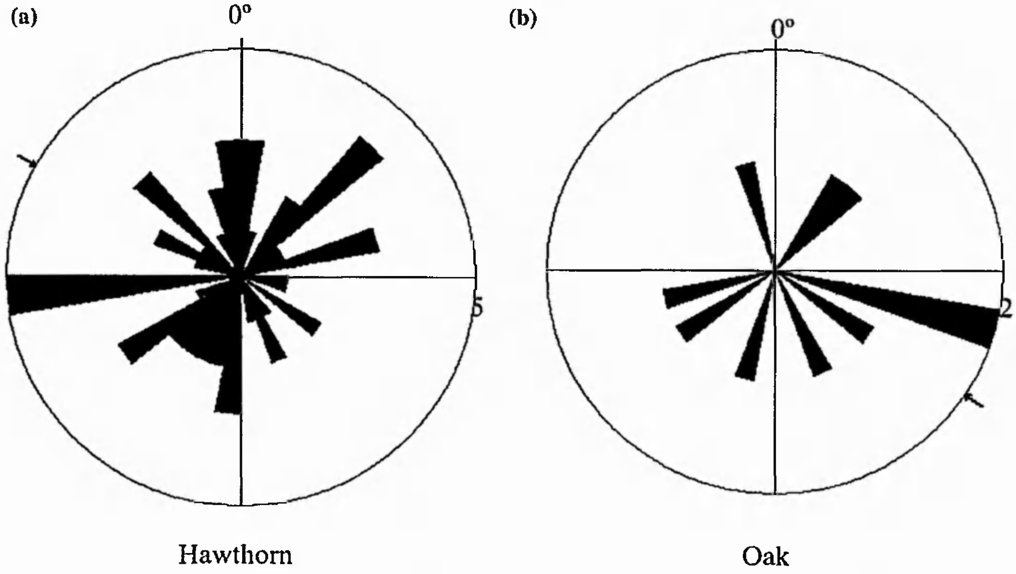


Figure 3. Root growth direction of (a) hawthorn (mean direction = 299° ± 2.2°) and (b) oak (mean direction = 124° ± 1. The length of each sector is equivalent to the number of roots occuring in that sector (e.g., 3 roots fall in the sector 1–10° in (Each sector angle is 10°. The arrow represents mean root growth direction. Upslope direction of the cut-slope is 150°.

rootlets along their length. Some roots forked into two or more branches near the root tips, others were multiple branches. Some showed right angle bends where they had obviously had to grow around an obstruction. All roots showed a gradual taper along their length.

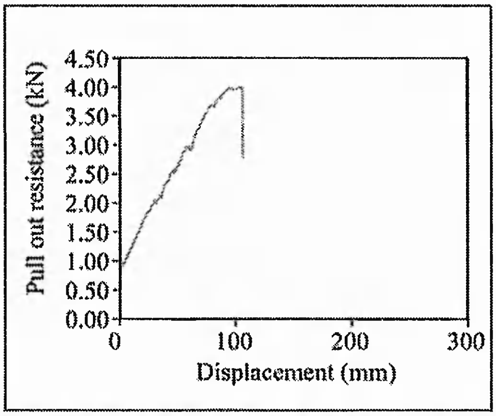
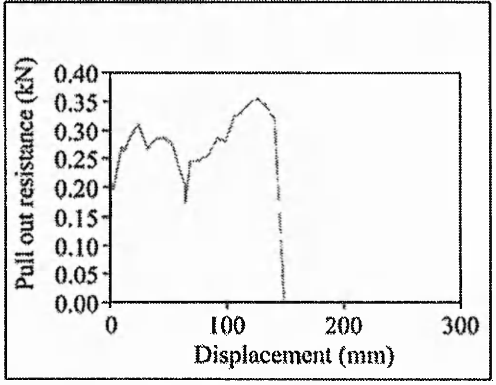
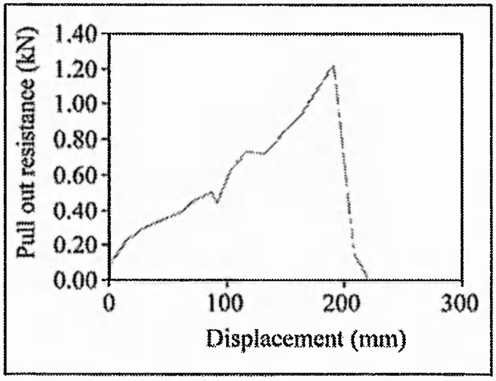
Many of the oak roots lost the cortex during pull-out, indicating a greater adhesion between the bark and the soil than between the bark and the stele.

Excavation of a comparable oak tree for root morphology observations was not possible, therefore the actual depth of the oak root system was not established. However, Lyford (1980) showed from investigating the root system of Red Oak (*Quercus rubra* L.) that saplings have a tap root system and if soils are well drained and friable the root system may reach a depth of 0.7 m between 3 and 5 years old. In the stiff clay soil, the root system of the *Quercus robur* sapling would probably have had a restricted growth thus preventing the tap root from reaching this vertical depth.

Mode of failure

On first inspection of the plots of root pull-out resistance against displacement, all roots seemingly had an initial rapid rise in pull-out resistance (force) with relatively small displacement, to a maximum peak failure point over larger c placements. However, if root morphology is c related to the failure curves, three different ty of failure can be recognised (Figure 4).

