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THRESHOLDS OF DAMAGE FOR PROPERTIES DAMAGED BY GROUND SUBSIDENCE

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ABSTRACT

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IMPLEMENTING THRESHOLDS OF DAMAGE FOR LOW-RISE RESIDENTIAL PROPERTIES SUBJECT TO GROUND SUBSIDENCE MOVEMENT

This study has investigated thresholds of damage for privately owned low-rise residential properties damaged by ground subsidence or heave movement. The primary focus of the research objectives has been the uncertainties created by subsidence damage. The study investigates thresholds of damage that can be used to assess the remedial action necessary for low-rise residential properties damaged by ground subsidence or heave movement. After investigating thresholds of damage, the study subsequently considers the implications that thresholds of damage would create if applied in practice.

The research was carried out through the collection and analysis of 236 case study properties. Each case study represents a privately owned low-rise residential property that was thought to have been damaged by ground subsidence or heave movement. The research has considered properties damaged by subsidence or heave movement caused by leaking drains, clay subsoil shrinkage or expansion and subsidence caused by coal-mining. Case study information has been gathered from a variety of sources, using data collected by professionally qualified chartered engineers, surveyors or other specialists. In addition to these case studies, the research has employed semi-structured interviews in order to consider the implications that thresholds of damage would create if applied in practice.

The research found that the evaluation of visible damage is a highly subjective matter and that any thresholds based upon an assessment of visible damage are an unreliable method to consider whether or not a property requires substantive repairs. The most robust threshold of damage which is found to emerge was to evaluate whether or not the movement causing the damage in the property is long-term progressive. The consequences of implementing this threshold of damage have been investigated. It has been concluded that if this threshold of damage was adopted, it could lead to both reductions in payments necessary to repair subsidence or heave damage and it could also reduce some of the uncertainties associated with subsidence.

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CHAPTER ONE: INTRODUCTION

1.1: INTRODUCTION

Over recent years there has been considerable publicity concerning compensation claims for subsidence damage to low-rise residential properties. Subsidence is considered a potential natural hazard which can cause extensive damage to all types of building structures. Low-rise housing is particularly vulnerable to damage caused by ground subsidence movement, because such structures predominantly have shallow foundations and are constructed using brittle materials. In the United Kingdom, the Association of British Insurers (1997) reported that in both 1995 and 1996 the annual payments by insurers for subsidence damage exceeded £300 million. This figure only reflects damage covered by insurance policies and does not include the costs of subsidence caused by underground mining, or subsidence repairs funded by individual property owners.

In the past, the traditional solution for properties damaged by subsidence was to underpin the foundations. However, underpinning can be an expensive procedure because of the uncertainties involved in working below ground level. Escalating costs associated with the repair of subsidence damage has resulted in fewer properties being underpinned in more recent times. The alternative solution is to repair the visible damage evident both internally and externally above ground level. However, because of the predominance of underpinning in the past, those properties damaged by subsidence which are not underpinned may be seen as a potential risk by some parties involved in the buying, selling and insuring of properties. Consequently, if a property shows symptoms of damage thought to be caused by subsidence movement, the uncertainties and repercussions relating to the form of remedial action adopted can have an adverse affect on the value of a property. This is sometimes referred to as subsidence "blight". It is probably correct to say that for the vast majority of home-owners, the physical damage to a property caused by subsidence is of lesser importance than the potential loss of market confidence in the property.

The principle of underpinning a building to repair damage caused by subsidence is well-established and accepted in virtually all academic and technical literature (for example, Hunt *et. al.*, 1991; BRE Digest 251, 1993 edition; ISE, 1994). Hunt *et. al.* (1991) reported that in the past much underpinning has been carried out which, from a strictly technical point of view, was not required. This work was largely undertaken to restore market confidence in a subsidence damaged property.

In order to study the technical aspects of repairing residential properties damaged by subsidence, a large number of interesting publications have been written, many of which are considered in subsequent chapters. However, these studies are mainly concentrated in developing and refining solutions to repair subsidence damage (Hunt *et. al.*, 1991; ISE, 1994), or prevent future damage from occurring (Biddle, 1983; Driscoll, 1983; BRE Digest 242, 1993 edition).

Previous work has established and refined effective methods necessary to both analyse and solve the technical and engineering problems caused by ground subsidence. However, little of this previous work has addressed the problems caused by subsidence blight. Therefore, this thesis uses the existing well-established knowledge relating to the technical and engineering issues in order to address some of the contemporary problems that subsidence blight causes.

After identifying the broad objective of this research, the remainder of this chapter will provide a more detailed introduction to this thesis. The chapter begins by explaining the contemporary problems relating to subsidence damage in privately owned residential low-rise housing. This identifies the relevance of this thesis and establishes the context of the research in the wider subject field. Following this, the research aims are defined and the study delimitations identified. The methodology employed to investigate the research aims is discussed and the final section of this chapter identifies the overall structure of the thesis.

1.2: BACKGROUND TO SUBSIDENCE AND IDENTIFICATION OF THE PROBLEM

Subsidence damage to buildings is not a new problem. In the nineteenth century, Bartholemew (1840, cited Driscoll, 1983) identified a potential for structures built on clay soil to be affected by subsidence movement. Pryke (1995) has reported cases of subsidence movement in clay soils dealt with by his family building business which date back to the early 1900s. At that time, such cases would appear to have been quite rare and hence received little publicity.

The nineteenth century also saw extensive coal-mining occurring in Great Britain. Around that time, the technique of longwall coal-mining replaced the pillar-and-stall method of mining, where pillars of coal were left to support the voids of extracted coal. The longwall technique extracts coal from beneath the ground, but makes no attempt to support the void created by extraction, which consequently results in the ground collapsing into the void, causing subsidence at the surface. Whilst longwall mining allows deeper, larger mines to be worked more economically, it invariably causes subsidence movement at the ground surface. This process will be more fully discussed in Chapter Two.

The resultant surface subsidence movement induced by longwall mining usually causes damage to surface structures, especially low-rise housing. Mechanisms for subsidence damage compensation and repair have been well-established and used, with claims being made to the agency carrying out the coal-mining and hence causing the subsidence. However, the number and value of claims for coal-mining subsidence damage is directly related to the amount of coal-mining activity, which in Great Britain has been substantially reduced throughout the 1980s and 1990s.

A watershed relating to subsidence damage in low-rise residential properties was reached in 1971. At that time, following pressure from building societies keen to protect the security of investments, insurance companies agreed to extend the standard buildings' insurance policy to include damage caused by ground subsidence movement. However, soon after this, in the summer of 1976, the worst period of drought in over 200 years of records occurred in Great Britain (Meteorological Society 1979, cited Driscoll, 1983). Prolonged periods of drought can cause clay soils to dry out and shrink, resulting in subsidence movement of the ground. Consequently, this shrinkage can result in the downwards movement of a buildings foundations causing potential damage in the building superstructure. The opposite of subsidence is known as ground heave and this occurs where a clay soil absorbs moisture. This can result in a volumetric expansion of the clay, thereby uplifting a buildings foundations and potentially causing damage to the building superstructure.

It appears widely accepted in published literature that the 1976 drought in Great Britain resulted in a large increase in the number and value of claims made to insurance companies for subsidence damage to low-rise properties. Similar periods of drought in 1984, and 1989, 1990 and 1991 resulted in further peaks in the number and value of claims for subsidence and heave damage.

1.2.1: Technical And Non-Technical Issues

Privately owned residential low-rise properties damaged by ground subsidence or heave movement are affected in two very distinct forms. Firstly, there is the physical damage caused to the property. The extent of this damage and the remedial action required to repair it will depend on a number of **technical** or engineering related issues. These are objective factual matters that can usually be accurately established by investigation, for example, type of building construction, depth of foundations below ground level, or the properties of the subsoil supporting the foundations. The second, and less publicised form of damage caused by subsidence relates to the **non-technical** issues. This occurs where conflicting opinions exist regarding the most appropriate form of remedial action. The costs of providing substructure repairs may be prohibitive, but if these are not carried out the property may be considered as a poor risk for investment and lose its market value and hence saleability. These non-technical issues result in subsidence blight, which can obscure or outweigh the objective technical issues.

The non-technical issues are often more difficult to establish and are influenced by matters including:

- Increasing levels of home-owner occupation have made a larger proportion of the population sensitive to damage in their homes which, for most people, is their largest investment.
- As claims for subsidence damage increased, the general public became more aware of subsidence and heave damage through the experience of family, friends and the news media.
- Over the long-term, increasing house prices have made home-owners more aware of damage and the effects that this might have on the market value of their property. This has potentially such far-reaching consequences as negative equity for some home-owners.
- Periods of high activity in the housing market have resulted in more houses being offered for sale, therefore requiring that these properties are inspected by surveyors who have become increasingly aware of subsidence damage.
- During periods of recession in the building industry, subsidence and heave damage to residential low-rise properties has provided a source of work to some sectors of the industry.

The technical issues associated with the causes and remedies of subsidence have been extensively investigated and reported in numerous pieces of previous work. Chapters Two and Three contain an extensive review of this work. This review highlights that the technical issues, at least in relation to subsidence damage in low-rise residential properties, form a substantial body of knowledge which is well-established.

In relation to the non-technical issues, there is evidence that these have had a significant effect on raising the number and profile of claims for subsidence damage to low-rise properties. In addition, these non-technical issues have created subsidence blight problems for many home-owners whose properties have been damaged. Previous works, including Hunt *et. al.* (1991); BRE Digest 251 (1993 edition) and Pryke (1993), have recognised the importance of the non-technical issues. However, very little previous work in this field has addressed the subject by focusing on the non-technical issues. Therefore, the aims of this research, as identified below, seek to investigate the non-technical aspects of subsidence damage in low-rise properties. In order to address these research aims, it is necessary to have a thorough understanding of the well-established body of knowledge which relates predominantly to the technical issues. Chapters Two and Three identify the relevant material contained within this body of knowledge that constitute the technical issues.

1.3: IDENTIFICATION OF THE RESEARCH AIMS AND OBJECTIVES

The context of this research is identified above. It is therefore necessary to focus upon the specific aims of this research. This is achieved through articulating the following principal research aims and objectives:

RESEARCH AIM ONE

BRE Digest 251 (1993 edition) has identified the lack of any qualification of damage in the standard buildings' insurance policy as one of the primary reasons for the large number of claims made to insurance companies for domestic subsidence damage. Pollard (1993) explained how many home-owners have come to consider their buildings' insurance policy as a maintenance contract, rather than an indemnity against damage caused by subsidence or heave. There exists no universal and accepted definition, in terms of either extent or severity, of what distinguishes genuine subsidence or heave damage as opposed to damage that can be regarded as routine building maintenance. Hence, damage that might be considered as minor aesthetic damage, can be interpreted as potentially serious structural subsidence or heave damage, causing the property to be blighted. Therefore:

The objective of Research Aim One is to investigate the threshold of visible damage that causes concern to professional advisors acting on behalf of property owners. Such a threshold of damage could subsequently be used as a basis to consider in which circumstances it is appropriate to further investigate a suspected case of subsidence, and in which circumstances it is appropriate to repair the damage as part of a program of routine building maintenance.

RESEARCH AIM TWO

When subsidence or heave movement occurs, it is the foundations of a building that transmit the movement to the superstructure of a property resulting in the visible damage. If the remedial action to the property requires repairs to the foundations of a building this can present significant consequences. The obvious consequences include the expense of the repairs, which is usually of an unforeseen nature because of the unknown conditions that exist below ground level. Other consequences of foundation repairs include the disturbance caused to the property, gardens, and adjacent properties. In some instances the property owners need to be temporarily re-housed during the remedial repair work.

The less obvious and more indeterminate consequences of substructure repairs concern non-technical issues. For example, if a property is diagnosed as having a subsidence problem, but no substructure repairs are carried out, this can have an adverse impact upon the market value and saleability of a property. In such circumstances the property becomes subsidence blighted because potential purchasers see it as not being structurally sound and hence a poor investment. Hunt *et. al.* (1991) and ISE (1994) reported that because of the concerns of property owners and their professional advisors, there have been many examples of substructure repair work which have not been required for technical reasons. This has resulted in unnecessary amounts of money being spent to repair alleged subsidence damage and has also resulted in many properties being unnecessarily blighted by subsidence damage. Therefore:

The objective of Research Aim Two is to determine a threshold of damage which can be used to objectively identify when a property damaged by ground subsidence or heave requires remedial substructure repairs to be undertaken.

RESEARCH AIM THREE

Research Aims One and Two each address clear and well-defined important issues. Both of these Research Aims seek to establish thresholds of damage which could be used in practice to objectively assess low-rise properties allegedly damaged by ground subsidence or heave movement. Research Aim Three considers the *manner* in which the thresholds of damage identified in Research Aims One and Two could be used to address the non-technical problems of subsidence damage to low-rise buildings. Therefore:

The objective of Research Aim Three is to assess how the non-technical problems caused by subsidence or heave damage in low-rise buildings would be influenced by the application of the thresholds of damage established in Research Aims One and Two.

The primary research aims of this study have been identified above, and can be summarised:

RESEARCH AIM ONE:

To investigate the threshold of visible damage that causes concern to professional advisors acting on behalf of property owners.

RESEARCH AIM TWO:

To investigate the threshold of damage that can be used to identify the need for substructure repairs.

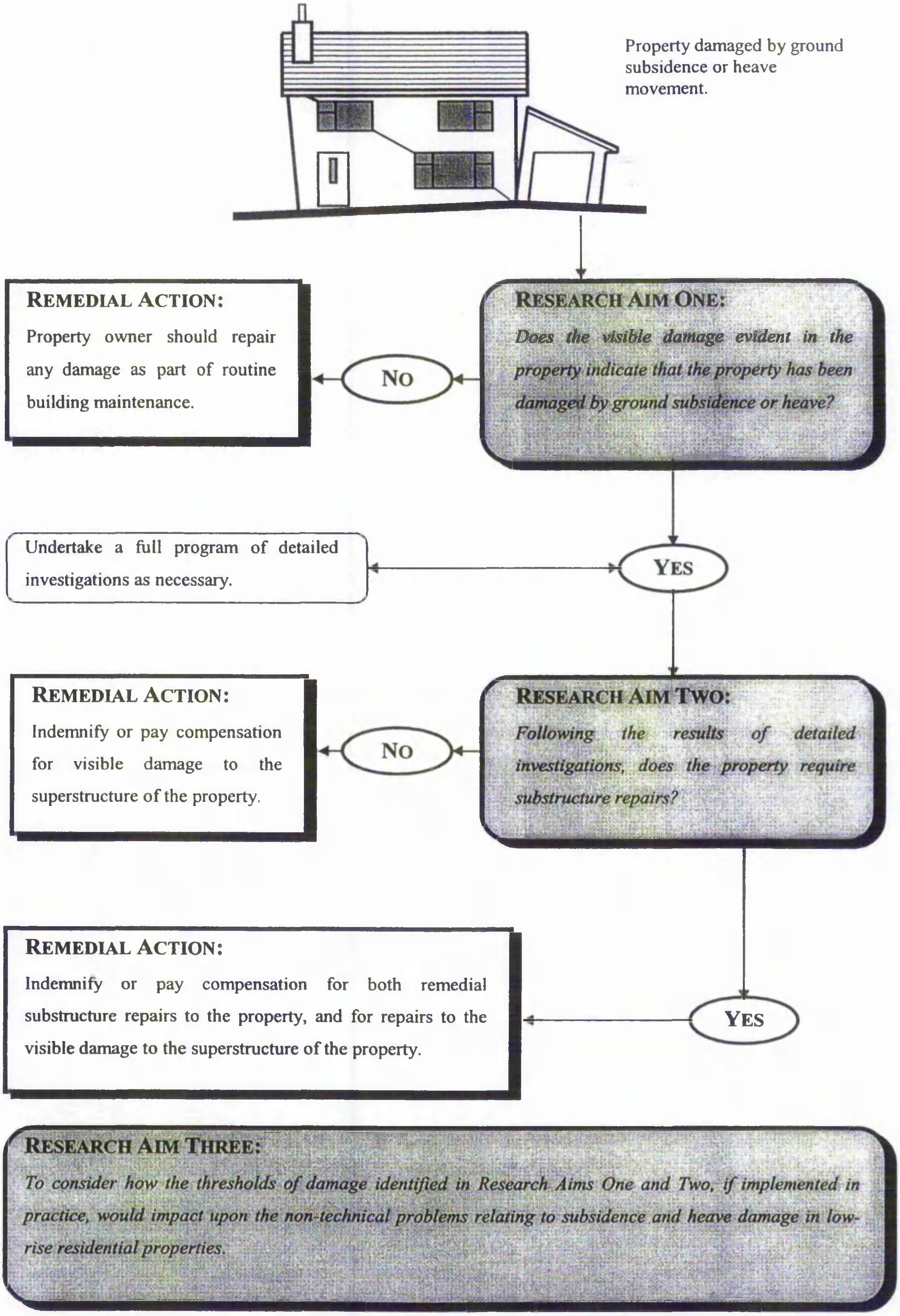
RESEARCH AIM THREE:

To consider how the thresholds of damage identified in Research Aims One and Two, if implemented in practice, would impact upon the non-technical problems relating to subsidence and heave damage in low-rise residential properties.

Figure 1.1 below provides a flow chart which serves to set into context the objectives of the three research aims being investigated. Research Aim One seeks to establish whether or not there exists a threshold of visible damage that can be used to identify if a property allegedly affected by subsidence or heave problems warrants detailed further investigation, or if the damage should be treated as part of routine building maintenance at the owners expense.

Research Aim Two seeks to establish a threshold of damage that can be used to identify whether or not a property, which has been found to be damaged by ground subsidence, requires above ground cosmetic/aesthetic repairs, or if the property requires repairs to the foundations of the building below ground level.

Research Aim Three considers how the introduction of any thresholds of damage identified in Research Aims One or Two would impact upon the non-technical aspects of subsidence, which have been outlined in section 1.2.1 above.



Property damaged by ground subsidence or heave movement.

REMEDIAL ACTION:

Property owner should repair any damage as part of routine building maintenance.

RESEARCH AIM ONE:

Does the visible damage evident in the property indicate that the property has been damaged by ground subsidence or heave?

Undertake a full program of detailed investigations as necessary.

REMEDIAL ACTION:

Indemnify or pay compensation for visible damage to the superstructure of the property.

RESEARCH AIM TWO:

Following the results of detailed investigations, does the property require substructure repairs?

REMEDIAL ACTION:

Indemnify or pay compensation for both remedial substructure repairs to the property, and for repairs to the visible damage to the superstructure of the property.

RESEARCH AIM THREE:

To consider how the thresholds of damage identified in Research Aims One and Two, if implemented in practice, would impact upon the non-technical problems relating to subsidence and heave damage in low-rise residential properties.

Figure 1.1: Flow chart to indicate the relationship between research aims

1.3.1: Identification Of Study Delimitations

The focus of this study is on low-rise privately owned residential properties damaged by ground subsidence or heave in Great Britain. In this context, the term "*low-rise building*" is taken to include buildings of up to three storeys above ground level. In occasional circumstances a low-rise building might contain a basement or roof space which would technically increase the number of storeys. However, for the purpose of this research, basement floors and habitable roof spaces are excluded in the determination of storey heights.

The reason that this study focuses specifically on low-rise privately owned residential properties is that this has been the ubiquitous type of housing constructed in Great Britain. It has accounted for the vast majority of all private owner-occupied housing, with this form of tenure representing approximately 67% of all homes in the United Kingdom (DOE, 1996). Since low-rise housing transmits a relatively small load to the ground and usually has a simple shallow foundation system, this makes low-rise housing potentially susceptible to ground subsidence or heave movement. Conversely, high-rise housing developments, which are almost invariably public sector developments, transmit greater loads and have individual specialist designed foundations affording such structures inherent resistance against subsidence movement. Therefore, high-rise residential buildings are considered beyond the scope of this research.