Typically applied force (pull-out resistan initially rises linearly with displacement to peak point at displacements of 50–100 m This initial peak is either (a) followed by rapid reduction of force until there is no re tance and the root completely pulls out of ground (Type A failure, e.g., Root H2C) or followed by a continued high resistance (for leading to a second peak failure (Type B f ure, e.g., Root H3E). In some cases, pull- resistance increases progressively as a series stepped peaks to a final maximum peak (T C failure, e.g., Root H3N), these peaks co spond to the failure of lateral root branch Type A failure generally has roots of a l length (> 0.7 m) with no or few branches. T B failures tend to have roots that are hig branched or forked. Forked roots diverge i two major branches, at angles of approximat 45°. Type C failures have roots of mu branched nature with significant lateral r branches failing before the main root. T number of branches or root divisions has m influence on the type of failure than the len of root.

Test No.	Plots of root pull-out resistance against displacement	Root morphology	Suggested failure type
H2C		 d = 26.7 mm ℓ_T = 1610 mm	Type A failure. Root is long and with no or few branches.
H3E		 d = 7.4 mm ℓ_T = 745 mm	Type B failure. A rapid rise in resistance with a maintained resistance before an abrupt failure. Root is forked and/or branched.
H3N		 d = 11.2 mm ℓ_T = 885 mm	Type C failure. Stepped failure. Root is multibranched.

d is diameter at the clamp (or top of root in each drawing). ℓ_T is total root length including root branches.

Figure 4. Examples of the three types of root failure and associated root morphologies for hawthorn roots.

Discussion

Root pull-out resistance

The pull-out resistance of the hawthorn and oak roots are affected by intra-species differences, inter-species variations and root size (diameter) in much the same way as root tensile strength varies (as measured in the laboratory). In the pull-out test, the applied force acting on the root acts over a much greater root area (multiple branches, longer lengths) than the short ~150 mm length of root used in the tensile strength test. The failure condition in the pull-out test is likely to be initiated at weak points within the root system, i.e. branching points, nodes or damaged areas, as opposed to the forced failure within the restricted length of the tensile test specimen. The pull-out failure stress is always going to be lower than the actual tensile strength of the roots but experience in the field indicates that the pull-out stress generally approaches to within 50–70% of the tensile strength. The tensile strength of fresh hawthorn roots from the M11 site was 15.5 ± 6.8 MPa (Norris, unpub data).

The resistance to pull-out may be marginally affected by the stiffness of the clay but this cannot be discerned from the data. It would be expected that roots would pull more easily through a wetter softer soil than a stiff soil. Other effects may be linked to root growth around stones or roots from other trees forming barriers to pull-out.

The non-significant relationship between root pull-out resistance and root length can be explained by the fact that only the recovered root length was used and not the total length of root pulled. According to Riestenberg (1994) and Stokes et al. (1996), root length is a factor in the pull-out resistance of roots and as such a positive correlation would be expected.

No relationship was determined for root pull--out resistance and root depth because of the uncertainty as to the actual depth of the root in the ground. However, observations of the hawthorn root system showed that the roots were only shallowly rooted in a plate-like system to a maximum depth of 0.5 m. Experiments on the resistance of model root systems to uprooting concluded that the depth of roots in the soil affected the pull-out resistance (Dupuy et al., 2004; Stokes et al., 1996).

The negative correlation between pull-out failure stress and root diameter (Figure 3) is consistent with the decreasing tensile strength increasing root diameter relationship as reported by several authors, e.g., Nilaweera (1994). A decrease in root diameter (from 5 to 2 mm) can result in a doubling or even tripling of tensile strength. This phenomenon may be partially explained by considering whether or not the root bark plays a role in the root resisting pull-out. Bark has been shown to have minimal strength and as such should not be used as a reliable indicator of tensile strength (Hathaway and Penny, 1975). However, in the root pull-out test, the bark is in contact with the surrounding soil through root-soil adhesio friction and mycorrhizal associations and as su affects the amount of pull-out resistance so is th taken into account when calculating failure stre The negative relationship has also been attribut to differences in root structure, with smaller roo possessing more cellulose than older thicker roo cellulose being more resistant than lignin in te sion (Commandeur and Pyles, 1991; Genet et a 2005; Hathaway and Penny, 1975; Turmanin 1965); and root straightening during tensile te ing.

Both the oak and the hawthorn had simil mean failure stresses of 7.4 and 8.1 MPa respe tively. If these failure stresses are compared wi published values of tree root tensile strengths c for example, Black Poplar (*Populus nigra*) 12 MPa and Sallow (*Salix cinerea*) 11 MPa (bo from Coppin and Richards, 1990) then the ha thorn fits within the range of this dataset. No pu lished tensile strength data exists for hawthor although the unpublished value of 15 MPa (Nc ris, unpub data) also agrees. However, the pu lished value of the root tensile strength of o (*Quercus robur*), i.e. 32 MPa (from Schiech 1980) indicates a discrepancy in the results. Tl discrepancy is most likely to occur because of t range of root diameters tested, the age of the tre tested and also that pull-out failure stress has lo er values than tensile strengths.