This study focuses exclusively on residential properties. Although subsidence and heave movement also physically affects commercial and industrial buildings, the non-technical consequences of such damage (the subsidence blight) are usually less significant. For example, non-structural cracking in an industrial building is likely to have less consequence to a property owner, insurer or surveyor than similar damage present in a privately owned low-rise residential property. The main reason for this being that industrial buildings are not usually required to provide such a high level of performance or be placed under such a high level of subjective scrutiny as residential properties.

A further important delimitation of this work is the fact that not all causes of ground subsidence are considered in this work. For example, mining subsidence encompasses a number of different causes including coal-mining, tin-mining, copper-mining etc. However, coal-mining and associated subsidence movement has occurred throughout many regions of the United Kingdom, often being undertaken in urban locations affecting a very large number of domestic properties and other structures. In contrast, other forms of mining tend to be much more localised, usually affecting only a small number of properties. Therefore, in recent times, coal-mining subsidence can be considered to have been a major cause of subsidence damage in domestic properties (see Chapters Two and Three). Another important example of subsidence that is not considered in this work is subsidence movement associated with filled or made ground. The primary reason for this is that foundations of buildings constructed in these types of ground should be specifically designed to accommodate any anticipated movement. Therefore, if damage does occur it is most likely to have occurred as a result of inadequate foundation design or site investigation for the type of ground condition.

1.4: METHODOLOGY

1.4.1: General

Before the three research objectives can be investigated, it is essential to carry out a critical analysis of the existing literature. Although reference has already been made to some of this literature, it is examined in greater detail in subsequent chapters. The initial review of literature was compiled through library searches. This readily identified several key organisations involved in this field, such as the Building Research Establishment (BRE), and several authors who were prominent in the subject field in terms of publications. Where possible, members of these organisations, and individual eminent authors were contacted directly to discuss the subject.

The literature review helped to analyse areas of previous research and enabled the research aims to be more precisely defined. In particular, the literature review highlighted that many of the technical issues relating to the subject had previously been covered. For example, BRE, through numerous digests, information papers and special publications, has extensively researched the shrinkage and swelling potential of clay soils. Similarly, technical issues including aspects such as tree root damage to buildings, design and construction of shallow foundations, and the repair of damaged structures have also been the subject of much previous research. All of the technical/engineering issues are founded upon the well-established principles of geotechnical engineering and are considered in detail in chapters two and three. In contrast, the non-technical issues, relating to subsidence blight have received comparatively little attention in both the academic and technical literature.

In addition to the literature review, several key conferences were attended (see Appendix A). This provided an opportunity to keep abreast of current developments in the subject field and also an opportunity to discuss the topic with some of the recognised experts.

Considering more specifically the methodology employed to investigate the three research aims, Mason (1996) highlighted that when considering research methodology, that it is necessary to develop an understanding of the methodological implications and to link research aims to research methods. This requires a clear understanding of how a particular method will address the research aims and also a consideration of the strengths and weaknesses of potential alternative research strategies.

In addressing research methodology, Mason (1996) distinguished between data sources and methods for gathering data from these sources. Therefore, before adopting a particular research method, it is first necessary to consider the potential sources of data collection. After identifying appropriate sources of data, the methods of gathering and analysing data can be addressed.

1.4.2: Sources Of Data

In linking research aims to methodology, Research Aims One and Two can be seen to address similar questions and therefore employ a similar methodology. However, the nature of Research Aim Three is somewhat different and this is reflected in the methodological approach adopted in the investigation of this research aim.

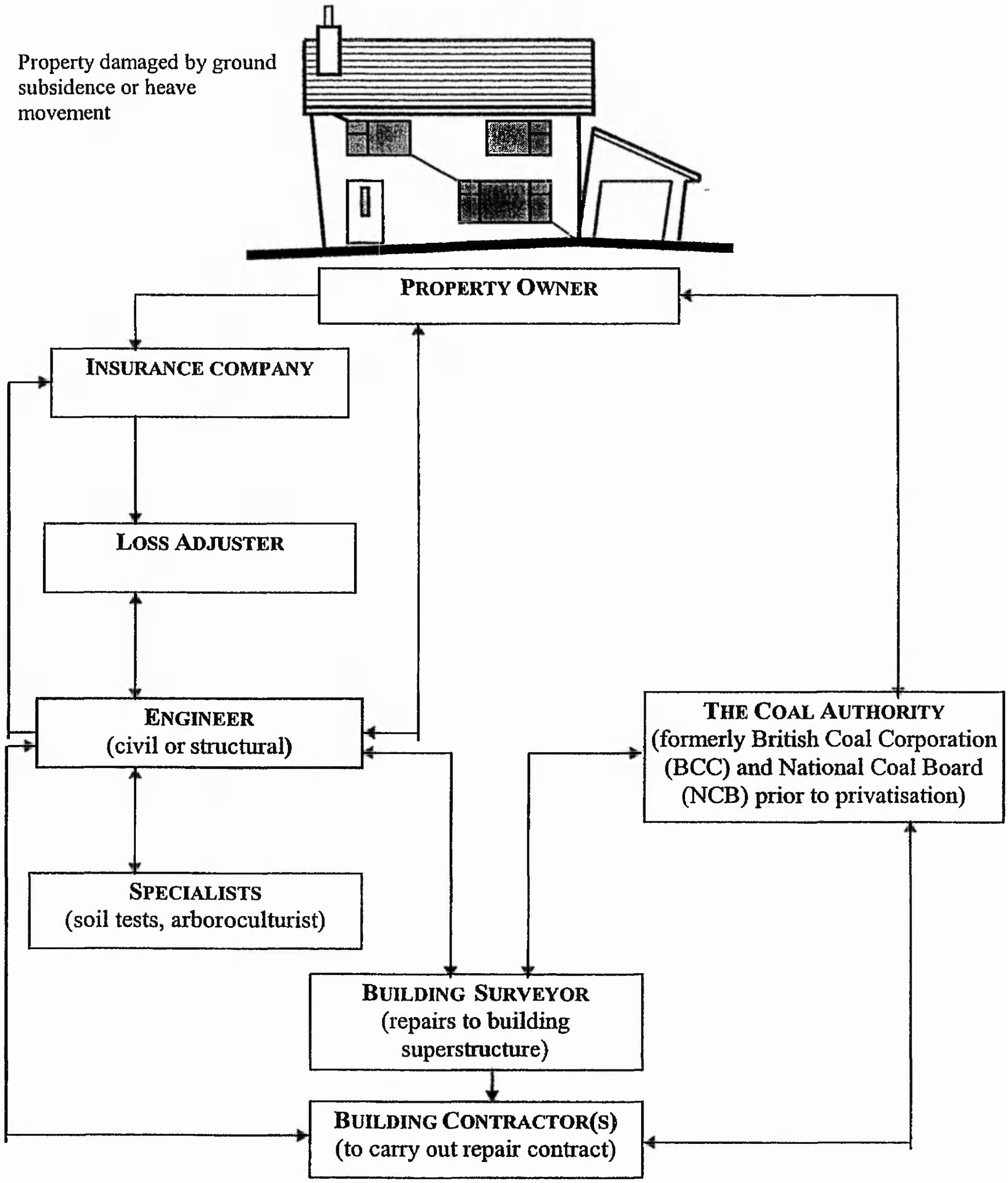
1.4.3: Data Sources To Investigate Research Aims One And Two

The nature of Research Aims One and Two suggest that it is necessary to gather quantitative data concerning low-rise properties damaged by ground subsidence and/or heave. Potential sources containing the data required are the various parties that become involved during a claim for subsidence or heave damage. For example, where a property owner suspects subsidence damage, he/she will seek professional advice about the matter. Subsequently, detailed information about the suspected damage in the property will be gathered by agencies including insurance companies, The Coal Authority, engineers, surveyors and building contractors. This information provides a valuable source of primary data for this research. The quality of this data, in terms of its reliability and validity, is enhanced by the fact that all investigations and analysis of the data are undertaken by professionally qualified chartered engineers, surveyors or other specialists. Therefore, data for the research was collected from this source.

Considering the relationships between the various parties that are involved in a typical case of subsidence or heave damage, Figure 1.2 shows the routes through which information 'flows'. The left side of Figure 1.2 relates to the situation in which an insurance company is responsible to deal with the consequences of the damage under the terms of a buildings' insurance policy. This indicates that all information 'flows' through an appointed engineer. In order to establish this, a number of interviews and desk studies were carried out with several engineering practices and building contractors specialising in subsidence work (see Appendix A). It was found that obtaining information about individual buildings from insurance companies and loss adjusters was difficult because these agencies regard their relationship with clients to be extremely confidential. However, it was possible to hold informal discussions with some agencies involved in subsidence work during conference presentations (see Appendix A). These discussions highlighted the role of the engineer as the agent who collected and analysed all data, and made recommendations based upon this data, although it was usually the loss adjuster or insurance company that sanctioned the recommendations of the engineer.

The right side of Figure 1.2 indicates the situation in which The Coal Authority are financially responsible for the consequences of coal-mining subsidence damage. Here it can be seen that all information 'flows' through The Coal Authority. This was confirmed through an initial interview with employees of The Coal Authority and was followed by a desk study review of the data held by The Coal Authority (see Appendix A).

An alternative source of data collection for this research would have been to examine and analyse actual buildings damaged by ground subsidence. However, a number of reasons made this approach impractical, the primary reason being that the number of individual detailed house surveys necessary to generate sufficient quantities of data would have proved problematical. For example, each building survey would have required an in-depth investigation, including, trial hole and subsoil analysis, tree root identification and the monitoring of any movement in the structure over a minimum 12 month period. To carry out these procedures on a potentially large number of buildings would be beyond the scope of this research. In addition, chartered engineers and surveyors establish their clients through their reputation built up over many years in practice. Therefore, taking into account the home-owner anxiety about the subject, it was considered that many home-owners would be unwilling to allow a third party to inspect their property, excavate trial holes, or fix monitoring equipment to the building fabric.



Left section of figure 1.2 indicating how information flows between agencies involved in a claim for compensation made under a household buildings' insurance policy

Right section of figure 1.2 indicating how information flows between agencies involved in a claim for coal-mining subsidence damage

Figure 1.2: The primary flow of information in a subsidence or heave compensation claim.

1.4.4: Methodology Adopted To Investigate Research Aims

After identifying the importance of the engineer and The Coal Authority as the primary sources of information, it was necessary to consider an appropriate research methodology to gather and analyse this data.

The data available at engineering practices and The Coal Authority was identified through a series of desk studies. A knowledge of the type of data available acted as a guide to the choice of methodology. For example, it was clear from the initial appraisal of data that a methodology employing experimental techniques was not appropriate to investigate the research aims as these techniques would not be compatible with the data available. Similarly, as much of the data was in a quantitative form, qualitative research methods, such as interviewing techniques were not considered appropriate. Therefore, the appropriate choices of research methodology were identified to be either survey research or multiple case study research. In the context of this research, both of these methodologies involved collecting information relating to a number of buildings damaged by ground subsidence or heave, and drawing conclusions.

Several authors, including Stake (1995) and Yin (1994) have advocated the use of case studies as a research strategy. Such a strategy involves examining an individual case or groups of multiple case studies in order to construct a theory based on the case studies. However, Yin (1994) identified that multiple case study research relies upon replication logic. This requires that each case must be carefully selected so that it either predicts similar results, or produces contrasting results but for predictable reasons. This approach can be contrasted with sampling logic used in surveys, where a number of subjects are assumed to represent a larger pool of subjects, so that data from the smaller number of subjects is assumed to represent data collected from the entire pool (Moser and Kalton, 1985).

A multiple case study research strategy, as described by Yin (1994) was rejected, because to rely on replication logic, and therefore select cases that predict either similar results, or contrasting results but for predictable reasons, would be restrictive and not consider the larger population. Therefore, any generalised theories constructed using this methodology would not be valid in a larger population of cases which had different results. Consequently, multiple case study research was not considered to be the best method to investigate the research aims.

Survey research was considered to be a more appropriate method to investigate Research Aims One and Two. This method involves gathering data from a sample of damaged low-rise buildings. For convenience, each of these individual buildings are referred to as '*case studies*', but in this context, the meaning of the term should not be confused with case study research as defined by Yin (1994) or Stake (1995).

After identifying survey research as the most appropriate method to investigate Research Aims One and Two, it was necessary to consider methods of generating data from engineering practices and The Coal Authority, which have previously been identified as the primary sources of data. Two approaches were considered as methods of data generation, these being:-

- <u>Direct access</u> (this method involves reviewing and assimilating '*first hand*' the information contained in the files of different engineering practices and The Coal Authority).
- <u>A postal questionnaire</u> (this method involves designing and administering a questionnaire to be completed by employees at different engineering practices and The Coal Authority).

The preferred method to generate data from the sources established was by reviewing and recording, first hand, individual files of cases produced by engineers and The Coal Authority. Within the context of this research, it was decided that significant methodological drawbacks existed in the use of a questionnaire survey, and these are discussed more fully below. In contrast, direct access to case files was considered to be potentially a much more robust method of data collection. This enabled all data to be collected according to defined selection criteria which followed the basic ideas of sampling (Moser and Kalton, 1985; Babbie, 1990 and Fellows and Liu, 1997). Selection criteria were applied to ensure that the data collected was both reliable and valid and the criteria used are discussed fully in the subsequent chapters covering the analysis of data. One potential disadvantage to using this method is the constraints involved in reviewing, recording and analysing data in sufficient detail to ensure adequate reliability and validity. This has therefore restricted the amount of information that can be collected for a study of this nature. However, a smaller sample of reliable and valid data is preferable to a larger sample of potentially unreliable data.

A postal questionnaire survey presented a possible method of data generation that would provide a convenient method of providing a potentially large sample of case studies. This approach was adopted in previous research undertaken by Wilkin (1993) in which respondents were asked to complete a series of prescriptive questions for a damaged building, and then repeat this procedure for up to ten additional cases of damaged buildings. This method would potentially allow a respondent completing the questionnaire to refer to the case file to ensure accurate answers are given. Set against this, several disadvantages must be taken into account.

The main disadvantage of a questionnaire technique, within the context of this research, is that there would be no guarantee that information would be based upon factual evidence rather than individual memory recall, particularly where information is supplied for multiple buildings. This could seriously compromise the reliability of the data.

A further problem associated with the use of a questionnaire methodology concerns question design and analysis of responses. Phrasing a set of questions aimed at obtaining data from such a complex and wide-ranging subject as a damaged low-rise building could be approached and overcome through the standard practice of pilot study exercises. However, perhaps the primary potential problem associated with a questionnaire in this context would be the analysis of responses. Questions requiring an open answer would make analysis between cases difficult restricting the validity of the data (Oppenheim, 1966). Therefore, closed questions would perhaps be more appropriate and provide a more robust method for answering factual questions, for example foundation depth. However, with reference to the issue of foundation depth as an example, in many buildings foundation depth is not uniform because of sloping ground. Without a detailed and laborious description in the questionnaire, respondents might provide different answers, such as the maximum, minimum, average, or depth of foundation in the vicinity of damage. Clearly, this would limit the validity of the answers as the questions might not actually test what they set out to test. Good questionnaire design should seek to eliminate such inconsistencies and provide both valid and reliable data. However, after careful consideration it was decided that to achieve this would require a prohibitively complex questionnaire. Consequently, other methods of generating data were considered.

1.4.5: Sources Of Data And Methodology In Relation To Research Aim Three

It has been explained that the objective of Research Aim Three is to establish what effect the findings emerging from Research Aims One and Two would produce if applied in practice. Therefore, to understand the implications of sources of data and methodology in relation to Research Aim Three requires a full appreciation of the findings emerging from Research Aims One and Two. Consequently, it is considered more appropriate to discuss the methodology employed to investigate Research Aim Three after the findings in relation to Research Aims One and Two have been presented, and this discussion is contained in Chapter Seven.

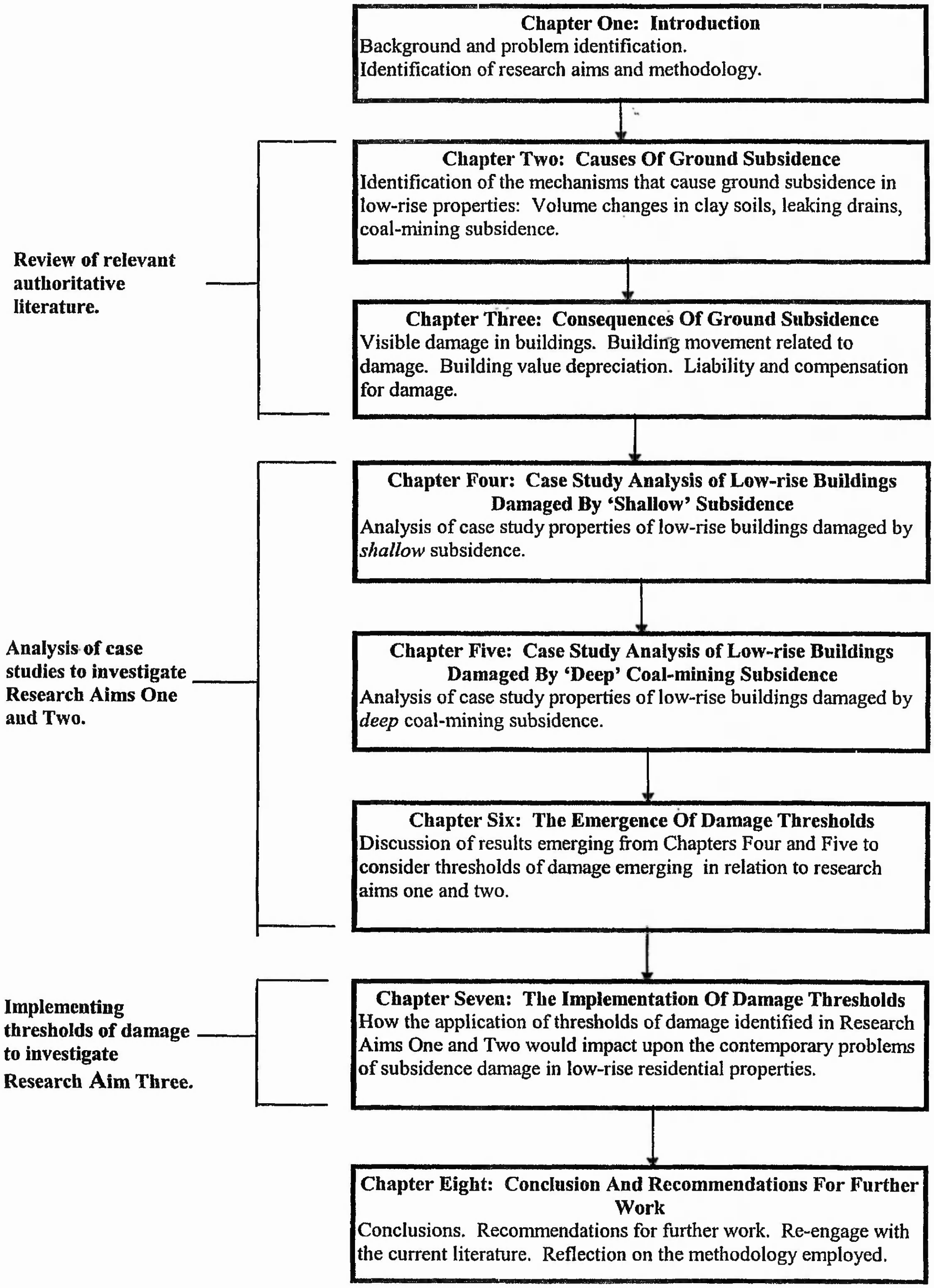
1.5: THESIS STRUCTURE AND CHAPTER SUMMARIES

Having identified the context of the research, the research aims and methodological issues, the following discussion indicates how the research aims and methodology relate to the content of this study. Figure 1.3 illustrates the thesis structure. This chapter provides an introduction to the content and structure of the thesis. Chapters Two and Three contain a review of the relevant literature relating to the subject. This is divided between Chapter Two, which considers the causes of subsidence and heave damage, and Chapter Three which considers the consequences. These two chapters, which focus on the relevant published literature, are intended to identify and explain the main problems and the previous work in the subject field.

After considering the literature, Chapters Four and Five analyse the data collected from case study buildings damaged by ground subsidence. Chapter Four relates to properties damaged by *shallow* subsidence, typically caused by volumetric changes in clay subsoil, or by leaking drains affecting the bearing capacity of the ground. Chapter Five relates to properties damaged by *deep* coal-mining subsidence.

Chapter Six draws on the results emerging from the case study analysis carried out in Chapters Four and Five to make a contribution to knowledge by considering the emergence of thresholds of damage in relation to Research Aims One and Two. After identifying these thresholds of damage in Chapter Six, Chapter Seven makes a further contribution to knowledge through considering what impact such thresholds of damage would make to the contemporary problems of subsidence damage, if these thresholds of damage were implemented in practice.

Chapter Eight draws together the main conclusions emerging from this research and identifies areas where further research in this subject field could be directed. This chapter also re-engages with the contemporary academic and professional debates and identifies the limitations of the research.



Chapter One: Introduction
Background and problem identification.
Identification of research aims and methodology.

Review of relevant authoritative literature.

Chapter Two: Causes Of Ground Subsidence
Identification of the mechanisms that cause ground subsidence in low-rise properties: Volume changes in clay soils, leaking drains, coal-mining subsidence.

Chapter Three: Consequences Of Ground Subsidence
Visible damage in buildings. Building movement related to damage. Building value depreciation. Liability and compensation for damage.

Analysis of case studies to investigate Research Aims One and Two.

Chapter Four: Case Study Analysis of Low-rise Buildings Damaged By 'Shallow' Subsidence
Analysis of case study properties of low-rise buildings damaged by *shallow* subsidence.

Chapter Five: Case Study Analysis of Low-rise Buildings Damaged By 'Deep' Coal-mining Subsidence
Analysis of case study properties of low-rise buildings damaged by *deep* coal-mining subsidence.

Chapter Six: The Emergence Of Damage Thresholds
Discussion of results emerging from Chapters Four and Five to consider thresholds of damage emerging in relation to research aims one and two.

Implementing thresholds of damage to investigate Research Aim Three.

Chapter Seven: The Implementation Of Damage Thresholds
How the application of thresholds of damage identified in Research Aims One and Two would impact upon the contemporary problems of subsidence damage in low-rise residential properties.

Chapter Eight: Conclusion And Recommendations For Further Work
Conclusions. Recommendations for further work. Re-engage with the current literature. Reflection on the methodology employed.

Figure 1.3: Thesis Structure.

1.6: CHAPTER SUMMARY

This chapter has introduced the background and context of the research undertaken in this study. The background relating to the subject of subsidence and heave damage to low-rise properties has been introduced to enable the research aims and objectives to be defined. Following this, the methodology adopted to investigate the research aims has been discussed, highlighting the importance of the research methodology in relation to the reliability and validity of data in the context of this study. Finally, the thesis structure and a brief summary of each chapter is included to guide the reader through the entire thesis.

CHAPTER TWO: CAUSES OF GROUND SUBSIDENCE

2.1: INTRODUCTION

This chapter considers the causes of ground subsidence and heave damage in low-rise residential properties. In order to fully appreciate the consequences of ground subsidence or heave damage, it is necessary to identify and understand the underlying cause(s) of damage. Any decision regarding the form of remedial action to repair a damaged property has to be based on knowledge rather than conjecture. In this respect understanding the cause of the damage is essential.

The previous chapter has highlighted that the aims and objectives of this thesis are primarily concerned with the non-technical aspects of subsidence damage. However, it is not possible to completely divorce the technical issues from the non-technical issues. Therefore, an understanding of both is necessary to fully understand the subject. Previous work has focused upon the technical aspects of subsidence damage in some detail, and there exists a well-established body of knowledge in this subject area. This chapter identifies the authoritative pieces of previous work that constitute this body of knowledge in relation to the causes of ground subsidence and heave.

2.2: DAMAGE IN LOW-RISE RESIDENTIAL PROPERTIES

Most low-rise residential properties are susceptible to damage caused as a normal consequence of minor variations in ground conditions, moisture effects and thermal effects. BRE Digest 251 (1993 edition) indicated that few buildings, if any, exist that do not have some form of damage, even if such damage is very minor and is not considered by the property owner to be significant.

This thesis focuses upon damage in low-rise properties caused by ground movement. However, it is important to be aware of the possible causes and consequences of damage that are unrelated to ground movement. A discussion of damage in low-rise properties that is unrelated to ground movement is beyond the scope of this research and can be found in many other references, for example, Hinks and Cook (1992); Bonshor and Bonshor (1996).

Page and Murray (1996), in a study of 501 traditionally-built low-rise residential properties in the East Midlands region of England, highlighted the significance of ground movement as the most common cause of structural defects. Although they highlighted that some structural defects can be specific to particular locations, it was found that 63.9% of structural defects in their sample were caused by ground movement.

Ground movement can result in damage to the foundations of a low-rise property, which in turn can cause damage to the superstructure of a property. There exists several causes of ground movement which can cause damage to low-rise properties. These include:

- Ground subsidence and heave.
- Differential foundation settlement.
- Frost heave.
- Chemical attack.
- Slope instability and landslip.
- Shock and vibration.
- Earthquakes.

Where damage in low-rise properties is associated with ground movement, Page and Murray (1996) identified differential foundation settlement and subsidence or heave as the primary causes of structural defects.

ISE (1994) provided a definition of the terms settlement and subsidence:

> **Settlement**
>
> "*Movement within a structure due to the distribution or re-distribution of loading and stresses within the various elements of construction*".
>
> **Subsidence**
>
> "*The downward movement of a building foundation caused by loss of support of the site beneath the foundations*".

Therefore, the principal test to distinguish between settlement and subsidence is to establish whether the downward movement of the ground would have occurred, at least to some extent, with no applied load from the building (ISE, 1994).

It has been set out in the previous chapter that this research specifically focuses on low-rise properties damaged by ground subsidence or heave. This is because damage associated with settlement normally occurs in the early life of a building as a result of the imposed load from the structure. In contrast, damage caused by ground subsidence or heave can occur at any time in the life of a building, but such movement can only occur as a direct result of an external factor, for example:

a. The loss of support associated with underground mining operations.

b. Changes in the ground moisture content.

2.2.1: Definitions Of *Shallow* And *Deep* Subsidence

For the purpose of this research, ground subsidence is divided into two types, these being ***shallow*** subsidence and ***deep*** subsidence. The term *shallow* subsidence is used in this research to define ground subsidence movement that occurs because of moisture content changes in the ground at relatively shallow depths. In such circumstances, the majority of ground movement is usually confined to the first 1.0m to 2.0m below ground surface level and rarely does movement extend to depths in excess of 5.0m below ground surface level. The term *deep* subsidence is used in this research to define ground subsidence movement that occurs as a result of underground coal-mining operations. Modern coal-mining operations take place several hundred metres below ground level and result in surface subsidence movement. The remainder of this chapter considers a review of the authoritative literature relating to the causes of ground subsidence.

2.2.2: Site Investigation

Before considering in more detail the causes of ground subsidence and heave, it is necessary to be aware of the relevance of site investigation. Site investigation can be divided into two categories, these being 'pre-construction' and 'post-damage'. In the context of this research, it is the 'post-damage' site investigation which is of relevance. In comparison with 'pre-construction' site investigation, there exists little published literature that covers the subject of 'post-damage' site investigation. However, some of the principles of 'pre-construction' site investigation apply to a 'post-damage' site investigation. In addition to considering the causes of ground subsidence, a full 'post-damage' site investigation should include reference to surface characteristics, including visible damage and whether or not movement is progressive. These important issues are considered in the following chapter, which along with the causes of damage identified in this chapter, covers all the necessary aspects of a 'post damage' site investigation.

Hunt *et. al.* (1991) made a distinction between '*site*' investigation and '*ground*' investigation. Their definition of ground investigation includes those activities that provide specific information about the properties of the ground. It is these issues that relate to the causes of ground subsidence and which form the remainder of this chapter.

2.3: GROUND MOVEMENT CAUSED BY SHALLOW SUBSIDENCE

The causes of shallow subsidence can be divided into two broad groups, these being:

a. Volumetric changes in clay soil.

b. The effect of leaking drains.

2.3.1: Volumetric Changes In Clay Soil.

An awareness that significant amounts of movement can occur in clay soil as a result of variations in soil moisture content was highlighted by Ward (1948). It was recognised that seasonal changes caused by the presence of large vegetation (such as tress or large shrubs) produce volume changes in clay subsoil, and that where foundations are too shallow, differential movement can result in damage to the superstructure of a property. In more recent times, the problems of volumetric changes in clay soils was highlighted by a period of drought in 1975-76. Ward (1948), BRS Digest 3 (1949) and Pryke (1979) all reported significant damage had occurred to buildings due to periods of drought in previous years. However, the drought of 1975-76 occurred only four years after the introduction by insurance companies of indemnity against subsidence damage occurring in privately owned low-rise properties. This increased public awareness of subsidence damage in low-rise properties.

It is beyond the scope of this research to consider a detailed study of soil mechanics, which can be found in standard text books, and therefore this section attempts only to provide an introduction to the complex subject of ground subsidence movement caused by volumetric changes in clay soil.

2.3.2: Properties Of Clay Soil

BRE Digest 240 (1993 edition) outlined the nature and extent of shrinkable clay soil in Great Britain. This Digest defined the terms liquid limit, plastic limit and plasticity index, which are used as a guide to the engineering properties of clay. The liquid limit (L.L.) identifies the water content at which a clay soil starts to lose its '*plastic*' (mouldable) properties, and begins to flow. The plastic limit (P.L.) identifies the water content at which a clay soil can no longer be moulded without breaking up. The water content of the soil is defined as the ratio of the mass of water in the soil to the mass of the oven dry soil. The plasticity index (P.I.) of the soil is given by the difference between the liquid limit (L.L.) and the plastic limit (P.L.), hence:

$$\text{P.I.} = \text{L.L.} - \text{P.L.}$$

BRE Digest 240 (1993 edition) stated that, as a general rule, the greater the plastic index, the greater the potential for a clay soil to change volume. In addition, Robson (1991) pointed out that another factor which has an influence on shrinkage or expansion is the fraction of non-clay particles within the soil, such as sand and gravel, which modify the shrinkage potential. BRE Digest 240 (1993 edition) defined soil particles which have a nominal diameter of less than 0.002mm as normally being considered to be of clay-size, and defined the term '*clay*' as a soil which contains enough clay-sized material or clay particles to exhibit cohesive properties. The fraction of clay sized material can be as low as 15%. Robson (1991) stated that there is no established point below which clay content is too low to affect shrinkage, but that its influence appears to decline rapidly below 30%.

The subject is further refined in BRE Digest 240 (1993 edition), by considering that the type of clay mineral in the soil is as important as the quantity in terms of behaviour of the clay, an issue also highlighted by Driscoll (1983; 1984).

2.3.3: Classification Of Clay Soils

BRE Digest 240 (1980 edition) proposed a classification of clay soil based on the plasticity index and percentage clay fraction. BSI (1981) identified a categorisation based on the liquid limit of a soil. BRE Digest 240 (1993 edition) suggested a classification of clay volume change potential that uses a modified plasticity index ($I'p$) which takes some account of the percentage of soil particles with a nominal diameter greater than 0.425mm. The percentage of material which is less than 0.425mm (%<0.425mm) is separated by sieving before measuring the liquid and plastic limit, and the modified plasticity index is given by:

$$I'p = \text{P.I.} \times \frac{(\%<0.425\text{mm})}{100\%}$$

The original classification proposed in BRE Digest 240 (1980 edition) was revised in BRE Digest 240 (1993 edition) to avoid confusion with the more commonly used classification given by NHBC (1994). In addition, it is demonstrated in BRE Digest 240 (1993 edition) that for most clays with a high volume change potential the difference between plasticity index (P.I.) and modified plasticity index ($I'p$) is minimal. These classifications of the volume change potential are shown below in table 2.1.

BRE Digest 240 (1993 edition)	NHBC (1994)	
Modified plasticity index $I'p$	**Plasticity Index (P.I.)**	**Volume change potential**
>60	>40	Very high
40-60		High
20-40	20-40	Medium
<20	<20	Low

Table 2.1: **Classifications of clay soil volume change potential (BRE Digest 240, 1993 edition and NHBC, 1994).**

It is widely reported that clay soils with a high volume change potential occur in the South Eastern half of England, to the south of an imaginary line drawn between Hull and Exeter as shown in figure 2.1, although Robson (1991) pointed out that clays with some degree of shrinkage potential are found in most other areas.

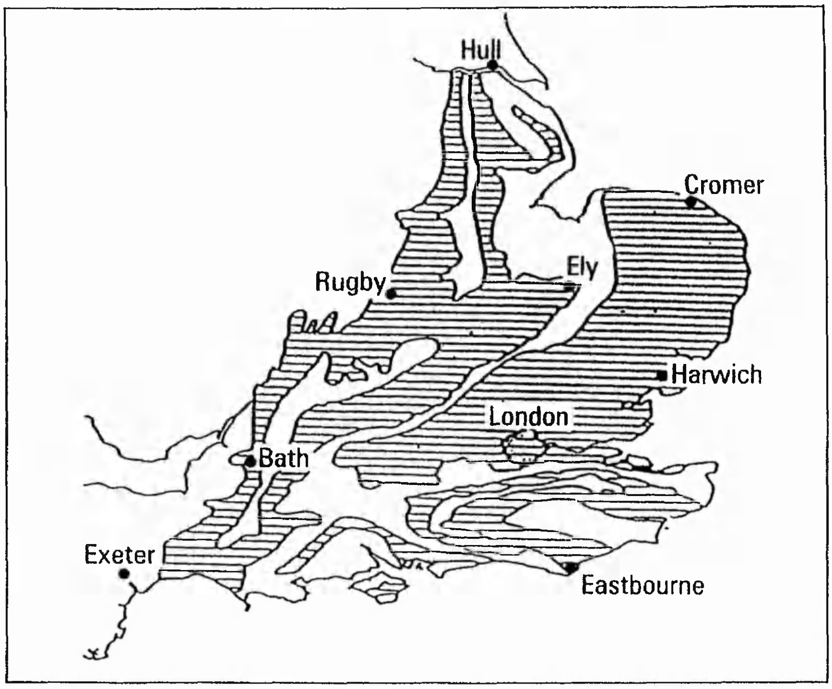


Figure 2.1: **The distribution of firm shrinkable clay soils within Great Britain (BRE Digest 240 1980 edition).**

2.3.4: The Effect Of Moisture Content On The Volume Change Potential Of Clay Soils

The previous part of this chapter has considered the volume change potential of clay soils. Hence, it can be appreciated that despite variations in the amount and type of clay minerals which are inherent properties of the clay, the moisture content of a clay has a direct influence on its volume change potential. BRE Digest 240 (1993 edition) explained that a reduction in soil moisture content results in shrinkage of the clay, defined as subsidence. An increase in the soil moisture content results in expansion of the clay defined as heave. Any change in effective stress, and hence any change in water content, can be brought about by:

A. A change in the imposed loading of the soil.

B. Changes in soil moisture content caused by:

- Leaking drains or service pipes.
- The effect of climate conditions.
- The effect of large vegetation (such as trees or large shrubs) extracting moisture from the ground.

2.3.5: Changes In The Imposed Loading Of The Soil

Any change in the imposed loading of a soil results in a change in the effective stress of that soil, which in turn changes the soil moisture content causing a volumetric change. An increase in the imposed loading of a soil, although resulting in a volumetric change of the clay soil, could be interpreted as settlement rather than subsidence. The definition of subsidence given by ISE (1994) indicated that the principal test to distinguish between settlement and subsidence is to establish if the movement would have occurred, at least to some extent, with no applied load from the building. Regardless of this, BRE Digest 240 (1993 edition) considered that, for most clays, the imposed loading of foundations of low-rise buildings is unlikely to result in any significant soil moisture content changes that could cause ground movement detrimental to low-rise properties.

2.3.6: Changes In Soil Moisture Content Caused By Leaking Drains Or Service Pipes

Changes in the soil moisture content of clay caused by leaking drains or service pipes can cause either subsidence by wetting a clay resulting in a loss of bearing capacity, or heave by increasing the moisture content of a clay and hence causing expansion. These causes of ground subsidence and heave are discussed below in section 2.3.16 of this chapter, where the effect of leaking drains or service pipes are considered in relation to both clay soil and granular soil.

2.3.7: Changes In Soil Moisture Content Caused By The Effect Of Climatic Conditions

Considering changes in soil moisture content caused by climatic conditions, Ward (1948) argued that on '*open field*' clay sites, clear of vegetation, it is necessary to place external wall foundations of brick and masonry buildings at not less than about 3 feet (900mm) deep to avoid the risk of ground movement. Such movements are caused by the effects of evaporation of soil moisture during periods of dry summer weather, usually in conjunction with periods of extended solarisation. Chandler (1993) explained that the seasonal '*open field*' pattern of shrinking and swelling, with its corresponding soil water content changes, is controlled by the local climate conditions. Seasonal variations in rainfall can typically result in a net infiltration of moisture into the ground for a few months during the winter at which time the ground is considered to be at its '*field capacity*'. However, on average throughout the year, the soil moisture content is below its field capacity and a soil moisture deficit (s.m.d.) exists. Figure 2.2 shows the national picture for the average s.m.d. (after Hunt *et. al.,* 1991) measured in millimetres (mm). The highest values of s.m.d. can be seen to exist in South East England, where there are also large areas of shrinkable clays. Hunt *et. al.* (1991) estimated that this same area contained approximately 80% of all underpinning work carried out in the United Kingdom.

The requirement for a minimum foundation depth of 900mm on clay sites clear of trees has been set out in relevant British Standards, Codes of Practice and BRE Digests published since the late 1940s (BSI 2004, 1972; BSI 8004, 1986; BSI 8103, 1986; BRE Digest 241, 1993 edition).

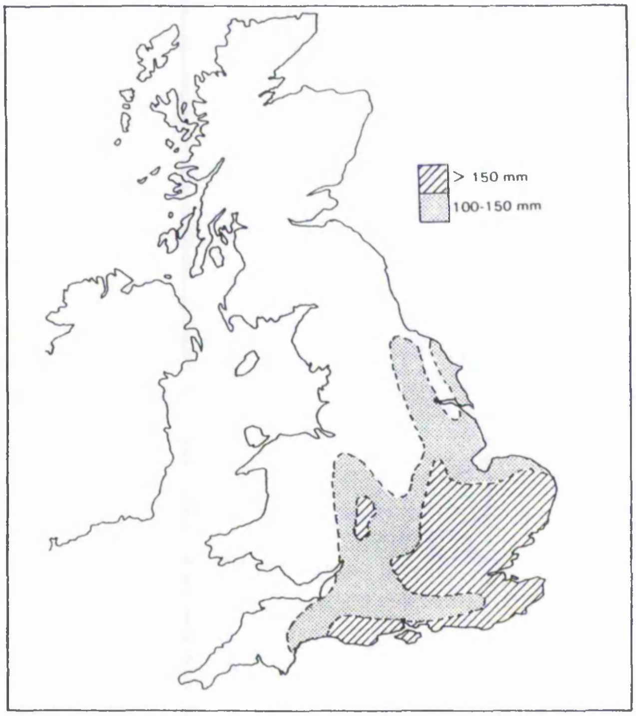


Figure 2.2: **Distribution of peak soil moisture deficit (s.m.d.) in the United Kingdom (Hunt *et. al.*, 1991).**

Both Tomlinson *et. al.* (1978) and Boden and Driscoll (1987) reported that even during the dry summer of 1976, there appear to have been few proven cases of damage to buildings founded at a minimum depth of 900mm (this depth being equivalent to three feet (3'), but nowadays taken as 1.0m). Driscoll *et. al.* (1996) confirmed this finding taking into account more recent periods of dry weather. However, Pryke (1974; 1979; 1993) considers that the requirement for a minimum foundation depth of 1.0m is inadequate in clay soil, even where there are no trees present and advocates the use of deeper foundations, including short-bored piled foundations as first suggested by Green (1952) and Ward and Green (1952). The logic behind Pryke's recommendation for deeper foundations is to take into account any future tree growth.