There is minimal variation in root pull-o resistance of upslope and downslope hawtho roots. Upslope roots with root diameters of 24 mm, had a mean pull-out resistance 8.1 ± 2.6 MPa, whereas downslope roots wi root diameters of 8–48 mm had a mean pull-o resistance of 8.2 ± 5.6 MPa). Schiechtl (198 suggested roots are stronger (have greater tens strengths) in the uphill direction. This observati was based on roots of alder (*Alnus incana*, *japonica*) and pine (*Pinus densiflora*). Howev differences in the tensile strengths of the upslo and downslope roots are relatively small and statistical information is provided to guarant that this assumption is significantly different.

Root orientation

Root growth in hawthorn is preferentially orie tated in the lateral (across) and downslope dire tions with very few hawthorn roots present in t upslope direction (150°)(Figure 3a). This pattern of root distribution in the hawthorn may be due to the location of the hawthorn trees on the cut-slope or it maybe an inherent anchoring mechanism for growth on slopes. All the hawthorn trees were situated on the upper part of the cut-slope in the densely vegetated area of mature trees, within close proximity (approximately 1 m) of the other trees. Competition for space for root growth and the availability of nutrients and moisture would be at a premium in this environment.

The one oak sapling investigated shows an asymmetric root growth distribution, with a slight tendency for more root growth in the upslope direction, this is in partial agreement with Chiatante et al. (2003). These authors found that roots on steep slopes are preferentially orientated in the up-slope and down-slope directions so that the plant's stability is increased. The oak sapling was situated on the lower part of the cut-slope within the immature vegetation cover dominated by grasses. The sapling in this environment would have less competition for nutrients and moisture so would therefore develop a root system that would ensure its optimum root network for growth, food requirements and stability. Detailed conclusions regarding root architecture cannot be drawn as only one oak tree has been studied.

Modes of failure

The three types of failure modes of the hawthorn roots can be related to different root-soil relationships. The roots which have no branches tend to fail in tension and pull straight out of the ground with minimal resistance (Type A; Figure 4). The root reaches its maximum pull-out resistance then fails suddenly at a weak point along its length. Weak points may be at a node or branch. The gradual tapering of roots (decrease in root diameter along its length) in the ground means that as the root is pulled out, the root is moving through cavity space larger than its diameter so subsequently has no further bond or interaction with the surrounding soil.

Roots that have multiple branches or forked branches (Type B), also have a tensile failure but tend to fail in stages as each branch breaks within the soil. These types of roots either break with increasing applied force in steps or initially reach their maximum peak resistance then maintain a high resistance which gradually reduces as the root branches fail after considerable strain. In some tests, significant adhesion between a section of the root and the soil can be measured before the root finally slips out of the soil mass. Forked roots resist failure as the increased root diameter at the point of the fork is larger than the root diameter above the fork, therefore more force is required to pull the root out of the soil, i.e. to pull a larger object through a substance that can be deformed. The clay soil was often uplifted and displaced during pull-out testing of forked roots.

Multiple branched root failure (Type C; Figure 4) in the form of stepped peaks corresponded to roots of greater diameters breaking sequentially. The root gradually releases its bonds with the soil until the final tensile failure.

In some cases, when the root is of a sinusoidal nature and has many small diameter rootlets along its length. The root reaches its maximum pull-out resistance on straightening and fails at its weakest point, however in this case, it does not fail suddenly and pull straight out of the ground, it adheres and interacts with the soil producing a residual strength. If the pulling was stopped at this point, the root would provide additional strength to the soil. Since, the root is pulled completely out of the ground, there is no further interaction with the soil (Greenwood et al., 2004; Norris and Greenwood, 2003b).

The oak roots, although pulled out using a manual root pull method, can mainly be classified as Type A failure, with long straight roots. Some multiple branched roots could be classified as Type B failure showing residual strength after the peak failure stress was achieved.

These modes of failures (Types A, B and C) are based on the shape of the failure curve and root morphology. In some cases, the shape of the failure curve may not be that distinct and relating branch failure points to drops in resistance is not straightforward, as proven by the non-significant relationship between number of branches and pull-out failure stress.

Dupuy et al. (2004) numerically modelled non-branching and branching root systems. These authors found that single non-branching roots have less effective resistance than branching root systems. When average pull-out resistances were determined for the three failure types (Type A (single roots): 3.3 kN, Type B (forked roots) – 2.8 kN and Type C (multiple branches) – 1.38 kN) the opposite correlation seems to apply. This difference may be due to the fixed arrangement of the root system branches in Dupuy et al's (2004) models which do not represent the type of morphologies and variation in root diamters as observed in the hawthorn roots. Some of the hawthorn roots classified as single branched roots had thin (approximately 1 mm in diameter) short root(-lets) occurring along their length. These rootlets would not necessarily be classed as a major subdivision or branch but would marginally affect the pull-out resistance of a single root.

The use of the hawthorn and oak for root reinforcement on highway slopes is questionable. The shallow rooting nature (0.5 m) of the hawthorn on this site does not lend itself to be used as a tree suitable for stabilising slopes that are prone to failing at depths of 1–1.5 m (Greenwood et al., 1985; Perry et al., 2003a, b). Although on other sites where root penetration to depths may be encouraged and not prevented by stiff clay or perched water tables, the hawthorn may, in conjunction with other species, form a suitable bioengineering solution. The English Oak is a slow growing tree, so would not be a suitable species for planting for immediate short term stability. However, when planted with other species that are quick growing and have only say a lifespan of 30–40 years, the oak would just be becoming established since it has a life expectancy of between 300 and 400 years (Miles, 1999).

The results presented in this paper are based on a small number of trees and on one soil type only. It is essential that more detailed investigations should be carried out to determine the relationship between root pull-out resistance and tensile strength of roots as determined by laboratory experiments. To validate the observations of the relationships between root morphology and mode of failure more experimental testing on other types of soils, trees and in other environmental settings must be carried out. The additional data obtained would increase the confidence in the value of shrubs and trees used in geotechnical engineering applications.

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Site investigation for the effects of vegetation on ground stability

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Abstract. The procedure for geotechnical site investigation is well established but little attention is currently given to investigating the potential of vegetation to assist with ground stability. This paper describes how routine investigation procedures may be adapted to consider the effects of the vegetation. It is recommended that the major part of the vegetation investigation is carried out, at relatively low cost, during the preliminary (desk) study phase of the investigation when there is maximum flexibility to take account of findings in the proposed design and construction. The techniques available for investigation of the effects of vegetation are reviewed and references provided for further consideration. As for general geotechnical investigation work, it is important that a balance of effort is maintained in the vegetation investigation between (a) site characterisation (defining and identifying the existing and proposed vegetation to suit the site and ground conditions), (b) testing (*in-situ* and laboratory testing of the vegetation and root systems to provide design parameters) and (c) modelling (to analyse the vegetation effects).

Key words. desk study, ground stability, *in-situ* and laboratory testing, site investigation, vegetation

1. Introduction

The procedures for site investigation before construction and environmental projects and the scope of necessary technical input have been defined by various guidance publications and texts (Site Investigation Steering Group, 1993; Clayton et al., 1995; Simons et al., 2002; Greenwood, 2005a; Highways Agency HD22/02). Little attention has been given during routine geotechnical investigation to the part that vegetation might play in contributing to the engineering stability of the existing site or proposed works.

Whilst the potential application of vegetation to assist stability is generally associated with slopes (Barker, 1986; Coppin and Richards, 1990; Gray and Sotir, 1995; MacNeil et al., 2001), it should be noted that vegetation also plays a part in stabilising horizontal surfaces to improve shear resistance. The penalty miss by footballer David Beckham during the European Cup finals of June 2004 (Figure 1) was claimed by Sven Goran Eriksson, the coach, to be due to the fact that 'he slipped with his foot once again

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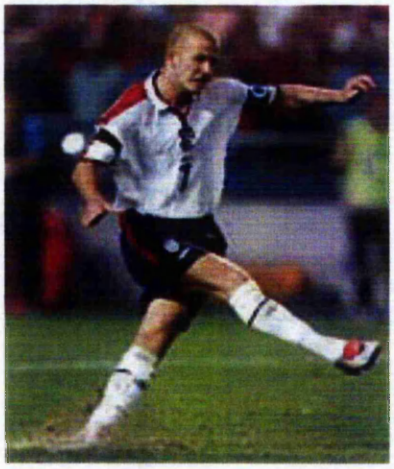

Figure 1. David Beckham misses a crucial penalty in the 2004 European Championships match against Portugal. (Robert Millward/Associated Press Web Site).

because the area around the penalty spot didn't have enough grass'. The significance of ground stability for multi-million pound/euro sporting events should not be underestimated in today's economy which increasingly depends on leisure activities.

The more traditional need for applications of soil bioengineering (or eco-engineering) to sloping ground are illustrated in Figures 2 and 3 where the occurrence of shallow landslides may well have been reduced with appropriate soil bioengineering measures. The investigation of the effects of vegetation is particularly relevant to shallow slope failures, preventative works and erosion control.

2. Current Procedures for Geotechnical Site Investigation

2.1. INVESTIGATION STAGES

The investigation work for most construction projects is divided into stages as illustrated in Table 1. The Geotechnical Advisor is normally appointed at the outset of the project and will ensure appropriate geotechnical input at each stage.

2.1.1. *The desk study/preliminary sources study*

The desk study, sometimes referred to as the 'initial appraisal' or 'preliminary sources' study is vital for determining a preliminary understanding of the geology of the site and the likely ground behaviour. The term 'desk study' can be misleading because in addition to collection and examination of existing information, it must include a walk-over survey. The study will determine what is already known about the site and how the ground should be investigated.