2.3.8: Changes In Soil Moisture Content Caused By The Effect Of Vegetation

The presence of vegetation on clay sites can cause volumetric movements to depths significantly in excess of 1.0m below ground surface level. The potential conflict between the proximity of trees in relation to buildings has resulted in much debate. Again, it was Ward (1948) who highlighted the effects of large vegetation in relation to volumetric changes in clay soil.

The effect of tree roots extracting moisture from clay soil is a common cause of subsidence and heave damage to low-rise buildings. Biddle (1979) highlighted this by presenting the results of over 200 detailed 'post damage' site investigations undertaken during the two years immediately following the 1975-76 drought. In 23 of these cases, there was no damage to the building, with the householder making a claim to their insurers on a precautionary basis. If these 23 cases are excluded, Biddle (1979) reported that in 88 cases (50%) full liability was apportioned to trees; in 57 cases (32%) partial liability was apportioned to trees; and in 32 cases (18%) no liability was apportioned to trees. The basis on which Biddle apportioned liability is not entirely clear, but despite this, the significance of trees as a cause or a contributory cause of damage is clearly evident. This assertion is reinforced in a more recent study by LPC (1995) which found that trees were implicated as a cause of damage in 73% of 708 cases of buildings damaged on clay soil.

The complex interaction between trees and buildings situated in clay soil is shown in figure 2.3 by Biddle (1979), who highlighted the factors that must be considered when assessing the involvement of trees as a possible cause of building damage. Biddle (1979) summarised these factors as follows:

- *Climate, affecting water input as rainfall, and water loss in evaporation and transpiration.*
- *Water demand of tree.*
- *The moisture deficit produced in the soil as a result of the water demand.*
- *Soil permeability affecting the moisture movements, and related to this the soil structure which influences the pattern of rooting.*
- *Soil shrinkage, which determines the amount of foundation movement that occurs.*
- *Soil strength, determining the risks of settlement damage, and of progressive foundation failure.*
- *Building movement, producing the structural damage.*

2.3.9: The Effect Of Tree Roots On Clay Soil

ISE (1994) identified three separate types of movement where trees and/or large vegetation interact with shrinkable clay soils. These are:

i. *Seasonal.*
ii. *Long-term.*
iii. *Extreme climatic movements.*

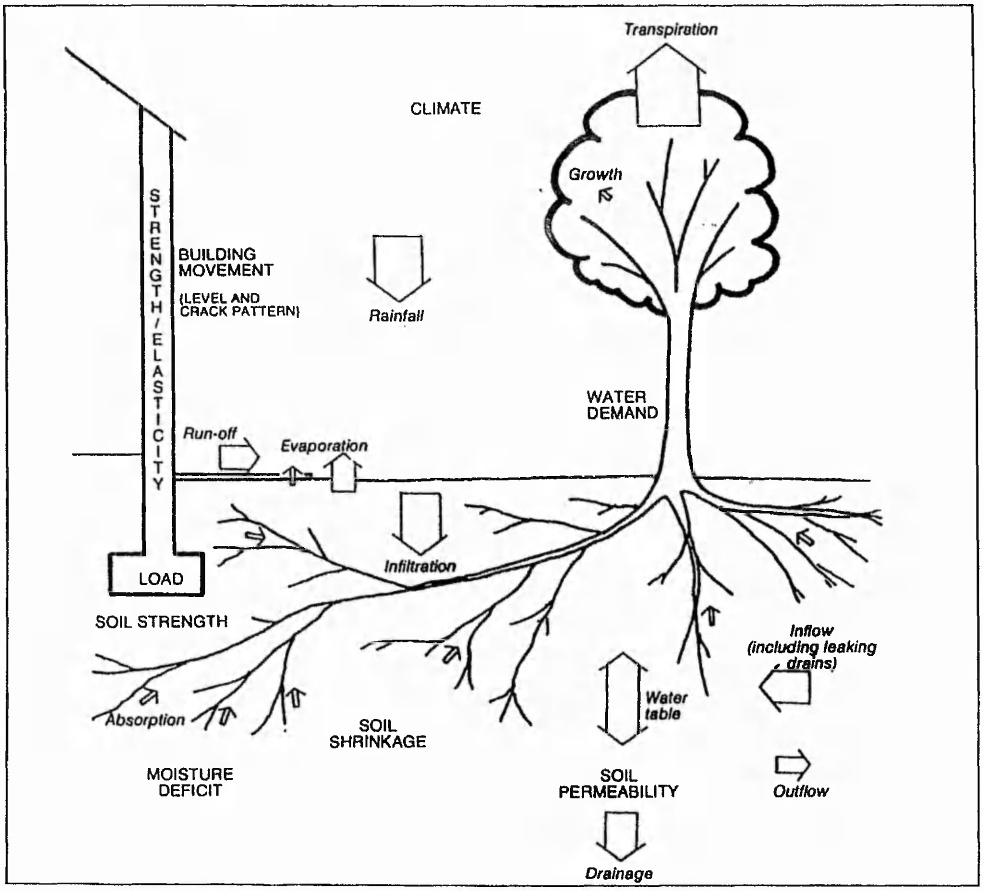


Figure 2.3: **Diagram showing main water movements (*italics*) and factors for consideration when investigating possible involvement of trees in cause of subsidence damage, after Biddle (1979).**

Seasonal movement occurs during summer months when trees extract most moisture and dry the soil progressively, with the soil reaching its driest in early autumn. In the autumn and winter there is little water extraction by trees and higher rainfall allows the ground to re-hydrate by late spring. This seasonal change in moisture content produces corresponding shrinking and swelling of a clay. The amplitude of movement depends on the plasticity index of the clay, the water demand, proximity of the tree, and the weather conditions.

Long-term movement occurs where the soil fails to regain moisture during the winter months. A persistent soil moisture deficit becomes established where the winter drawback of moisture (through rainfall) is inadequate and a zone of permanently desiccated soil develops below the surface soil (desiccation is considered below in section 2.3.13). Desiccation occurs where winter rainfall is low, or because a tree continues to grow extracting increased amounts of moisture over a period of years, which in turn increases the zone of desiccated soil causing long-term subsidence in the vicinity of the tree. This situation can often be made worse as the surface layer of a clay can expand on initial wetting, resulting in reduced permeability at the surface and therefore preventing the ingress of further moisture to re-hydrate the soil.

Extreme climatic movements occur during particularly hot summer periods, which cause trees and vegetation to search harder for moisture. This results in increased levels of desiccation, extending the boundaries of an existing zone of desiccation. This can be so severe that recovery cannot occur during a single winter period. Where one dry year follows another there is a cumulative effect on desiccation and therefore ground movement. ISE 1994 explained that such periods of extreme climatic movements occurred in 1975-76 and 1989-90, causing an increase in the number of subsidence claims.

2.3.10: The Potential Conflict Between Trees And Buildings

The debate within relevant literature has tended to consider two separate approaches in relation to the proximity of trees and buildings. The first approach has focused mainly on lateral separation of tree and building, whilst the second approach has focused mainly on designing building foundations to avoid damage caused by tree roots.

2.3.11: Lateral Separation Between Tree And Building

In clay soils found in South East England, Ward (1948) suggested, as a rough working rule, that the roots of isolated trees extend laterally in open ground to a distance of at least the height of the tree. Cooling (1951; cited Ward, 1953) suggested that buildings with shallow foundations should be kept away from trees a distance equal to the height of the mature tree. Ward (1953) suggested that in the case of dense rows of trees that the building and trees be separated by one and a half times the height of the trees. These guidelines were re-iterated in BRE Digest 63 (1965). NHBC (1969) refined these guidelines by taking into account the higher water demand of poplar, elm and willow trees.

However, it was the drought of 1975-76 which focused attention upon the potential conflict between trees and buildings. The nature of this conflict was echoed by Pryke (1979),

> *"There is a school of thought amongst professional surveyors and engineers that reasons that when damage is caused by foundation instability arising from moisture changes in shrinkable clay and that trees are nearby with roots that penetrate beneath foundations, then the cure is to remove the tree and after an interval to repair the crack"*.

These sentiments were also expressed by Driscoll (1983) considering the drought of 1975-76,

> *"......an increased public awareness of the possible contribution of tree roots to foundation movement and house damage resulted in many trees being felled without evidence of their culpability"*.

The above statements highlight the conflict concerning the potentially damaging effect that trees can have on buildings. In contrast, several arguments have been suggested that questioned the extent of tree damage to buildings. These arguments originated from arboroculturists rather than surveyors or engineers. Aldous (1979) considered that the role of trees in relation to building damage was much exaggerated following the aftermath of the 1975-76 drought. Flora (1978) was critical of the guidelines suggested by Ward (1953) in relation to the proximity of trees and buildings. These criticisms included the argument that Ward's work related to houses with foundations of only about 425mm deep which were in close proximity to lombardy poplar trees. Flora (1978) argued that it was unreasonable to assume that all trees behave in the same manner and therefore that Ward's guidelines should not be applied where different circumstances exist. Flora (1978) also considered the implications of strictly applying the recommendations suggested by Ward (1953) by highlighting the loss of amenity value and the environmental impact of removing trees.

Reynolds (1979), considering the issue of proximity of trees and buildings, highlighted that guidelines pre-supposed that the rooting of trees is reasonably regular and can be related to the tree height only with an unacceptably large safety margin. However, after conducting a review of world-wide literature on tree roots, Reynolds (1979) was not able to suggest any alternative to the guidelines of Ward.

Cutler and Richardson (1981; 1989) collected data on buildings damaged by tree roots and provided information including tree species, the distance from the tree to the damaged building, tree height and soil type. Driscoll (1983) used the results obtained by Cutler and Richardson (1981) to suggest that a more practical working rule for most tree species would be to restrict the distance between tree and building to about half the expected mature height of the tree. According to the results of Cutler and Richardson (1981), this rule would have prevented 75% of all cases of tree root damage to the buildings in their study. However, Driscoll (1983) did not provide any explanation for the remaining 25% and Statham and Thomas (1984) expressed concerns by stating that if the recommendations of Driscoll (1983) were accepted,

> "*....we can probably all look forward to even higher professional indemnity premiums in the future*".

Biddle (1983) indicated that the results of Cutler and Richardson (1981) were based on the existing housing stock, much of which had very shallow foundations, and their results provided no data on the depth of tree roots in relation to building foundations.

2.3.12: The Design Of Building Foundations To Avoid Tree Root Movement

BSI (1991) advised that consideration should be given to future tree planting or self-seeding and foundation design should consider this. Reynolds (1979) suggested looking for an alternative solution to the problem of trees and buildings rather than having to admit to some rule of proximity. Reynolds (1979) highlighted that the building foundation is the best understood part of the interaction between tree and building.

Biddle (1983) considered a different approach towards the prevention of subsidence damage, suggesting that emphasis should be placed on the acceptance that trees will be planted or grow near to buildings, and therefore foundations should be designed to take this into account. Biddle's work investigated patterns of soil moisture deficit near 36 different trees, covering a range of tree species and clay types. Although it had previously been known that poplar, elm and willow produce greater effects of movement, the magnitude of these differences was demonstrated by Biddle (1983). This finding can be seen to support the argument of Flora (1978), who suggested that to apply the guidelines suggested by Ward (1953) for all tree types was unnecessarily restrictive when Ward's work related mainly to poplar trees. Biddle (1983) further suggested that an increase in foundation depth to 1.5m on very high shrinkable clay should be sufficient to accommodate most tree planting designs with species of moderate water demand (excluding poplar, elm and willow). The findings of Biddle (1983), supported the view of Pryke (1974; 1979; 1993) in calling for increased foundation depths in clay soils. However, Biddle (1983) goes on to suggest that a foundation depth of 1.0m is adequate for clay with a lower shrinkage potential.

The work of Biddle (1983) was partly commissioned by NHBC and formed the basis of its guidelines relating to trees and buildings, published in various editions of NHBC standards. These standards provide guidelines on appropriate foundation depth near trees and proximity of trees from buildings, by taking into account tree water demand, distance from tree to building and soil type. Commenting on the proposed introduction of these guidelines by NHBC, Biddle (1985) stated that the benefits would include making houses less vulnerable to foundation movement and provide greater freedom in landscaping. Biddle (1985) further asserted that, although the guidelines would result in more expensive foundations, these costs would be offset by reduced insurance premiums through reduced need to re-decorate because of frequent minor damage.

A criticism directed towards the work of Biddle (1983) is that his observations did not include a drought period (Statham and Thomas, 1984; Wilson and Burbidge, 1984) and that foundation design should take this into account. However, Biddle acknowledged this fact by stating that during his research none of the years had been particularly dry. In addition, NHBC guidelines have been criticised by Crilly (1994) and Pryke (1995) who identified that many problems caused by tree roots to low-rise buildings occur after the ten year warranty provided by NHBC has expired, when trees have matured.

The approach of designing foundations to avoid tree root movement was considered by Ward and Green (1952) and Green (1952), who advocated the use of short-bored piled foundations with ground beams in clay soils. Since this time, BRE has suggested that trees and buildings can exist without conflict, regardless of proximity, where piled foundations are used. The use of piled foundations on clay soil in the presence of trees was also considered to be the best technical solution by Johnson (1982), who reviewed eight case histories of buildings damaged by clay shrinkage or swelling.

After reviewing the literature, there appears to exist little or no consensus concerning the placing of trees and buildings in relation to each other. In the presence of such a lack of consensus, it would appear that the precautionary principle prevails.

2.3.13: The Effect Of Desiccation On Clay Soils

The term '*desiccation*' is used to describe a soil which has a reduced soil moisture content. Desiccated clay soil is a major cause of subsidence damage to low-rise buildings. A soil can be described as desiccated even where soil moisture content is reduced by only 1% or 2%. Driscoll (1983) used the results of Croney (1977) to show that, for some undisturbed samples of expansive British clays, there is a relationship between moisture content (and hence volume change) with the suction exerted by a clay soil. If the moisture content of a soil is increased, the clay is allowed to expand and this expansion results in an increase in stress within the soil. Driscoll (1983) considered that the onset of desiccation could be presumed to commence where the reduction in moisture content of the soil (usually caused by tree roots extracting moisture) causes a notable increase in stress change. He further considered that significant desiccation could be taken to have occurred where the increase in stress in the soil is sufficiently large to lift a low-rise building. Driscoll (1983) went on to suggest that crude estimates of various states of desiccation can be detected by relating the moisture content of the soil (w) to the liquid limit (L.L.), such that the onset of desiccation occurs where $w = 0.5$L.L., and significant desiccation occurs where $w = 0.4$L.L.

It has been shown by Statham and Thomas (1984) that the crude method suggested by Driscoll (1983) to detect desiccation may not be reliable. BRE Digest 412 (1996) identified and assessed four main groups of techniques for detecting desiccation, which are:

i. Comparison of soil water contents with soil index properties (as suggested by Driscoll (1983)).
ii. Comparison of soil water content profiles.
iii. Comparison of strength profiles.
iv. Effective stress or suction profiles.

BRE Digest 412 (1996) acknowledged that the first option can give misleading results and that the other three methods were preferable. However, BRE Digest 412 (1996) stated that the first method of desiccation detection, comparing index properties with moisture content, is usually the least expensive and least complicated method to detect desiccation. It has also been found to be the method invariably employed in practice in the case studies used in this research (see Chapter Four).

2.3.14: Ground Heave Caused By The Removal Of Trees

Where a tree has extracted moisture from a clay, if the tree is removed, water is allowed back into the clay. This can result in swelling, as the re-hydration of moisture reduces the effective stress within the clay. Such swelling pressure can be very large. Boden and Driscoll (1987) explained that such forces can easily lift buildings of up to three storeys in height. Samuels and Cheeney (1974) and Cheeney (1988) reported the effects of up to 160mm heave on a bungalow. Driscoll (1983; 1987) also documented cases of damage caused by ground heave resulting from tree removal. BRE Digest 241 (1993 edition) and BRE Digest 242 (1993 edition) provided guidance for house foundations in swelling soils. BRE Digest 298 (1987 edition) considered the influence of trees on house foundations in clay soils and provided guidance to prevent damage caused by ground heave.

The potential effects of ground heave resulting from desiccated clay subsoil can be demonstrated by considering that the increase in stress imposed on the soil by a low-rise building supported on strip foundations is between 20 - 60 kN/m^2. However, the stress changes caused by the release of suction as a desiccated clay re-hydrates are typically 300 kN/m^2, and can be as high as 1400 kN/m^2 (BRE Digest 240, 1993 edition). The resultant volume changes in the soil are therefore significantly large and up to 100mm to 200mm of ground heave can occur as a result of desiccated clay soil (ISE, 1994).

2.3.15: Solutions To The Problems Of Tree Root Damage To Buildings

BRE Digest 298 (1987 edition) considered solutions to tree root problems caused to low-rise buildings. These solutions considered the age of the tree in relation to the house and the future growth of the tree. Biddle (1992) stated that when movement is entirely seasonal, it may be possible to reduce such movement by pruning the tree to remove leaf area. Biddle (1979) suggested controlling growth rate and therefore water demand by pruning, indicating that there exists a relationship between growth and transpiration, and that about 99.9% of water demand of a tree is required to meet transpiration losses.

Biddle (1992) further suggested that where a persistent soil moisture deficit exists, pruning alone will not be effective and it may be necessary to underpin the building. He indicated that the majority of foundation movements caused by tree root activity are predominantly, or entirely, seasonal. Where the foundations would be adequate but for the presence of trees, dealing with the trees by pruning or felling is usually the preferred option. Driscoll (1987) considered that the removal of an offending tree may be a preferable alternative to expensive, disruptive underpinning, although Biddle (1992) highlighted the environmental value of trees. Both BRE Digest 298 (1987 edition) and Biddle (1992) considered that root barriers are not a practical solution.

2.3.16: The Effect Of Leaking Drains

Little published literature exists which considers the subject of leaking drains or service pipes causing ground subsidence. However, leaking pipes remain a significant cause of damage in low-rise properties. Biller (1997) considered that, in a typical year, claims to insurance companies for subsidence caused by leaking drains or service pipes accounted for a consistent proportion of all claims made for subsidence and heave damage to low-rise buildings. Each year this proportion is supplemented by claims resulting from volumetric changes in clay soil which are related to the weather conditions for the year (Biller, 1997).

Page and Murray (1996) found that leaking drains were a contributory factor in 27.4% of all structural defects investigated in a study of 501 traditionally-built residential properties. LPC (1995) found that failure of drains was a contributory factor in 21% of 1,121 suspected or proven cases of subsidence damage in low-rise properties.

Leaking drains mainly result in subsidence in granular soils by washing away constituent soil particles, although Robson (1991) pointed out that leaking water causing subsidence in clay by softening is not unknown. Water escaping from leaking drains can also result in clay heave. However, in clay soil the permeability of the clay will usually restrict the ability of water to flow into the clay.

In granular soils, water movement can transfer fine soil particles away from the ground supporting a building, leading to possible subsidence. Ground water movement can be due to natural causes; seepage from, or into, fractured drains, sewers or water mains and the effect of rainwater discharging into the ground adjoining a building.

Leaking drains can be caused by a variety of circumstances, for example, volumetric changes in clay soil resulting in movement of drains below ground level, or tree roots penetrating defective or decaying drainage pipes in their search for moisture. Not all drainage systems are designed to accommodate movement, especially drains serving older properties. Therefore, the movement of the ground, or action of the tree roots causing ground movement could result in drainage damage, which in turn causes water leakage. In these circumstances, leaking drains can be seen as an effect, or consequence of ground movement, rather than be classified as the primary cause of damage. However, leaking drains can also occur in other circumstances, which include deterioration due to age, poor workmanship and incorrect positioning of drains. In these circumstances, the effect of escaping moisture caused by defective drains can be seen to be the primary cause of subsidence.