Before embarking on intrusive ground investigation work, much valuable information may be readily gleaned from existing sources such as geological and Ordnance

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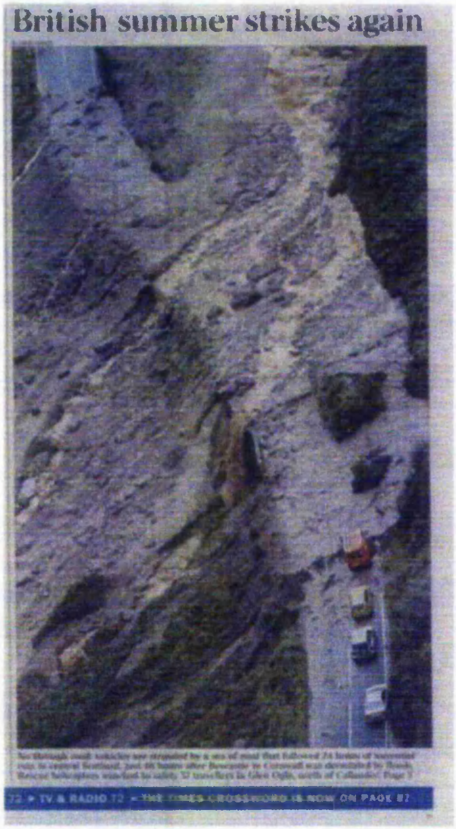

British summer strikes again

Figure 2. Shallow landslide problems blocking roads and trapping motorists in Scotland, after heavy rains in August 2004 (Times Newspapers).

Survey maps, aerial photographs and archival material. Such documents can yield much about site conditions. The information from these sources is combined with the walkover survey to enable preparation of a geotechnical ('geohazard') plan of the site. A check list of information to be sought in a desk study is given by Perry (1996).

The desk study often represents the most cost effective element of the entire site investigation process revealing facts that cannot be discovered in any other way. The preliminary engineering concepts for the site are prepared and developed at the desk study phase based on the acquired information. The ground investigation in the field is then designed to confirm the conditions are as predicted and to provide ground information for the detailed design and project construction.

2.1.2. *The walkover survey*

The walkover survey is a detailed inspection of the site often done in stages with the initial visit for familiarisation, photography and checking of the current site

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Figure 3. Instability of cutting slopes on the M11 near Loughton. Adjacent vegetated areas appear more stable.

conditions and with subsequent visits to confirm features noted on historical maps and photographs, etc. Features should be sketched at an appropriate scale on a base plan for inclusion in the desk study report.

Table 1. Stages of a geotechnical investigation (Greenwood, 2005a)

Construction phase	Investigation work
Definition of project	Appointment of Geotechnical Advisor for advice on likely design issues
Site selection	Preliminary Sources Study (Desk Study) to provide information on relative geotechnical merits of available sites.
Conceptual design	Detailed Preliminary Sources Study (Desk Study) and site inspections to provide expected ground conditions and recommendations for dealing with particular geotechnical design aspects and problems. Plan Ground Investigation (Procedural Statement)
Detailed design	Full Ground Investigation and geotechnical design. (Additional ground investigation if necessary for design changes or for problematic ground conditions)
Construction	Comparison of actual and anticipated ground conditions. Assessment of new risks (Additional ground investigation if necessary)
Performance/maintenance	Monitoring, instrumentation, feedback reporting.

2.1.3. *The procedural statement*

The key to successful site investigation lies in the planning process. If all aspects of the investigation work are considered in advance together with necessary actions relating to the likely findings, then the outcome is likely to be satisfactory for all parties involved.

A convenient way to bring together and record the proposals for each stage of site and ground investigation is by a 'Procedural Statement' (sometimes referred to as the 'Statement of Intent' or the 'Ground Investigation Brief'). This approach was formally introduced by the Department of Transport/Highways Agency in the 1980's and has now become widely accepted as good practice (Highways Agency HD 22/02). An example of headings and topics covered in a Procedural Statement is given in Table 2. Headings and content will change slightly for each phase of the investigation process as more information is accumulated.

The Procedural Statement is usually prepared by the Geotechnical Engineer/Advisor responsible for the work and should be agreed by all interested parties, and in particular the client, before the investigation proceeds.

The Statement encourages the designer to consider relevant aspects of the proposed investigation and to seek authority to proceed. It forms a valuable document within a quality management system and it becomes a base reference as the investigation proceeds in case changes are needed in the light of the findings.

3. Addition of the Vegetation Investigation

The proposed additional sections and notes to consider the effects of vegetation in the Procedural Statement are shown in bold italic in Table 2. This will draw the attention of the project team (and funders) to the possible application of the vegetation to assist the engineering performance. It will highlight the need for specialist consultation and help plan the necessary investigation to demonstrate the potential of the vegetation.

3.1. SUGGESTED OUTLINE PROCEDURE FOR INVESTIGATION OF VEGETATION

Table 3 outlines the typical factors relating to vegetation which may be considered at each stage of the investigation. It is noted that the major part of the vegetation study can (and should) be completed at the desk study/preliminary stage.

4. Review of Techniques Available to Help Investigate the Effects of Vegetation

The following paragraphs briefly review the techniques which may be used for investigation of vegetation effects and provide references for further consideration of the various techniques.

Table 2. Example content of a Procedural Statement to be prepared before the Ground Investigation phase (HD 22/02) ***(Suggested additions for vegetation investigation shown in bold italic)***

THE PROCEDURAL STATEMENT – Prepared by the responsible Geotechnical Advisor and agreed by the client and interested parties prior to each investigation phase.

1. SCHEME
Details of Scheme and any alternatives to be investigated; Key location plan.

2. OBJECTIVES
(For example) To provide information to confirm and amplify the geotechnical and geomorphological findings of the desk study as reported separately and to obtain detailed knowledge of the soils encountered and their likely behaviour and acceptability (for earthworks). To ascertain ground water conditions and location of any underground workings ***and nature of existing vegetation and potential for planting to enhance soil stability***. (Work limits to be defined).

3. SPECIAL PROBLEMS TO BE INVESTIGATED
Location of structures. Subsoil conditions below high embankments. Aquifers and likely water-bearing strata affecting the proposed works. Rock stability problems. Man-made features to be encountered. Effects on adjacent properties etc. ***Vegetation problems and benefits***.

4. EXISTING INFORMATION
List of all relevant reports and data. ***Including survey of existing vegetation and its potential contribution to stability. Review of plant suitability guidance***.

5. PROPOSED INVESTIGATION WORK
Fieldwork – Details of exploratory work proposed for specific areas with reasons for choice of investigation methods selected. Proposed sampling to match laboratory testing ***(including studies of vegetation and its effects)***.
Laboratory work – Details of proposals with reasons for choice of tests and relevance to design ***(including root strength assessment)***.

6. SITE AND WORKING RESTRICTIONS
Assessment of risk associated with proposals. Site safety, traffic management, difficult access, railway working, ***preservation of existing vegetation, topsoil*** etc.

7. SPECIALIST CONSULTATION
Details of specialist needed to support proposals ***(including plant specialists, bioengineers etc)***.

8. PROGRAMME, COST AND CONTRACT ARRANGEMENTS
Anticipated start date, work programme, contract arrangements, cost estimates, specification and conditions of contract. Arrangements for work supervision, etc.

9. REPORTING
Responsibility for factual and interpretive reporting. Format of reports and topics to be covered ***(including assessment of existing and proposed vegetation)***.

4.1. VEGETATION SURVEY

The extent of a survey of existing vegetation will relate to its relevance to the planned works. There is little point in carrying out detailed surveys of existing vegetation if the proposed works require re-profiling of the ground and removal of vegetation and topsoil. On the other hand, where existing vegetation can be preserved its nature

Table 3. Factors to be considered for inclusion of vegetation effects in stages of routine site investigation

VEGETATION CONSIDERATIONS

Desk study phase
i) Soils
Existing Topsoil – shallow hand dug pits to provide initial information on soil and vegetation
Subsoils – likely penetration and distribution of plant roots
Proposed fill materials - possible provision of irrigation/drainage layers to encourage deep root growth
ii) Vegetation
Typical presence and distribution of vegetation (detail depends on project)
Consider use of non invasive techniques (Ground Profiling Radar) to assess root distribution.
Identification of indigenous species with potential to assist stability (recognising need for biodiversity)
Grass cover (survey by quadrats – one metre square with 100 mm grid) - Detail to be considered
Plan of vegetation types, trees, etc. across site
List uncertainties re: vegetation (i.e., root distribution, root penetration, tensile strength, pull out resistance, etc.) that may be assessed during main investigation phase
iii) General
Review vegetation influences on adjacent sites
Consider areas of proposed works which might benefit from vegetation to assist stability
Draw up schedule of site zones and information required
Check reference texts and Slope Decision Support Systems for guidance on likely benefit
Check availability of plant / seeds (liaising with specialist plant producers and landscape architect)
Carry out preliminary ground modelling and stability analysis based on assumed properties for soil, hydrology and vegetation.

Main ground investigation
If existing vegetation to be assessed:-
Trial Pits to :-
a) describe topsoil, depth, organic content, standard tests for topsoil classification (BS5930)
b) assess root distribution and carry out *in situ* pull out resistance tests
c) take samples of roots for laboratory tests on tensile strength
d) carry out *in situ* shear tests on root reinforced soils (larger investigations only)
e) compare moisture content profiles in vegetated and non vegetated areas due to different types of vegetation
Possible seasonal monitoring of moisture content profiles by access tube (TDR or Theta Probe technologies)
For future vegetation:-
Assess vegetation growth on adjacent sites
Assess topsoil and subsoil types available and likely vegetation types which can be supported in the region

Analysis
Stability analysis by limit equilibrium methods (numerical methods for ground modelling on larger projects) to assess the influences of the vegetation and help design additional planting and vegetation maintenance schemes
Where little or no existing vegetation is present (regraded slopes etc) analyse benefits/disbenefits of proposed planting scheme

Table 3. (Continued)

Construction stage
Monitoring and protection of existing plants and topsoil
Treatment of soils to encourage deeper rooting
Topsoil /subsoil preparation and planting (in association with plant specialist and landscaper)
Review conditions on site as found against those predicted – modify design if necessary
Confirm that dependency on vegetation does not introduce inappropriate risks to property and life (If so a 'hard' engineering solution is essential)
Feedback/maintenance
Report on achieved objectives of vegetation and planting and provide programme of necessary on-going maintenance inspections and actions to be taken in light of certain 'foreseen' events

should be recorded and possible contribution to ground stability assessed. The following is recommended:-

- All trees and shrubs should be identified and locations recorded with local investigations of root extent where possible.
- The general presence and nature of ground cover (grasses, 'weeds', etc.) should be recorded.
- The maturity and vitality of the vegetation should be recorded.

Where existing (or proposed planted) vegetation is to play a role in engineering stability, more detailed surveys should be carried out as suggested by Cammeraat et al. (2002). The survey is carried out by placing a suitable square grid (quadrat) over the soil and vegetation to record and monitor factors such as the seasonal variation, percentage ground cover and the determination of the mass of vegetation (biomass). The advice of a plant specialist to assist with such surveys is recommended.