2.4: GROUND MOVEMENT CAUSED BY COAL-MINING (DEEP SUBSIDENCE)

Some degree of movement in the land surface is an unavoidable but inevitable consequence of modern deep coal-mining operations. The Coal Authority has a considerable amount of knowledge of subsidence damage from its experience of deep coal-mining. Analysis of empirical observations of subsidence in different mining and geological conditions has enabled the effects of deep coal-mining on the ground surface to be predicted with a high degree of sophistication (Coal and the Environment, 1981).

2.4.1: The Nature Of Modern Coal-Mining Operations

Underground coal-mining in the United Kingdom has, in modern times, been by the use of the longwall method, in which a wall of coal is continuously cut across a width of a coal seam. Each cut results in the progress of the face further into the coal seam. As the coal face advances, no attempt is made to provide long-term support to the void created by the extraction of coal. The ground above the void is therefore allowed to collapse. The consequences of this collapse are transmitted to the surface, which results in a lowering of the ground causing subsidence (see figure 2.4).

The extent of surface subsidence depends on the depth below ground level of the coal face, the width of the face, and the thickness of coal extracted. The thicker the coal seam extracted, the greater the void that will be left for the ground above to collapse into, and therefore, the greater the amount of subsidence at the ground surface.

Subsidence caused by coal-mining is not restricted to the area vertically above the coal that is extracted from the ground. The area at the surface that will be affected by subsidence extends beyond the area of coal that is extracted below ground level. The angle between the outside edge of the zone of coal extracted and the outer limit of ground movement is known as the angle of draw. In most British coalfields it averages about 35 degrees (NCB, 1975). As the depth of mining below ground level increases, the larger the surface area that is influenced by subsidence. However, for a given thickness of coal extracted, the deeper the coal-mining below ground level, the less the effects of subsidence. This is because the effects will be attenuated through a greater depth of ground above the void (see figure 2.5).

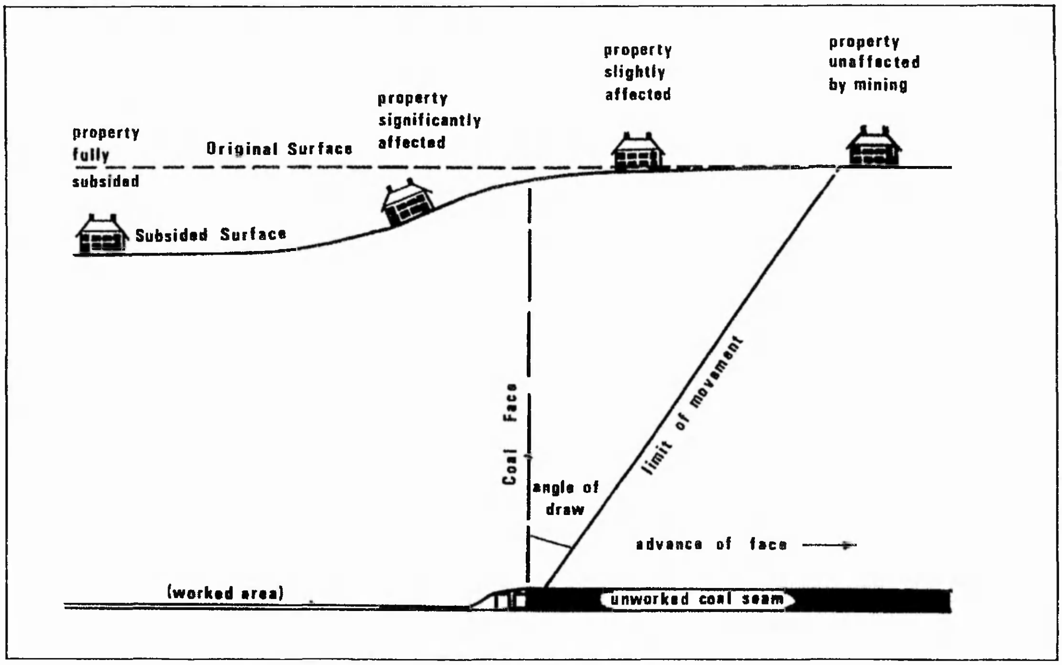


Figure 2.4: Development of coal-mining subsidence.

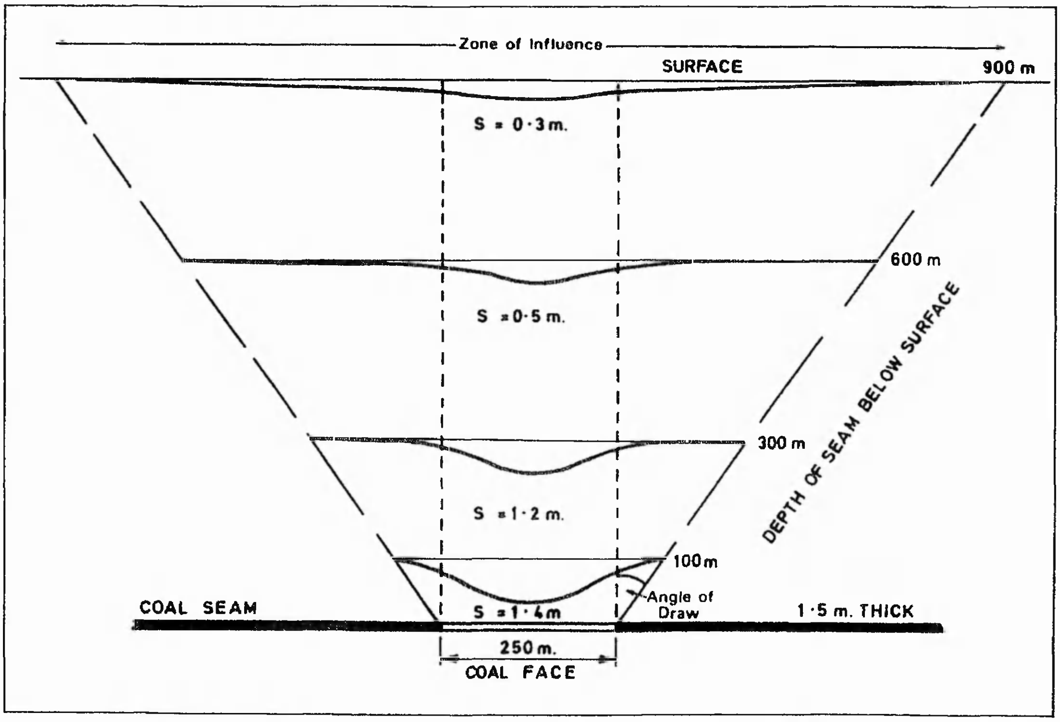


Figure 2.5: Influence of the depth of coal extraction on the amount of subsidence.

Figure 2.6 shows that for a given point, A, on the ground surface, this can be considered to be supported by a cone of underlying ground, the extent of which is determined by the angle of draw. Any coal which is extracted within the boundary of the cone will result in some degree of subsidence at the surface. Subsidence caused by coal-mining normally occurs almost instantaneously as the coal is extracted (Coal and the Environment 1981). Therefore, any subsidence will occur at the same time that any coal is extracted within the cone of support. The occurrence of subsidence movement will continue until all mining within this area has ceased. Consequently, any subsidence of the ground surface may not be complete for many years, especially as more than one coal seam may be extracted within the cone of support. Orchard (1957) showed how the rate of subsidence is related to the advance of a face of coal which is extracted from within the area of the cone of support. The maximum amount of subsidence at point A will only occur if the entire coal face within the cone of support is extracted. Even where this is the case, the maximum subsidence never exceeds about 90% of the thickness of the coal seam extracted.

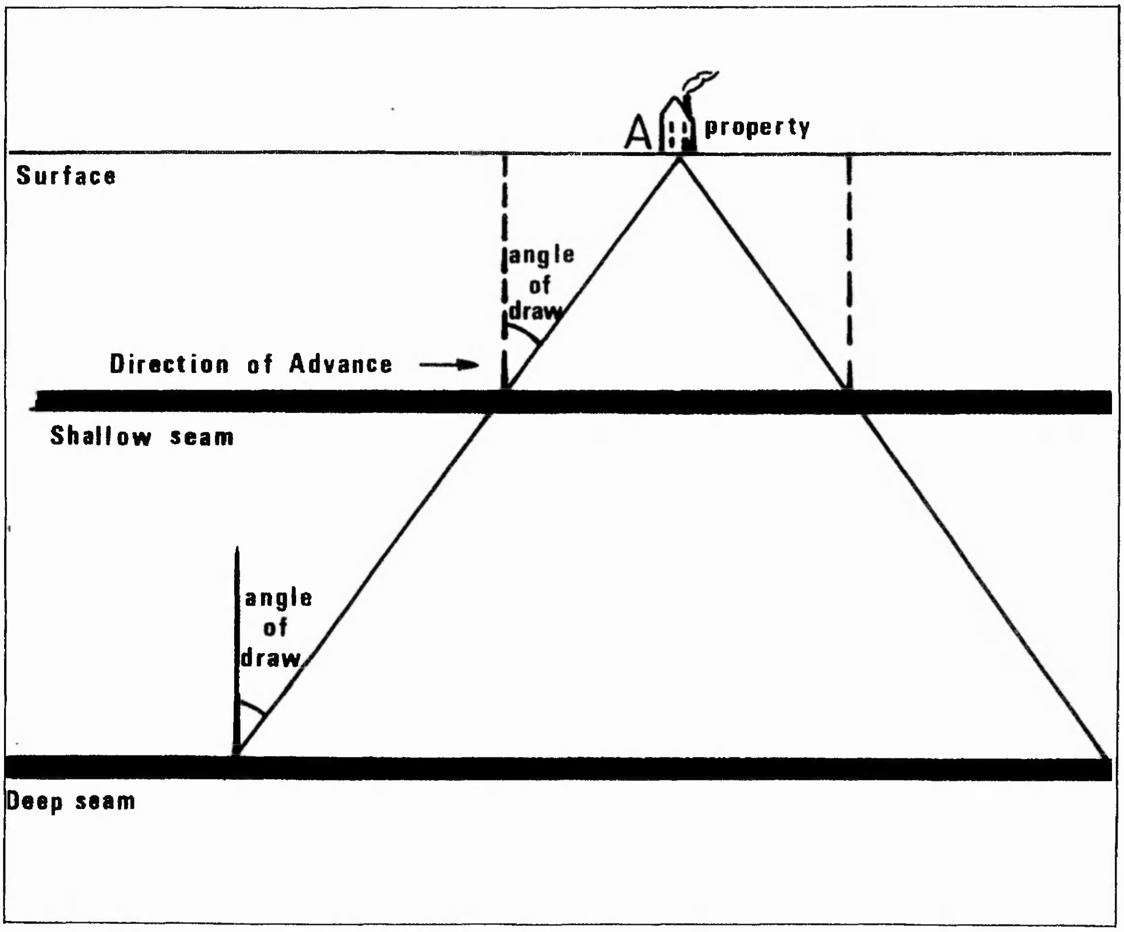


Figure 2.6: Critical area of support in relation to depth for a point at the surface.

2.4.2: The Influence Of Width And Depth Of Workings

An important factor which influences the amount of subsidence is the width-depth (w/d) ratio of the panel of coal extracted. Orchard (1954) showed that if a seam of coal is extracted which has a width equal to the diameter of the cone of support (see figure 2.6), the width of this face will be equal to 2dtanA, where d is the depth of the seam and A is the angle of draw. If the angle of draw is taken as 35°, then according to basic trigonometry, maximum subsidence will occur at a width-depth ratio of 1.4 : 1. This width is known as the "*critical width*". Figure 2.7 shows that if a face of coal is extracted which has a width greater than the diameter of the cone of support, so that w/d > 1.4 : 1, the amount of subsidence remains constant, but the area over which the subsidence occurs has widened, giving a flat-bottomed profile. This width is known as the "*super-critical width*". Conversely, where a face of coal is extracted which has a width less than the critical width, so that w/d < 1.4 : 1 and un-worked coal remains within the cone of support, the surface will undergo a degree of subsidence less than the maximum possible and is referred to as "*partial subsidence*" (Littlejohn, 1987). Where this is the case, this width is known as the "*sub-critical width*".

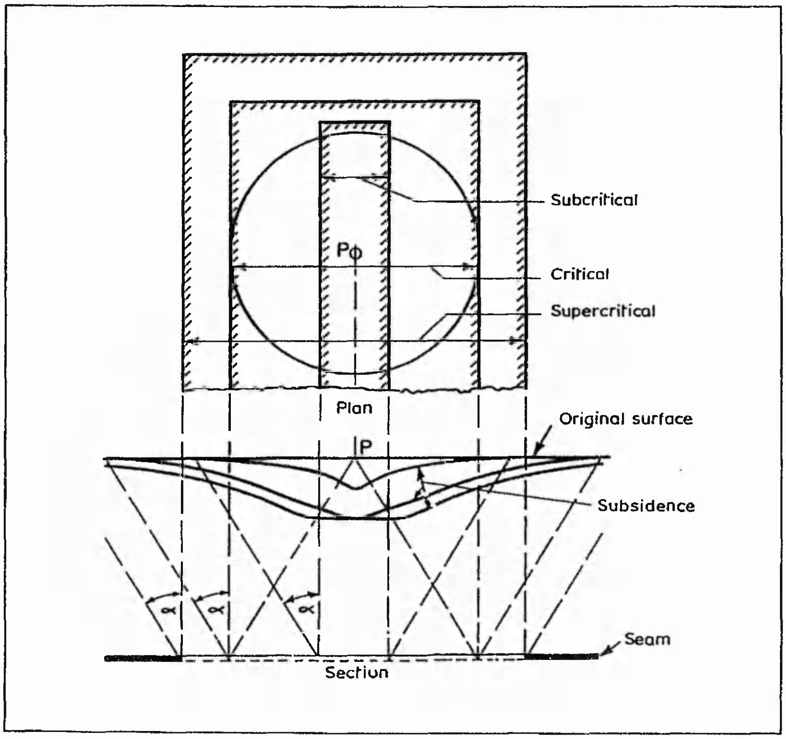


Figure 2.7: **Relationship of subsidence to different widths of extraction in a coal seam of given depth.**

Past experience of coal-mining subsidence has resulted in empirical rules being developed that enable the prediction of subsidence with some degree of accuracy. However, the magnitude of any surface movements are also influenced by less determinate factors which are discussed by Littlejohn (1987).

a) **Geology of the overburden**

The nature of the overburden above the void of coal extracted can influence the magnitude of any subsidence. For example, strong massive beds of sandstone or limestone may subside erratically, leading to irregular subsidence at the surface, whereas shales and clays tend to absorb erratic displacements in the underlying ground and thus reduce irregularities at the surface.

b) **Presence of old coal workings**

Voids from previous coal-mining activity above the seam being worked cause particular concern as their presence is superimposed upon the normal subsidence, thus causing problems in relation to the prediction and magnitude of the subsidence at the surface. Such voids were left by old *pillar and stall* extraction methods, where pillars of coal were left in to act as supports to the voids of coal extracted. This mining technique became obsolete at the end of the 19th century due to the greater efficiency of deep longwall mining. However, areas of uncharted *pillar and stall* workings still exist throughout Great Britain. For deeper workings, the weight of the overlying strata usually caused the voids to collapse, but for shallower workings the voids can remain open for decades, or even centuries, and their collapse can be created by the additional extraction of coal from modern longwall mining. Such voids may not always be recorded and they are of particular concern where they are very shallow, less than about five times the thickness of the void, as such voids can collapse through to the surface.

c) **Presence of faults**

The presence of geological faults can cause erratic changes in the subsidence profile which tends to concentrate relative movement at the interface between the faulted strata (Littlejohn, 1987).

2.4.3: Horizontal Movement Resulting From Coal-Mining Subsidence

An important component of coal-mining subsidence is the horizontal strains. When a trough of subsidence is formed (as shown in figure 2.5) the centre part subsides vertically only; the remainder moves inwards in addition to moving downwards. This results in differential horizontal displacement of the ground causing both tensile or compressive strains. King and Smith (1954) showed that the magnitude of the tensile or compressive strains is proportional to the amount of subsidence and inversely proportional to the depth of workings.

Where a face of coal is extracted which has a sub-critical width (w/d ratio < 1.4 : 1), compressive and tensile strains occur over the width of the subsidence trough, and the intensity of the compressive strains is greater than the tensile strains (see figure 2.8a). If a critical width is extracted (w/d ratio = 1.4 : 1), tensile and compressive strains develop over the area of subsidence, but there exists a point which is strain free (figure 2.8b). Where a supercritical width is extracted (w/d ratio > 1.4 : 1), on either side of the subsidence trough there is a zone of tension accompanied by a zone of compression of about equal magnitude, while the centre of the trough remains strain free. However, surface subsidence caused by coal-mining is three-dimensional in character and movements of the two horizontal components and the vertical component may occur simultaneously.

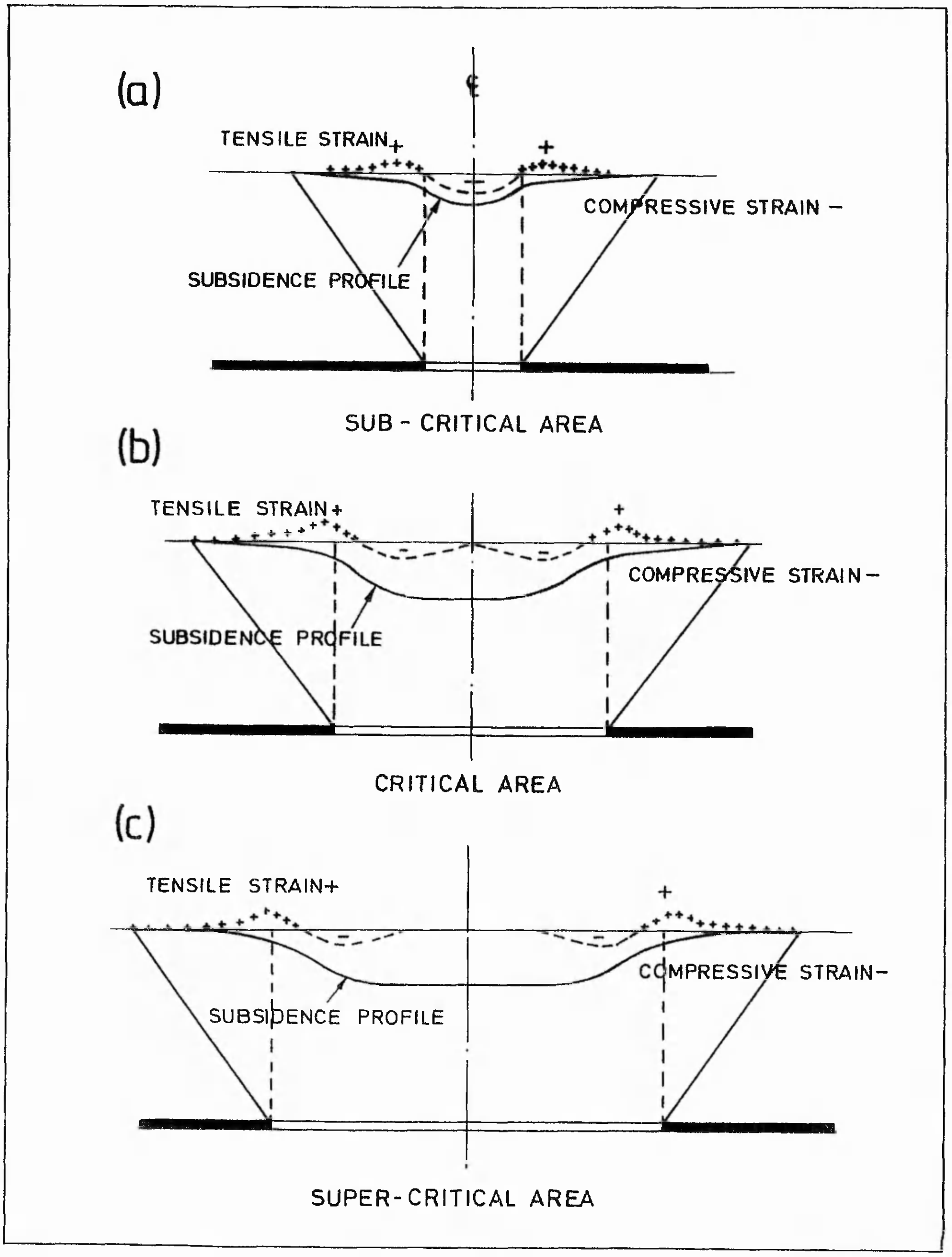


Figure 2.8: The development of tensile strains in relation to the width/depth ratio of a face of extracted coal.

Figure 2.8 has illustrated the final position that is reached when subsidence is complete. As the extraction of a face of coal advances, a wave of subsidence is initiated at the surface in which tensile and compressive strains are experienced as the extraction of the face of coal advances. These transient strains are also responsible for damage that occurs to low-rise structures. For example, a property located in the central zone of a supercritical area of extraction would be subjected to transient strains as coal-mining proceeds, but after extraction is complete, it would return to a strain free condition, but at a reduced level.

The curvature of the subsidence profile tends to be greater with shallower workings due to the reduced extent of the draw. As the curvature of the subsidence profile increases, differential displacement increases and therefore greater strains are produced. For this reason, shallow workings cause more damage to surface structures than deeper workings.

2.5: CHAPTER SUMMARY

This chapter has established the key technical concepts that are considered in the literature in relation to the main causes of ground subsidence. The literature review examines the causes of ***shallow*** subsidence and heave in both clay soils and granular soils, in addition to examining ***deep*** subsidence caused by coal-mining operations.

In the absence of any definitive guidelines concerning '*post-damage*' site investigations, the following issues have emerged from the literature to be important when considering the causes of ground subsidence. These have been divided into *shallow* and *deep* subsidence.

2.5.1: ***Shallow*** **Subsidence**

The basic properties of clay soil have been described and the potential for volumetric changes has been considered in relation to the moisture content of the clay. The volume change potential of a clay can be assessed by considering the plasticity index of the clay, and the content and type of clay minerals that are found in the clay. However, the plasticity index is the main parameter that provides a measure of volume change potential and hence the greater the volume change potential of a clay, the greater the subsidence or heave potential.

Actual volume changes in clay can only be caused by changes in soil moisture content. It has been widely reported that climatic conditions on '*open field*' sites clear of trees is limited to a depth of 900mm below ground level even on very highly shrinkable clay. However, as many older buildings have been constructed with foundations less than this depth, foundation movement and subsequent damage still occurs.

The presence of trees can significantly increase the depth to which foundation movement can occur. Therefore, it is necessary to either separate trees and buildings by a distance where roots will not cause damage, or alternatively, increase foundation depth. In an attempt to establish the influence and extent of any tree damage to a building, it is necessary to consider many factors concerning the interaction of tree and building. Where tree roots are found at a depth equal to or below the depth of foundations of a damaged building, it must be assumed that the tree has had a contributory influence to the damage regardless of foundation depth.

In relation to foundation depth, it is clear that a depth of less than 900mm below ground level can be considered to constitute "*shallow foundations*". However, where trees are present, defining what constitutes shallow foundations becomes more difficult. Where foundations are deeper than 900mm below ground level, and tree roots are found in the vicinity of the foundations, it must be assumed that the presence of the tree(s) had a contributory effect on the damage in the building, unless it is possible to identify another cause for the damage. Consequently, in this research, foundations in excess of 900mm below ground level are not considered to be shallow foundations, regardless of whether trees are present or not.

To establish if a clay soil is desiccated, crude guidelines have been developed which relate the moisture content of the clay to its liquid limit (the onset of desiccation can be assumed to occur where soil moisture content < 0.5L.L.). These guidelines have been criticised in relation to their accuracy and appropriateness, and more accurate guidelines have been proposed. However, the simplicity and convenience of the method has made it the one almost invariably used in practice, and in this research it is used as a definition of desiccation.

Insufficient literature exists that considers the effect of leaking drains as a cause of ground subsidence or heave. It is possible to identify defective drains from a closed circuit television survey (CCTV) or other drains tests. Defective drains can affect both clay soils and granular soils. In clay soils, discharging drains can cause either subsidence by softening the clay, or heave by allowing a desiccated clay to re-hydrate. In granular soils, discharging drains can cause moisture to transport fine particles and hence create a void in the ground supporting the building foundation. When considering defective drains, it is necessary to first establish if the leaking drains are a cause or an effect of subsidence.

2.5.2: Deep Subsidence

A review of the literature covering the prediction of ground subsidence caused by underground longwall coal-mining has highlighted that this subject first became fully understood during the

1940s and 1950s. Prior to this, it was known that underground coal extraction resulted in surface subsidence, but the process of subsidence prediction, and the magnitude and type of forces which developed at the surface were not fully understood. Empirical methods of predicting surface subsidence have been developed from observation of actual subsidence, and these methods are described in detail by NCB (1975).

In relation to subsidence caused by longwall coal-mining, this chapter has reviewed the general principles which can be used to assess whether or not a property is within an area of influence of coal-mining operations. An understanding of these principles can be used to establish if a property lies within such an area.

This chapter has considered the main pieces of authoritative literature concerning the causes of ground subsidence and heave movement in relation to low-rise residential properties. The following chapter considers the literature in relation to the consequences of ground subsidence, and consequently highlights the importance of the non-technical aspects of subsidence damage.

CHAPTER THREE: CONSEQUENCES OF GROUND SUBSIDENCE

3.1: INTRODUCTION

This chapter examines, through a review of relevant literature, the consequences of ground subsidence movement to low-rise buildings. At a simple level, a logical sequence of events can be seen to occur as a building is subjected to ground subsidence movement. Firstly, visible damage occurs in the superstructure of the property. This visible damage is investigated in order to identify the cause. Where it can be established that the damage has been caused by ground subsidence movement, an assessment is often, but not always, made to establish if movement within the property is progressive. Finally, having assessed the visible damage, established the cause and progression of movement, an appropriate remedial action strategy has to be decided upon and implemented.

The importance and limitations of visible damage are firstly considered in this chapter. Following on from this, the effects of building value depreciation caused as a result of visible damage are highlighted. Where damage is thought to be caused by ground subsidence or heave, a 'post-damage' site investigation is usually adopted to precisely establish the cause of damage (see Chapter Two). If ground subsidence or heave movement are identified as the cause of damage, then particularly in the case of properties damaged by shallow subsidence, the movement in the building is monitored. Therefore, this chapter considers the importance of monitoring buildings to establish whether or not movement is progressive. Consideration is then given to the different aspects of remedial action necessary to arrest movement and rectify damage. This process focuses on the more general aspects of remedial action, rather than specific technical details which are beyond the scope of this thesis. The subject of liability for damage is also addressed, and the perspective of those agencies financially responsible for damage is considered. Finally, this chapter considers a critique of two previous pieces of literature that have investigated broadly similar aims to part of this thesis.

3.2: VISIBLE DAMAGE

A building subject to ground movement will react in a unique manner depending upon a number of different factors, such as the ground/structure interaction and construction details. However, damage associated with ground movement usually follows well-defined patterns that can permit assumptions to be made about the cause and extent of movement. Hunt *et. al.* (1991); BRE Digest 251 (1993 edition) and ISE (1994), amongst many others, have identified typical damage caused to low-rise structures as a result of ground movement, and have also considered the assessment of such damage.

Perhaps the most common symptom of visible damage that results from ground movement is *cracks*. However, cracks can occur as a result of many causes that are not related to ground movement. Much confusion and misunderstanding about the cause and significance of damage can be generated by considering only cracking in a structure, and particularly crack size. An objective assessment of visible damage must attempt to consider all aspects of damage in a building.

Jennings and Kerrich (1962), in a study of the economic consequences of the heave of buildings on swelling clays, devised a simple classification of visible damage. This was intended to act as a guide to ease of repair of brickwork and masonry rather than a direct measure of the degree of damage. NCB (1975) produced a classification of subsidence damage similar to that published by Jennings and Kerrich, with the NCB classification based on wide experience of damage to buildings resulting from coal-mining subsidence in Great Britain. MacLeod and Littlejohn (1974) and Tomlinson *et. al.* (1978) considered the importance of adopting objective methods of damage assessment and suggested classifications of damage based on the work of Jennings and Kerrich (1962) and NCB (1975). This damage classification has also been adopted by BRE and the latest version is published in BRE Digest 251 (1993 edition) shown in table 3.1 below.

Category of damage	**Description of typical damage** *Ease of repair in italic type*
0	Hairline cracks of less than about 0.1mm which are classed as negligible.
1	Fine cracks of up to 1mm width which can be *treated easily using normal decoration*. Perhaps isolated slight fracturing in building. Cracks rarely visible in external brickwork.
2	Cracks up to 5mm width which *can be filled easily. Redecoration probably required. Recurrent cracks can be masked by suitable linings.* Cracks not necessarily visible externally; *some external re-pointing may be required to ensure weather-tightness.* Some distortion, so windows and doors may stick slightly.
3	The cracks, which may be from 5mm to 15mm in width (or several, each up to 3mm), *require some opening up and can be patched by a mason. Re-pointing of external brickwork and possibly a small amount of brickwork to be replaced.* Doors and windows sticking. Service pipes may fracture. Weather-tightness often impaired.
4	Extensive repair work to cracks of 15mm to 25mm width (depending on number) which involves *breaking-out and replacing sections of walls, especially over doors and windows.* Windows and door frames distorted, floor sloping noticeably. Walls leaning or bulging noticeably, some loss of bearing in beams. Service pipes disrupted.
5	Cracks usually greater than 25mm width (depending on number) *require a major repair, involving partial or complete rebuilding.* Beams lose bearing, walls lean badly and require shoring. Windows broken with distortion. Danger of instability.

Table 3.1: Classification of visible damage to walls with particular reference to ease of repair of plaster and brickwork or masonry (BRE Digest 251, 1993).

Tomlinson *et. al.* (1978), explained that at the simplest level, damage classification may consist of three types; '*aesthetic*', '*serviceability*' and '*stability*'. In the first, only the appearance, internal and external is affected; in the second, some functions are impaired, for example, doors jam or moisture penetrates cracks; in the third, there is a reasonable possibility that some part of the structure may collapse. BRE Digest 251 (1993 edition) stated that damage falling within or below category 2 can be considered to be '*aesthetic*', category 3 or 4 as '*serviceability*' and category 5 as '*stability*'.

Pryke (1979; 1981) considered classification of damage to walls of buildings in relation to their use in service. This classification is shown in table 3.2 below (Pryke, 1981).

Class	**Crack size along direction of crack mm**	**Degree of Damage**
P0	<0.1	**Insignificant.**
P1	0.1 - 0.3	**Very slight.**
P2	0.3 - 1.0	**Slight.** Wallpaper may wrinkle. Typically found at ends of lintels, junctions between walls and ceilings and at junctions between different materials.
P3	1 - 2	**Slight to moderate.** Wallpaper may wrinkle or tear. Bricks, blocks, cills and lintels may fracture.
P4	2 - 5	**Moderate.** Cracks conspicuous. Doors and windows stick, brick arches may loosen. Diagonal cracks may appear in ceilings.
P5	5 - 15	**Moderate to severe.** Shear patterns may develop with diagonal cracking in ceilings. Cracks may split into two or more parallel fractures leading to shattering of brickwork panels.
P6	15 - 25	**Severe to very severe.** Cracks develop into clear patterns. Distortion is evident and walls may bulge. Horizontal movement at bearings or d.p.c. level may occur.
P7	>25	**Very severe to dangerous.** Bearings may be seriously weakened.

Table 3.2: Classification of visible damage after Pryke (1981).

Pryke (1979) acknowledged the similar results of his classification of damage to that of Tomlinson *et. al.* (1978). The classification published by Pryke (1981) can be related to the classification published in BRE Digest 251 (1993 edition) by considering crack size, effect of damage on structure and building use, and description of damage. This is shown in table 3.3 below.

Classification of damage after BRE Digest 251 (1993 edition).	**Type of Damage**	**Classification of damage after Pryke (1981).**
	AESTHETIC DAMAGE	P0
0		P1
1		P2
2		P3
3	SERVICEABILITY DAMAGE	P4
		P5
4		P6
5	STABILITY DAMAGE	P7

Table 3.3: Relationship between damage classification published in BRE Digest 251 (1993 edition) and Pryke (1981).

3.2.1: Visible Damage Other Than Cracking

Biddle (1979) advocated the use of a level survey of the damp proof course (d.p.c.) as a method of considering damage in a building. Level surveys make the assumption that the building was constructed level initially, and, if this assumption is true, the amount of movement that has taken place can be quantified. Biddle (1979) stated that a level survey is often omitted from investigations, which can lead to incorrect deductions about the cause of ground movements.

Hunt *et. al.* (1991) highlighted that movement of brickwork at d.p.c. level is a common effect of ground movement. Horizontal movement can occur at the corner of a structure as the d.p.c. acts as a '*slip plane*', for example, sagging movement of a foundation can result in the brickwork beneath d.p.c. moving inwards. Hunt *et. al.* (1991) considered out-of-plumb walls, but indicated that where foundation movements are suspected, it is preferable to consider an out-of-plumb survey of walls in conjunction with a level survey of the d.p.c. Discrepancies between the two surveys would identify the possibility of damage unrelated to foundation movement, such as roof spread or wall tie failure.

Building movement can occur without any cracking in the structure. An example of such movement is associated with coal-mining subsidence, when the whole structure of a building is tilted out of level as a single unit without any cracking.

3.2.2: Relating Visible Damage To Building Movement

No discussion of visible damage in buildings would be complete without considering previous literature which has attempted to relate visible damage to building movement. Previous literature has considered how measurements of the amount of actual, or anticipated, building movement can be used to define various thresholds of damage. Several notable studies in this subject field have been made by eminent authors, and a brief summary of this work, and its significance to this research, is considered.

An important piece of work considering the allowable settlements of buildings was published by Skempton and MacDonald (1956), who used as their criterion for damage the ratio of maximum differential settlement δ and the distance l between two points after eliminating the influence of tilt of the building. The ratio δ/l was defined as '*angular distortion*' (see figure 3.1). From a study of 98 buildings, 40 of which showed signs of damage, they concluded that cracking occurs when $\delta/l > 1/300$, but recommended designing to $\delta/l > 1/500$. The work of Bjerrum (1963) agreed with these findings.

A further notable piece of work by Burland and Wroth (1974) made the assumption that most cracking results from tensile strains. It was suggested that the onset of **visible** cracking might be related to a concept called '*limiting tensile strain*' (E_{lim}). As limiting tensile strain relates to visible damage rather than collapse, Burland and Wroth suggested that it can be thought of as a **serviceability parameter**.

Using the results of tests on brick in-fill frames and walls built on reinforced concrete beams, Burland and Wroth (1974) concluded that the value of tensile strain at which cracking becomes visible is quite well defined for a wide range of strengths and types of material. Burland and Wroth suggested that $E_{lim} = 0.05\%$ to 0.1%. Such values would correspond to category 1 to 2 damage of BRE classification, which represents the onset of visible aesthetic damage.

Burland and Wroth (1974) showed how the concept of E_{lim} could be applied to a simple beam structure taken to represent a building undergoing movement. They recognised that in practice structures are very much more complex, but that a simple beam analogy helps to illustrate a number of important points. Using this analogy and applying the concept of E_{lim}, they proposed the deflection ratio Δ/L (see figure 3.1) as a parameter to consider the response of buildings to movement. Limiting values of Δ/L suggested by Burland and Wroth (1974) for the onset of visible damage in non-reinforced load-bearing masonry walls are given in table 3.4. These values identify the different responses of a building to either a sagging or hogging mode of distortion.

Hogging tends to be more damaging than sagging because of the greater restraint offered by the foundations of a building compared to the eaves. Burland and Wroth also recognised the importance of the length to height ratio (L/H) of a building, with greater restraint being offered as the L/H ratio decreases.

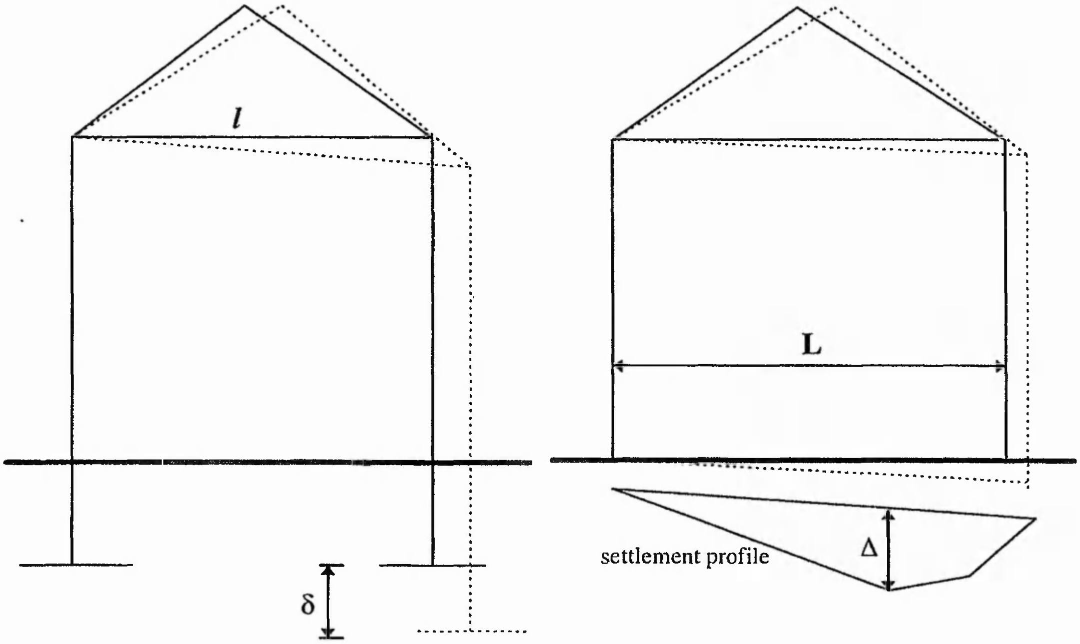


Figure 3.1: **Definition of terms (1) 'angular distortion' δ/l after Skempton and MacDonald (1956) and (2) 'deflection ration' Δ/L after Burland and Wroth (1974).**

	L/H = 1	L/H = 5
Sagging	1/2500	1/1250
Hogging	1/5000	1/2500

Table 3.4: **Limiting values of deflection ratio Δ/L for onset of visible cracking in non-reinforced masonry walls after Burland and Wroth (1974).**

Burland and Wroth (1974) showed how deflection ratio Δ/L could be related to angular distortion δ/*l*. It was shown that a limiting value of δ/*l* of 1/500, as recommended by Skempton and MacDonald (1956) to represent the onset of visible damage, is in reasonable agreement with Burland and Wroth's own recommendations, where L/H ratio does not exceed 2.5.

In a study of 77 houses damaged in Ottawa, Canada, Bozoduk (1962) suggested a limiting δ/l value of 1/180 as the onset of visible damage. Driscoll (1984) demonstrated how such a value of δ/l corresponds to a deflection ration Δ/L of around 1/450 at a L/H ratio of 1.4. This provides a limiting value substantially less than those suggested by Burland and Wroth (1974). However, the form of construction of the houses investigated by Bozoduk (1962) was significantly different to traditional United Kingdom construction practice. Timber framed construction is common practice in Canada, but the use of a masonry outer skin in low-rise housing is less common in Canada than in Great Britain.

Boscardin and Cording (1989) further developed the work of Burland and Wroth to show that values of E_{lim} can be correlated to the six categories of damage suggested in the BRE classification of damage. Therefore, where the deflection ratio Δ/L is known, or can be predicted from some analytical or empirical method, a value of E_{lim} can be calculated and related to BRE classification of damage.