4.2. TOPSOIL AND SUBSOIL

As the prime growing medium, the available topsoil and subsoils (upper 1.5 m) should be classified in horticultural terms so that existing suitable plants can be encouraged or new plants selected for their engineering contribution.

Consideration might be given to possible treatment of the topsoil and subsoils by aeration and/or fertiliser, to encourage the development of mycorrhizal associations and deeper, healthy root growth (Ryan and Bloniarz, 2000).

4.3. TRIAL PITS AND BOREHOLES

Shallow trial pits, preferably hand dug, can often be put down with minimal disturbance and provide an excellent means of assessing root distribution and the nature of the topsoil and subsoil layers. As the excavation only represents a snapshot in time, the likely seasonal influences of changing moisture conditions need to be considered (Greenwood et al., 2001).

Root size and distribution may be assessed and recorded by image analysis of the trial pit wall or by manual counting using a 'quadrat' or square grid, typically of 100 mm squares, placed over the vertical sides or horizontal base of the pit (Greenwood et al., 2001).

Boreholes are less valuable than pits for root distribution analysis but horizontal sections through recovered core samples can provide a limited indication of root counts (Greenwood et al., 2001).

4.4. GEOPHYSICAL TECHNIQUES FOR ROOT LOCATION

Geophysical techniques such as Ground Penetrating Radar (GPR) have been used with partial success to map tree root systems. The four fundamental factors to consider with any geophysical method are penetration, resolution, signal to noise ratio and contrast in physical properties (McCann et al., 1997). There is a trade off between resolution and penetration depth, penetration may be increased by using a lower frequency but resolution is improved by using a higher frequency (Hruska et al., 1999). However, the attenuation also depends on the conductivity of the soil, therefore, soil type and overall root depth are important factors determining the success of this method. Dobson (1995) and Hruska et al. (1999) have reported successful plan and three dimensional images of roots, but Stokes et al. (2002) reported problems with root crossover and branching, and in determining the location of roots less than 20 mm diameter.

The geophysical techniques are worthy of further consideration to supplement the physical investigations particularly as computer processing power increases to help interpret the geophysical survey results.

4.5. MOISTURE CONTENT DETERMINATION

Moisture content is a fundamental property relating to soil strength and consolidation characteristics. Changes in moisture content will occur primarily due to seasonal effects but also due to the influence of the vegetation. Seasonal comparisons of moisture content profiles in vegetated and non vegetated areas of the site will be of assistance in considering the vegetation effects.

Physical sampling inevitably involves partial destruction of the site by trial pit or borehole and therefore can only provide a snapshot of conditions at the time of excavation. Moisture profiles at close centres (say 50 or 75 mm) on a vertical profile or as a grid around root networks can provide helpful information. The 'moisture in the bag' technique (Greenwood and Norris, 1999) saves time on sampling and laboratory drying procedures.

Other techniques such as time domain reflectometry (TDR) (Topp and Davis, 1985), Theta probe (Gaskin and Miller, 1996), and Neutron probe (Vickers and Morgan, 1999) permit monitoring of moisture content over extended periods by having either a permanent access tube installed for insertion of a probe or by leaving

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an instrument buried in the ground to allow continuous real time monitoring. Considerable success is reported with these devices (Vickers and Morgan, 1999; Greenwood et al., 2001) although caution is needed in their calibration which should preferably be done against physical moisture content determination. The remote devices generally record volumetric moisture content (volume of water divided by total volume of specimen) as compared with the gravimetric moisture content (mass of water divided by dry mass of soil specimen) which is more familiar to geotechnical engineers (BS 1377; 1990). Relating the two approaches to moisture content requires the measurement or assumption of the dry density of the soil, i.e.,

$$\text{Gravimetric moisture content} = \text{Volumetric moisture content} \times \frac{\text{Density of water}}{\text{Dry density of soil}}$$

Greenwood et al. 2001.

4.6. WATER PRESSURES

Effective stresses which govern the stability of soil slopes are dependent on the pore water pressures present in the soil mass. Traditional monitoring devices of standpipes and piezometers (BS5930, 1999) are valuable for general slope stability monitoring but are unlikely to detect the specific influences of the vegetation (Greenwood et al., 2001). More detailed studies of wetting fronts during rainstorm events (Vickers and Morgan, 1999) and seasonal variation in water pressures are possible by means of tensiometer installations (Greenwood et al., 2001). Tensiometers are considered to be most helpful for assessing water pressures and suctions where the effects of vegetation and other hydrological influences are to be considered in detail (Anderson et al., 1996; Greenwood et al., 2001).

4.7. ROOT STRENGTH

For analysis of root reinforced soil an estimate of the contribution of roots to stability is required (see '*stability modelling*'). This may be obtained directly from *in-situ* root pull-out tests (Norris and Greenwood, 2003) or from laboratory tests (Coppin and Richards, 1990). Again account needs to be taken of the season at which the testing is completed compared with the most critical 'wet' periods for the site.

Laboratory measurements of root tensile strengths are helpful and should provide root characterisation data to be checked against published results for the particular species (Ecoslopes manual, in preparation).

In situ shear tests can give a direct indication of the shear strength of root reinforced soil but are difficult to interpret in relation to the drained/undrained conditions and the stress distribution within the sample (Norris and Greenwood, 2000a, 2000b, 2003; Greenwood et al., 2004).

4.8. STABILITY MODELLING

The modelling tools available for analysing the effects of vegetation need to be considered at the outset so that the investigation is designed to provide the required data.

Various methods of limit equilibrium stability analysis are available in commercial packages such as SLOPE/W (Geoslope International Ltd.). Methods based on equilibrium of hydrological forces are shown to be most reliable for estimating the factor of safety and are readily adapted to include the vegetation effects (Greenwood, 2005b). The SLIP4EX program based on Microsoft Excel, compares methods for a single slip surface and is freely available (contact: john.greenwood@ntu.ac.uk or on-line Journal of Geotechnical and Geological Engineering web site?) for initial exploration of vegetation effects (Greenwood, 2005b). Root effects may be represented by radial zones of enhanced soil properties around a single tree or by depth related zones parallel to the slope for general vegetation cover (Greenwood et al., 2003, 2004). Other models for consideration of soil–root interaction are discussed by Wu (1995, 2005) and Operstein and Frydman (2002).

When incorporating vegetation root effects, high partial factors of safety (typically around 8–10) are recommended to take account of the uncertainty of root distribution and anchorage lengths and the large strains necessary to generate the full tensile resistance of the root (Greenwood et al., 2003, 2004).

The power of numerical modelling by finite element or finite difference methods is such that both stress and strain and the generation of water pressures can be modelled for situations of root–soil interaction and ground water infiltration. The problem is that the setting up of accurate models and selection of appropriate parameters is not straightforward. Commercial programs such as Plaxis (Brinkgreve, 2002) and Seep/W (Geo-slope International Ltd.) are helpful, particularly for assessing the sensitivity of the analysis to the assumed parameters.

Programs such as Forest Gales (Gardiner et al., 2000) are available to assess specific problems of the vulnerability of trees to wind damage. Other numerical programs are under development to record and model root systems and include their influence in ground models, e.g. Dupuy et al. (2004).

4.9. SLOPE DECISION SUPPORT SYSTEM

One of the key objectives of the EU funded ECOSLOPES project was to provide a slope decision support system (SDSS) to help practitioners to assess their slopes and select appropriate vegetation to help stabilise them. The SDSS may be trialled as a development version (Mickovski and van Beek, 2005; Ecoslopes Manual, in preparation) and it is intended that with the benefit of user feedback its scope will be confirmed to provide the necessary guidance for eco-engineering and soil bioengineering applications.

5. Discussion

The application of vegetation to assist engineering functions is not always straightforward and expectations as to what might be achieved must be realistic. However the costs are relatively low particularly at the preliminary (desk study) phase and therefore benefit/cost ratios may be high. The linking of the engineering solutions to an improved environment is a satisfactory and rewarding achievement.

Mistakes will inevitably be made and vegetation alone should not be relied on where life and property are directly at risk from resulting landslip.

As experience is gained the checklists and investigation techniques provided in this paper will be reviewed and updated. For all investigation work it has been recognised that there must be a balance of effort between the site and strata definition, the testing and the modelling (Burland, 1989). As vegetation considerations are included, this balance must be maintained with the site characterisation (defining strata, hydrological conditions and vegetation), balanced against the testing (on site and in the laboratory) and modelling (Figure 4). It is pointless carrying out detailed, sophisticated modelling if the strata, hydrology and vegetation properties are not properly defined. Equally, it is pointless doing many tests to determine vegetation characteristics and strengths if the results are not relevant to the site modelling.

6. Conclusions

Much of the assessment of the potential benefits (and dis-benefits) of vegetation can be efficiently completed at the desk study (preliminary) investigation stage and does not involve large expenditure. Furthermore, vegetation studies at the main ground investigation stage are again relatively low cost involving minimal ground intrusion.

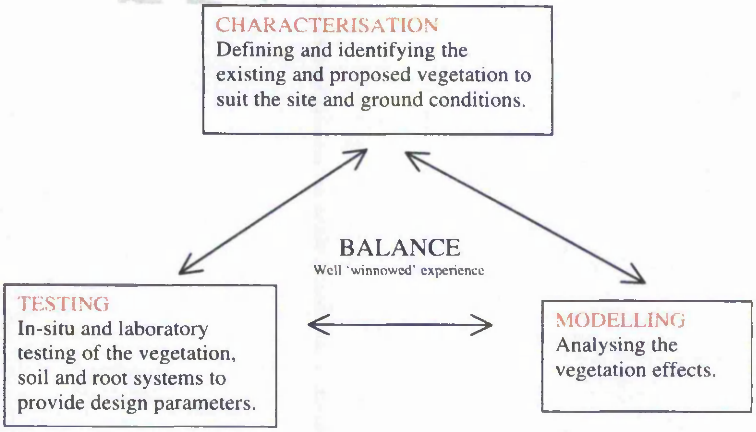

Figure 4. Balance of input into vegetation investigation work (Developed from Burland 1989)

Whilst the application of bioengineering will not be appropriate or relevant for all construction projects, the framework provided should encourage the project team to review the options for preservation or inclusion of vegetation which may enhance the engineering stability in addition to improving the landscape and environment.

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