Any attempt to predict the significance of damage in a structure using the approach adopted by Boscardin and Cording (1989) is fraught with difficulties. It is first necessary to estimate the anticipated ground movement. This may be predicted from some analytical or empirical technique, but in the case of low-rise housing, it can be complicated by unpredictable factors including: geology, climate and the presence of trees. Equally, it can be extremely difficult to predict the response of a building to ground movement. For example, Page (1995) stated that low-rise housing rarely behaves as expected. This can be demonstrated by considering that in a typical house subject to ground subsidence movement, damage would be expected around the weak points in the structure, such as around window or door openings. However, less obvious weak points may exist as a result of the construction process. For example, during construction a batch of weak mortar may be used at the end of a day. Should this brickwork be left uncovered for a period of several days, and construction continued with a stronger mortar this could create an inherent weak point. If the building was subsequently subjected to a degree of ground movement at a later date, cracks could appear where these would not usually be expected. Consequently, a misleading interpretation of the cause and significance of damage might be created.

Almost all previous literature that has considered limiting amounts of building movement and damage has been carried out in relation to structures other than low-rise housing, mainly focusing on the initial settlement of large structures due to their imposed loading after construction. Driscoll (1984) and Boden and Driscoll (1987) have raised this issue when considering limiting movements for dwelling houses to those limits that have been developed in previous work, notably Burland and Wroth (1974). The application of such limits to low-rise housing is not based on observed cases of damage in such buildings and Driscoll (1984) identified that, until such time as a large body of data on low-rise masonry distortions is established, it will not be possible to offer more reliable guidelines.

NCB (1975) attempted to relate the amount of damage that a building can tolerate to the change in length of a building that undergoes horizontal ground strains. The change in length of a building can be estimated by multiplying the horizontal ground strain by the length of the building. Based on observations of damaged buildings and field measurements of horizontal ground strains, NCB (1975), using a damage classification similar to that in table 3.1, indicated the change in length of a structure that could be expected to be associated with different categories of damage.

3.2.3: The Limitations Of Visible Damage Classification

The damage classification published by BRE is virtually ubiquitous in literature relating to the classification of visible damage in low-rise structures. However, several limitations of this classification have been raised and are considered below.

BRE Digest 251 (1993 edition) highlighted that damage classification can only be considered at a given point in time and no account can be taken of the cause or progression of damage.

The damage classifications proposed by both Pryke (1981) and BRE Digest 251 (1993 edition) places emphasis on cracks and crack sizes. A reliance on cracks in assessing visible damage can be misleading, as demonstrated above by Page (1995). Both BRE and Pryke placed little emphasis on the quantity of damage, and instead placed emphasis on the significance of damage, mainly crack size, regardless of quantity, although BRE Digest 251 (1993 edition) does state,

> "*Great care must be taken to ensure that the classification of damage is not based solely on crack width, since this factor alone can produce a misleading concept of the scale of the damage. It is the ease of repair which is the key factor in determining the overall category of damage for the whole building*".

3.2.4: Visible Damage Related To Building Value Depreciation

A further issue which limits the usefulness of the classifications of visible damage considered above, and arguably the most significant, is that no account is taken of loss of market value to a property as a result of damage. Over the last two decades, government policy has encouraged home-ownership, which has made owner occupation the dominant form of tenure. In the 1970s, Pryke (1979) recognised that homes are the major asset of their owners who are keen to protect their value.

Pryke (1993) explained how houses which show signs of cracking, possibly caused by ground subsidence, can become "*blighted*". Any subsidence blight resulting in a loss of value becomes very difficult to quantify objectively because of the complexities of market value. Consequently, it would appear difficult to attempt to classify damage in low-rise properties according to loss of market value. However, it would seem reasonable to assume that, in the majority of cases, it is the potential reduction in value of a property which causes most concern to home-owners, as opposed to physical signs of damage.

Reduction in market value as a result of subsidence damage, or suspected subsidence damage, is considered further in the following sections of this chapter.

3.3: PROGRESSIVE BUILDING MOVEMENT

To establish if movement within a building is progressive, it is necessary to monitor the building. Robson (1991) stated that monitoring has two requirements; to detect movement below the threshold of damage that exists in a building; and the monitoring results must be unambiguous. However, Robson (1991) considered that monitoring only of crack widths can provide ambiguous results as a crack may develop for one reason and progress for another.

ISE (1994) advised that where damage is slight and exacerbated by the presence of trees or other large vegetation on shrinkable clay soil, the only objective way of deciding whether tree removal or pruning will offer a long-term alternative to underpinning is to monitor. The same applies in the case of defective drains.

Robson (1991) expressed caution about monitoring a building and considered that it should be undertaken only as a last resort. If adopted as a regular tool, Robson considered that there was a temptation to assume that other aspects of the building investigation can afford to be less rigorous. ISE (1994) suggested that there is no purpose in monitoring a building which is considered to be close to structural collapse as remedial works will be required.

Freeman *et. al.* (1994) considered monitoring as a very powerful tool, which in many cases is the fairest and most objective way of deciding whether or not a property needs to be underpinned.

Hunt *et. al.* (1991) suggested reasons why monitoring is not used more frequently. These include:

i Expense.
ii The time period taken to establish results.
iii Monitoring is not always conclusive.

Considering the above three points, Hunt *et. al.* (1991) highlighted that the cost of monitoring is high in comparison with the cost of remedial measures, which inflates the overall costs of a claim. Robson (1991); ISE (1994) and Freeman *et. al.* (1994) all stated that monitoring should usually be undertaken for a minimum period of twelve months. Such a time period can cause anxiety to the home-owner, especially where the property is for sale.

A minimum monitoring period of twelve months enables the effects of seasonal movement to be distinguished from long-term movements. Seasonal movements, which are typified by cracks opening during summer/autumn and then closing to some extent during winter/spring, occur because of climatic conditions, and/or because of the presence of vegetation in clay soil. If monitoring identifies a pattern of seasonal movement, it is often possible to remove or reduce the cause of movement, and continue monitoring to establish if movement is seasonal or long-term progressive. Hunt *et. al.* (1991) defined long-term progressive movement as:

> *"A movement which will continue and lead to the scale of damage rising to a level where serviceability is impaired".*

Therefore, the literature indicates that monitoring can establish one of three outcomes; '*no progressive movement*', '*seasonal movement*' or '*long-term progressive movement*'. Where '*seasonal movement*' is identified, it may be possible to attempt to remove the cause of the damage and establish whether movement is '*non-progressive*' or '*long-term progressive*'.

From the above discussion, it can be appreciated that monitoring can have two purposes. It can be used as a tool to help establish the cause of damage, or to eliminate certain causes of damage. In addition, monitoring can also be used to establish if movement is progressive or not.

In using monitoring as a tool to establish the cause of damage, Robson (1991) highlighted that crack monitoring can be ambiguous and considered the main disadvantage to be that it merely watches the symptoms. Robson advocated the use of a level survey around the d.p.c. of a building and relating this to a datum to establish overall building movement.

Where the cause of damage has been clearly identified without using monitoring to help establish the cause, a programme of monitoring the property by crack monitoring, level survey, or other means, will identify whether or not movement is progressive.

BRE Digests 343 and 344 (1989) discussed the use of different methods and techniques to monitor movement in low-rise buildings.

3.4: REMEDIAL ACTION

Where a property is damaged by ground subsidence or heave, remedial action can essentially be divided into two components, these being superstructure (above ground) repairs and substructure (below ground) repairs.

3.4.1: Superstructure Repairs

Regardless of whether or not remedial substructure repairs are required, it is almost always necessary to repair the visible damage in the superstructure of a property which first caused concern and alerted the home-owner to existence of damage. This damage is commonly aesthetic in nature and does not represent a threat to the structural stability of a property. However, in some circumstances it may be necessary to carry out structural superstructure repairs, for example, where structural members such as beams or lintels lose bearing.

In relation to claims for shallow subsidence, when insurance companies first indemnified against damage caused by ground subsidence, no qualifications were placed on the amount of damage occurring to initiate a claim. BRE Digest 251 (1993 edition) reported that, as a consequence of home-owners realising that they could claim against their insurers, many causes of damage hitherto regarded as of no great importance had become the subject of insurance claims. Following the drought of 1975-76, insurers introduced a policy excess which made the insured liable for the first £500 of a subsidence claim, although most insurers increased the policy excess to £1,000 in the early 1990s. The introduction of this policy excess can be seen as an attempt to introduce a threshold of damage to discourage home-owners from claiming for minor damage.

Pryke (1993) argued that a '*serviceability limit*' should be imposed based on crack size. This serviceability limit would introduce a threshold of damage which Pryke (1993) suggested to eliminate the effects of subsidence blight on properties with minor levels of damage. Pryke suggested that this serviceability limit be based on a crack size of 3mm, although he acknowledged that cracks have many causes apart from differential foundation movement.

Pryke (1993) implied that properties with cracks less than 3mm should be considered unaffected by subsidence and only when cracks have exceeded this threshold should the possibility that the property has been damaged by subsidence be entertained. However, the adoption of this threshold could result in the discouragement of early identification and remedy of subsidence damage, with such damage going undetected until extensive remedial action is required. Pryke (1993) has acknowledged that reliance on cracks can lead to misunderstandings but identified that cracks are what those involved in the buying, selling and insuring of houses are most concerned with.

At present, insurance policy excess, usually of £1,000, is the only form of threshold imposed to discourage home-owners from claiming for minor damage. Where a property is sufficiently damaged to require repairs, the "making-good" of damage will depend on the extent of the damage and the quality and type of construction. Pryke (1993) highlighted the importance to the property owner of repairing the visible damage in a property. This issue has caused much controversy in relation to the repair of coal-mining subsidence damage.

3.4.2: Substructure Repairs

Remedial foundation underpinning is the most common method used to restore the function of foundations damaged by ground subsidence or heave. However, underpinning can be an expensive and technically complex process and cause much disruption to the home-owners, who in some circumstances may have to move into temporary accommodation.

Pryke (1981) made an important distinction between the terms *failure* and *danger*. Buildings exhibiting signs of damage thought to be caused by subsidence are often referred to be suffering from *foundation failure*, even if such damage is relatively minor. The term failure could be taken to imply that the structure is dangerous, but in the vast majority of cases of so defined *foundation failure* in low-rise properties, the structure never becomes dangerous, even where substructure repairs are necessary. As Pryke (1981) pointed out, in this context, failure and danger are distinctly different concepts, as the phrase *fail safe* clearly emphasises. Burland and Wroth (1974) suggested that, apart from a few notable exceptions, buildings will usually become unserviceable before there is a danger of structural collapse.

However, it would appear that all parties involved in the buying, selling and insuring of properties are often unwilling to differentiate between *failure* and *danger*. When damage noticed is thought to be associated with subsidence, the market value of the property falls. The market value can be restored by undertaking substructure repairs (usually underpinning) and "making good" the superstructure. Hunt *et. al.* (1991) claimed that underpinning in the past has been carried out with the sole purpose of restoring market value and enabling the house to be sold, or in other circumstances because insurers may require a 'once-and-for-all' solution, to minimise any potential future risk.

The above discussion has highlighted that the decision to undertake remedial substructure repairs is the central issue relating to the problems generated by subsidence or heave of domestic low-rise properties. The literature suggests, particularly in relation to shallow subsidence, that underpinning is the most effective way to restore both the market value and saleability of a property. As superstructure repairs are usually always required in association with underpinning, a clear definition between the importance of substructure repairs and superstructure repairs can be appreciated. In simple terms, as substructure repairs generally involve underpinning, the crucial distinction is usually to identify whether or not the building needs underpinning.

From the above discussions of the literature suggesting that underpinning restores the value of a property, it could be suggested that if it is possible to establish that a building is stable and free from the risk of future movement, and therefore no substructure repairs are required, the value of the property should not be impaired. However, Hunt *et. al.* (1991); Pryke (1993) and ISE (1994) have all suggested that this has not necessarily been the case in the past.

The distinction between substructure repairs and superstructure repairs is not only of fundamental importance to property owners, but also to agencies responsible for the financial consequences of damage. These agencies will only be prepared to pay for substructure repairs where this is strictly necessary because of technical factors, and are not prepared to pay for what might be considered to be unnecessary substructure works recommended because of non-technical factors. Remedial foundation underpinning can be an expensive procedure, as Hunt *et. al.* (1991) identified, because there are uncertainties in the extent and cost of works below ground level.

In certain circumstances it might be more economical to demolish and re-build a whole structure, or part of a structure damaged by ground subsidence or heave, rather than to repair the structure. However, there exists many other factors that might influence the necessity or otherwise to demolish a building. This is a debate which is beyond the scope of this research.

3.5: LIABILITY FOR DAMAGE

Damage caused by shallow subsidence is usually covered as part of a buildings' insurance policy, while damage for deep subsidence caused by coal-mining operations is covered by legislation.

3.5.1: Liability For Shallow Subsidence

Indemnity against damage caused by subsidence was first included in the standard comprehensive building insurance policy in 1971. This was a result of pressure from building societies which were keen to protect the value of their investments. Pryke (1992) explained that, prior to 1970, subsidence damage had occurred, but that home-owners treated damage as part of routine maintenance, or in more severe cases of damage, funded remedial works themselves.

ISE (1994) reported that in the early 1970s, few subsidence claims were made, and insurers tended to meet them in full, with little regard to the extent to which the repairs might be justified from a technical point of view. ISE (1994) further explained that following the dry summers of 1975-76, thousands of properties became damaged by ground subsidence movement and that home-owners became concerned for two possible reasons:

i Was their home becoming structurally unsound and therefore dangerous?

ii Was their home being affected so severely that value would appreciably decrease?

Whilst the first question was relatively easy to answer by obtaining technical advice, the second question was more difficult to address because it relates to the non-technical factors. Much previous work has investigated point (i). However, there appears to exist a lack of previous published work that considers point (ii).

3.5.1.1: The Number And Value Of Claims To Insurers

After the introduction of insurance cover, home-owners began to appreciate that they could claim against their buildings' insurance policy for damage caused by subsidence. Insurance policies provided no definition relating to either the extent or the severity of damage that necessitated remedial works following subsidence damage. The consequence was an increase in the number of claims made to insurers. ISE (1994) reported that in the past, the common practice was to attempt to stabilise the property itself rather than to identify the cause of damage, hence underpinning became common practice.

Both Hunt *et. al.* (1991) and ISE (1994) highlighted the conservative approach adopted by professional advisors involved in subsidence damage. It was suggested that professionals assessing damage found it easier to recommend extensive remedial works rather than to fully appraise damage, even where damage was relatively minor. Such an approach limited the risk of professional indemnity claims.

Pressure for a house sale to proceed has also been suggested by Hunt *et. al.* (1991) and ISE (1994) as a reason why underpinning became common practice. Lending institutions became cautious in providing mortgages for properties which showed signs of subsidence damage. Insurers were often unwilling to provide cover for such properties, and without insurance cover it was not possible to obtain a mortgage. Consequently, property owners unable to sell their homes would initiate claims against their own insurers. ISE (1994) highlighted that many subsidence/heave problems are identified at the point of sale when a property is inspected. Therefore, it can be appreciated that, in times of a buoyant housing market, the identification of potential subsidence damage increases.

Clancy (1995) considered the issue of continuity of insurance cover when houses are sold to be central to the problems of subsidence and heave. As many potential subsidence or heave problems are not identified until the point of sale, it is argued that the existing insurance cover should be offered to the new purchasers of a property even where signs of subsidence damage exist. This would eliminate problems in obtaining a mortgage and, since a potential sale would be more likely to proceed, the necessity to underpin could be assessed more objectively over time. Clancy (1995) further considered that it is in the long-term commercial interests of insurance companies to offer continuity of cover.

Figure 3.2 shows the number and value of claims made to insurance companies since 1971 for subsidence and heave damage to low-rise properties. It appears widely accepted in the literature that the peaks occurring in 1976, 1984 and 1990 are a direct result of the dry summer weather experienced in these years (Hunt *et. al.*, 1991; ISE, 1994). Hunt *et. al.* (1991) pointed out the learning effect to suggest that the number of claims has risen as public awareness has increased.

3.5.1.2: The Extent Of Insurance Cover

The wording of a typical buildings' insurance policy will vary from company to company. The typical statement regarding the issue of cover provided by a policy is:

> "*Damage to building caused by subsidence, heave or landslip of the site on which the buildings stand*".

However, some insurance policies may exclude cover for some forms of damage. For example, subsidence or heave damage to ground floor bearing slabs may be excluded unless the foundations below the external walls of the building are damaged by the same cause and at the same time.

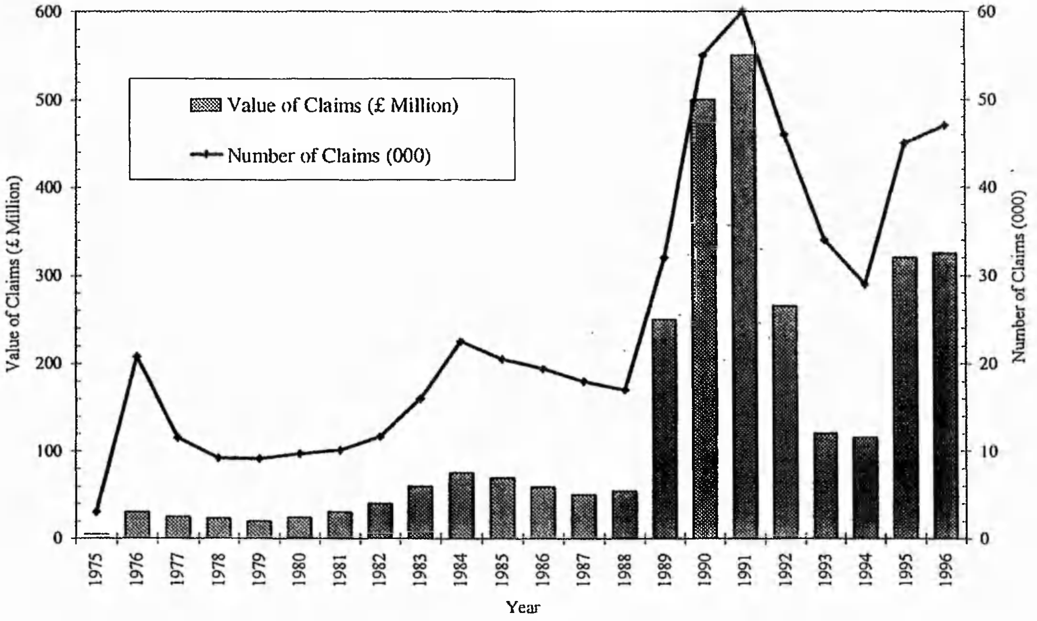


Figure 3.2: **Number and value of claims for subsidence and heave damage made to insurance companies (Source: Association of British Insurers, 1997).**

Damage caused to garden walls, tennis courts and swimming pools may also typically be excluded. Insurance companies will normally only permit a claim for remedial works that are necessary in order to restore a property to the same condition before it became damaged. No payments will be made to upgrade existing foundations which might not comply with current building standards.

The costs of insurance claims for subsidence or heave damage will ultimately be passed back to the insured through increased premiums. This will be especially expensive for those who live in areas known to be at high risk of ground movement from an analysis of past claims history in the area. Clearly, a reduction in the number and value of claims would be to the benefit of all those involved in the buying, selling and insuring of houses.

Considering both the number and value of claims, a claim for subsidence or heave damage which involves only superstructure repairs often represents significant financial expenditure to insurers. Pollard (1993) explained that many home-owners came to see their insurance cover as a maintenance contract and claim, for what in some cases, could be considered as routine maintenance. On this same theme, BRE Digest 251 (1993 edition) stated:

> "*....that one single factor had been responsible for the massive increase in damage claims*: [following the 1975-76 drought] *when house insurance cover had been enhanced in 1971 by insurance companies to indemnify against damage caused by ground subsidence, no qualification had been placed on the amount of damage occurring*".

Pryke (1992; 1993) argued that if lenders and insurers were to accept a threshold of damage which could identify a valid claim for subsidence, much dispute could be eliminated in the buying, selling and insuring of properties showing signs of minor subsidence damage. Pryke (1993) criticised the "*simplicity and openness*" of subsidence clauses in insurance policies and considered that the amount of damage occurring to justify a claim should be clearly defined. If this, or a similar approach were adopted, it would help to reduce the number of claims and consequently the value of claims.

Considering the value of claims, it has been highlighted above that many substructure repairs (usually underpinning) have been carried out which have not been required from a technical perspective, but which have helped to restore the value or saleability of the property. This suggests a need to be able to effectively differentiate between properties requiring substructure repairs (usually underpinning) from those requiring superstructure repairs only. This distinction would help to reduce any unnecessary expenditure on underpinning that is not required on technical grounds and hence reduce the overall value of claims.

Having discussed above the subject of liability for damage caused by shallow subsidence, the subject of liability for damage caused by deep coal-mining subsidence is discussed below.

3.5.2: Liability For Deep (Coal-mining) Subsidence

Historically, the owner of land had a right of support for that land to help keep the surface at its natural level. Various legislation that protected the right of support was consolidated when the coal industry in Great Britain was nationalised in 1947, to form the National Coal Board (NCB). The Coal Mining (Subsidence) Act 1957 was introduced which gave rights of compensation to virtually all owners of land and buildings damaged by subsidence.

The Coal Industry Act 1975 clarified the rights to withdraw support in certain circumstances. In addition, a voluntary code of practice was introduced by NCB in 1976. This code of practice extended the liability of NCB.

The Coal Mining Subsidence Act 1991 was introduced to supersede previous legislation and incorporate the voluntary code of practice. By this time, NCB had been renamed to British Coal Corporation.

The coal-mining industry in Great Britain was privatised in 1995 following the introduction of the Coal Industry Act 1994. This Act permitted private companies to operate mines and made such operators responsible for the consequences of any surface subsidence damage, through the provisions of the Coal Mining Subsidence Act 1991.

Following privatisation, The Coal Authority became the agency that oversees the coal industry in Great Britain. The Coal Authority[1] administers all coal-mining subsidence claims which were made prior to privatisation, and also has been delegated as the agency that administer claims for some private mine operators after privatisation.

Under the provisions of the Coal Mining Subsidence Act 1991, and all previous legislation, it is the duty of The Coal Authority to either carry out remedial works, make payment for remedial works, or make a compensation payment. The main priority has always been to repair properties rather than make compensation payments. This serves the public interest by maintaining the nations housing stock and avoiding dereliction and blight.

Under the provisions of the 1991 Act, the owner of a property that suffers coal-mining subsidence damage must notify damage within a period of six years from the time when the damage first became apparent.

To establish if a property is located within an area that could have been affected by surface subsidence caused by coal-mining operations, rules based on empirical observations made over many years by NCB (1975) are used. The basic principles of these have been considered in the previous chapter.

3.5.2.1: The Number And Value Of Claims For Coal-mining Subsidence

Figure 3.3 shows the number and value of claims made to The Coal Authority for coal-mining subsidence damage. This data has been supplied by The Coal Authority and is only available for the period 1985 to 1995.

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[1] For simplicity, The Coal Authority is used to refer to its predecessors, British Coal Corporation, and National Coal Board (NCB).

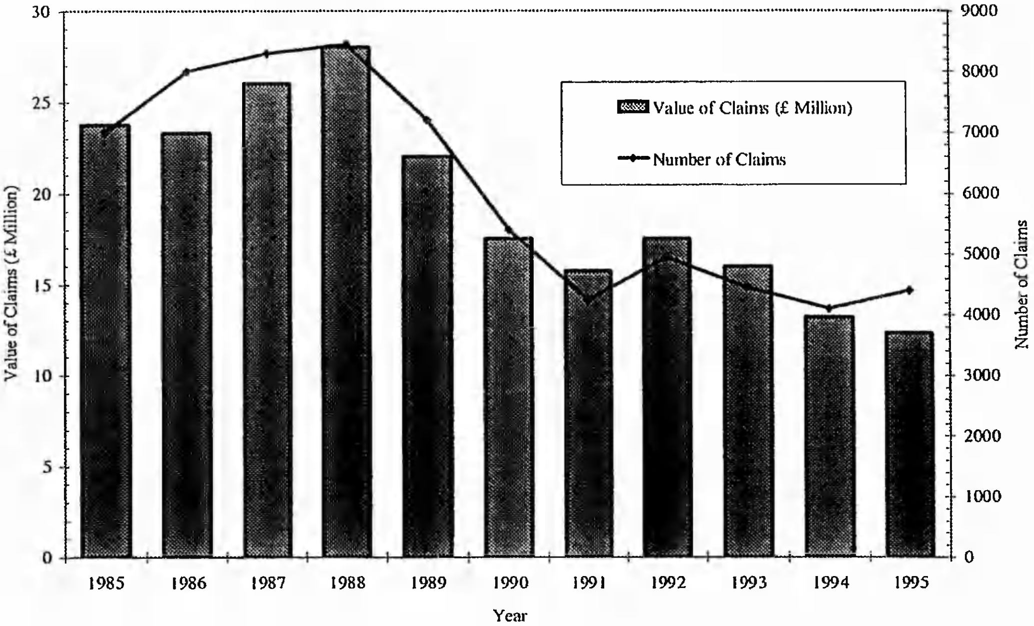

Figure 3.3: **Number and value of subsidence claims for coal-mining subsidence damage to domestic low-rise housing (Source: Coal Authority, 1995).**

The declining number and value of coal-mining subsidence damage claims can be seen in figure 3.3. The principal reason for this decline is the rationalisation of the coal industry over this period. A comparison of figures 3.2 and 3.3 shows that the number and value of claims made for coal-mining subsidence is significantly less than the number and value of claims made to insurance companies. In addition, while coal-mining subsidence claims have declined since the late 1980s through the 1990s, insurance claims have significantly increased over this same period.

Within the context of the literature covering coal-mining subsidence damage, it would appear that the main concerns of property owners relate to the quality of repairs (Subsidence Compensation Review Committee, 1984; The Repair and Compensation System for Coal-Mining Subsidence Damage, 1987; House of Commons Energy Committee, 1990). However, this literature also identified similar problems for coal-mining subsidence damage issues that exist for damage that forms the basis of insurance claims, including loss of property value and subsidence blight.

3.6: CRITIQUE OF EARLIER LITERATURE

The previous part of this chapter has examined specific issues through a review of the relevant sections of the authoritative literature. In undertaking this, the literature has necessarily been treated in a somewhat disjointed manner. Consequently, the review of literature has not focused entirely on previous work that is of direct relevance to the aims and objectives of this work. This section of the chapter therefore seeks to consider the main findings of two previous studies that are of particular relevance. Both of these pieces of work relate mainly to subsidence caused by volumetric changes in clay soil.

Hunt *et. al.* (1991) carried out a review of all the various agencies associated with the design, construction, funding and regulation of underpinning. This review was carried out by using a questionnaire survey followed by structured interviews, the objective being to produce guidance on a number of issues including why remedial underpinning has become so widespread and how to determine the necessity for underpinning.

Considering the issue of why underpinning has become so widespread, Hunt *et. al.* (1991) highlighted the inclusion of subsidence as an insured peril without qualification on the amount of damage as one of the primary reasons. Other reasons included periods of dry weather and the learning effect after the inclusion of subsidence cover in buildings' insurance policies. Hunt *et. al.* (1991) also identified the significance of owner-occupied housing and the value of housing as an investment as important influences on the increasing number of claims.

In relation to determining the necessity for underpinning, Hunt *et. al.* (1991) identified that a belief existed among non-technical specialists that underpinning was required to ensure the marketability of a property showing signs of damage. They considered that it is now generally accepted that remedial underpinning is strictly only required to arrest progressive foundation movement, and argue that probably a proportion of remedial underpinning currently [1991] carried out is not required on technical grounds alone.

Wilkin (1993) tested the hypothesis that underpinning is undertaken too frequently and considered the technical factors taken into account when professionals investigate damage in low-rise buildings on shrinkable or expansive clay. This was carried out through a questionnaire survey of consulting engineers practising in Essex, which enabled data to be collected on 282 individual cases of damaged buildings.

Wilkin (1993) confirmed the initial hypothesis that underpinning is undertaken too often. He used the data from the 282 cases of damaged buildings to investigate which factors are taken into account by engineers in forming recommendations to install underpinning and to evaluate which of these factors influences the final decision to recommend underpinning.

In collecting data of low-rise buildings damaged by subsidence or heave, Wilkin (1993) used a questionnaire that allowed engineers to enter data for the following fields of investigation for a number of individual cases of damaged buildings:

- Presence of trees?
- Tree water demand?
- Ratio of tree height to building?
- Age of tree?
- Foundation depth?
- Subsoil shrinkage potential?
- Moisture content of soil?
- Classification of visible damage (according to BRE Digest 251, 1993 edition)?
- Was the building monitored?
- How long was building monitored?

- **Was the building underpinned?**

Wilkin (1993) sought to establish whether a relationship existed between a building being underpinned and any of the other fields of data investigated. Wilkin showed that the only statistical correlation which existed was between the field, '*was the building underpinned*', and the field, '*classification of visible damage*' with some subsidiary association from the field '*was the building monitored*'.

Wilkin and Baggott (1994) published a summary of the main findings of Wilkin (1993), and concluded that:

> "*It can be concluded from this study that professionals look only at damage when deciding whether it is necessary to underpin*".

3.7: DISCUSSION

The preceding sections of this chapter have considered the consequences of ground subsidence or heave movement to privately owned low-rise domestic properties. This has been considered through a review of literature which has focused on the issues of visible damage, progressive building movement, remedial action, liability for damage and a critique of relevant earlier literature.

3.7.1: Visible Damage

It would appear that much emphasis is placed on crack size when assessing damage in low-rise properties. Nevertheless, the literature warns against solely relying on crack size as a measure of damage and highlights the importance of considering all aspects of visible damage. BRE have proposed a classification of visible damage that was based upon several criteria, including the ease of repair of damage, and crack size. Similar classifications have been proposed by Pryke (1979; 1981) and also by NCB (1975) in relation to coal-mining subsidence. However, some of the potential limitations of this format of damage classifications have been highlighted. Two major limitations include the fact that most emphasis is placed on the severity of damage as opposed to the quantity of damage, and that no account is taken of the loss of market value, which is arguably the most important aspect of damage. Despite these limitations, it would appear that such a method of damage classification is the only objective method of assessing a number of buildings to the same standard.

The literature on visible damage has also considered the subject of relating visible damage to building movement. Although theoretical models have been developed, it would appear that their use in defining thresholds of damage in low-rise housing are limited, the main reasons for this being the individual and unpredictable response of low-rise buildings to movement.

3.7.2: Progressive Movement

Monitoring building movement can be used as a tool to identify or eliminate causes of damage, or as a method to establish if movement is progressive or not. Arguments exist for and against the use of monitoring low-rise buildings. Those who are cautious of monitoring (Robson, 1991; ISE, 1994) suggested that it merely watches the symptoms of damage, whilst those who advocate its use (Hunt *et. al.*, 1991; Freeman *et. al.*, 1994) considered it a very powerful tool to identify whether or not a property requires underpinning. Although not explicitly stated in the literature, this apparent confusion relating to building monitoring could be related to a failure to define its purpose. For example, monitoring only crack width is of limited use to help establish or eliminate a cause of damage (i.e. it only watches the symptoms), but if the cause has been established by other means, monitoring can be used to identify if building movement is either, '*non-progressive*', '*seasonal*' or '*long-term progressive*'.

3.7.3: Remedial Action

To rectify damage, remedial action can be divided into two main types: superstructure repairs and substructure repairs. Superstructure repairs involve making-good damage above ground level. Where damage is minor, the repair of such damage might be considered as part of routine maintenance, but in more severe cases this might involve extensive building repairs.

Substructure repairs usually involve underpinning and invariably include repairs to superstructure damage that occurs at the same time. In severe cases it may be necessary to demolish and re-build all or part of a structure.

In relation to properties damaged by shallow subsidence, it has been shown that the correct distinction of remedial action involving only superstructure repairs as opposed to remedial works requiring substructure repairs (usually underpinning) is an essential distinction to make. The primary reason being that such a distinction can have an important influence on the market value and consequently the saleability of a property.

3.7.4: Liability For Damage

Buildings' insurance policies cover damage for shallow ground subsidence or heave movement, and legislation places a responsibility on those who cause coal-mining subsidence to compensate for surface damage.

The number and value of claims to insurers has shown a marked and general increasing trend since the introduction of cover for subsidence in the early 1970s. The 'openness' and lack of qualification of the amount of damage necessary to justify a valid claim have been highlighted as reasons for the increasing number and consequently increasing value of claims. It has also been highlighted that, in the past, insurers have sanctioned underpinning which has not strictly been required on technical grounds.

In contrast, the number and value of claims for coal-mining subsidence has declined, mainly because of the rationalisation of the coal industry. However, the physical effects of subsidence damage, in terms of the visible damage to a property, are essentially the same regardless of the cause of subsidence. In addition, the non-technical aspects of damage in terms of subsidence blight are also very similar. Therefore, damage to low-rise properties resulting from coal-mining subsidence is considered to be one of the central aspects to this thesis.

3.7.5: A Review Of Earlier Literature

A review of two directly relevant research publications investigating themes similar to this research have been considered and the main findings of relevance highlighted. These issues will be returned to and commented upon in light of the findings of the case study analysis carried out and reported in subsequent chapters.

3.8: CHAPTER SUMMARY

The main issues relating to the consequences of ground subsidence or heave movement have been considered in this chapter and summarised in the discussion above. This has highlighted the consequences of subsidence or heave movement in terms of visible damage to a property, whether or not movement is progressive and the remedial action required to rectify damage. These aspects of damage, in addition to the causes of subsidence and heave movement considered in the previous chapter, are used in the following chapters to analyse case studies of damaged buildings.

In addition, this chapter has also highlighted important issues in relation to liability for subsidence damage. A consideration of these issues has clarified the original research aims, which are re-stated below and investigated in the subsequent chapters of this thesis:

i. The importance of establishing a threshold of visible damage that can objectively identify a genuine subsidence or heave claim.
ii. The importance of establishing a threshold of damage that can objectively identify where substructure repair (usually underpinning) is required.
iii. The consequences, in terms of number and value of claims, of introducing such thresholds of damage.

Having carried out a review of the literature to identify the important issues relating to subsidence and heave damage of low-rise properties, the remaining chapters address the research aims of this thesis that were identified in Chapter One. In order to investigate the research aims, the subsequent chapters draw upon the existing body of knowledge in this subject field, the salient parts of which have been covered in the review of literature carried out in this Chapter and Chapter Two.

CHAPTER FOUR: CASE STUDY ANALYSIS OF PROPERTIES DAMAGED BY SHALLOW SUBSIDENCE

4.1: INTRODUCTION

This chapter pursues the research aims of this thesis through the collection and analysis of case study properties that have been damaged by ground subsidence or heave. In relation to the main research aims of this thesis, as set out in Chapter One, this chapter primarily investigates Research Aim Two.

The objective of Research Aim Two is to investigate whether a threshold of damage exists that can be used to identify the need for substructure repairs when a property is damaged by ground subsidence or heave. The importance of being able to differentiate between properties that require remedial substructure repairs (usually underpinning) from properties that require superstructure repairs has been highlighted from a review of the literature in previous chapters.

To investigate the research objective, 127 case study properties damaged by *shallow* subsidence are considered. Chapter Five considers Research Aim Two in relation to properties damaged by *deep* coal-mining subsidence. Each case study examined in this chapter represents a privately owned low-rise residential property that has been damaged by *shallow* subsidence or heave and consequently has been investigated by a chartered structural engineer or a chartered civil engineer. The chapter identifies the sources from where case studies have been collected and the selection criteria used to identify appropriate case studies. Using this case study data involves collecting information which has been evaluated by an engineer appointed to investigate the damage. After discussing the collection of data, the chapter considers the information contained within the case studies and discusses the limitations of the data. This data is then analysed to investigate the objective of this chapter. The method used to analyse the data is initially through the use of cross-tabulation and chi-square tests of association. These initial tests are followed up by more substantive statistical methods involving multiple regression analysis. Finally, the findings that emerge from this analysis are considered in relation to the chapter objective.

4.1.1: Context Of Research Aim Two

Research Aim Two seeks to identify thresholds of damage which can be primarily applied to address the non-technical issues associated with subsidence and heave damage. Thresholds of damage emerging from Research Aim Two are intended to be of relevance to policy makers – notably insurance companies – who can apply these thresholds across a portfolio of properties indemnified against subsidence and heave damage in order to address contemporary problems created by such non-technical issues. In setting the context of Research Aim Two, it is also imperative to stress that this is **not** intended to provide definitive rules of engineering/surveying investigation which can replace professional judgement and experience.

4.2: COLLECTION OF CASE STUDY DATA

4.2.1: Sources Of Case Study Data

One hundred and twenty-seven case studies of residential low-rise properties allegedly damaged by *shallow* subsidence have been collected and analysed. Each case study represents an individual residential property damaged by structural movement caused by ground subsidence or heave. The damage evident in the property was investigated by a professionally qualified structural or civil engineer. For each case study property, the engineer's file was used to gather all available information relating to the damage in the property. The methodology section in Chapter One discusses the reasons why data has been gathered directly from engineering practices in preference to alternative methods of gathering data.

After identifying the appropriate sources of data, a significant problem encountered concerning the collection of this data was the highly confidential and commercially sensitive nature of the information being sought. Different agencies were contacted which are known to be involved in work relating to structural defects in low-rise residential properties. Three agencies were found which held the data required and were prepared to permit access. Each of these three agencies provided access to a wide variety and potentially large number of case studies. It was therefore considered that the data available from these three agencies would be adequate to enable the research to proceed. The criteria used for the selection of case studies are discussed later in this chapter.

The first source of case study data was a private practice of structural engineers from where 32 case studies were selected. The second source of case study data was a practice of civil, structural and building design consultants, which allowed access to their files and from this 30 appropriate case studies were selected. The third source of case study data was from the Royal Insurance Company, from which 65 case studies were collected. This company maintains a panel of approved structural and civil engineering practices located throughout the United Kingdom, which are appointed to handle claims allegedly involving damage caused by the insured perils subsidence heave or landslip. Seven different approved engineering practices were visited and between 6 and 12 case studies were collected from each practice. Each approved engineer was visited once to collect data. The collection of case study data continued in this way until sufficient case studies had been collected to allow the subsequent case study analysis to proceed. The justification and limitations of a sample size of 127 case studies is considered in the following case study analysis.

4.2.2: Selection Criteria For Case Study Data

Each of the three agencies mentioned above permitted access to a wide variety of information. It was, therefore, necessary to devise a selection criteria to ensure that all case study data was selected on a common basis.

It was identified in Chapter One that this research considers only privately-owned low-rise residential properties and it was a selection criterion that all case studies showed signs of damage that was attributable to ground subsidence or heave. When analysing case study data, it was necessary to be able to identify both the remedial action required and the basis upon which this had been established. Therefore, a further selection criterion included the proviso that it was possible to establish the remedial action taken and the basis for its implementation.

A further important aspect in the collection of case study data was the time-scale involved in each case study. The time period between the start and completion of each case study was unique. To establish commonality between case studies, two "*time thresholds*" can be defined. The first threshold starts with the initial inspection of the property, when an engineer inspects and records the visible damage. The second threshold occurs when the remedial action necessary to rectify the damage is approved by those responsible to fund it financially. Therefore, the variable factor in the time period of each case study is the length of time that it takes to determine the remedial action necessary. No account has been taken of the differing time periods between each case study, because this depends on the different methods of investigation employed by engineers and the individual facts of each case. The more important criterion has been to be able to identify **why** the remedial action was recommended.

Of the 127 case studies collected, 103 involved claims made by property owners under the subsidence, heave and landslip section of their buildings' insurance policy. A further 18 case studies involved properties that had been offered for sale. In each of these 18 case studies, because of concerns about potential subsidence or heave damage raised by a valuation surveyor, the opinion of a chartered structural or civil engineer was required. Six case studies involved the support group Age Concern. These claims were made on behalf of elderly persons, by Age Concern, to either the property owner's insurance company, or to the relevant local authority for an improvement grant.

For each case study property, the file of the engineer investigating the damage was made available for unrestricted examination. From this file it was possible to extract the relevant details. The extent of detail in each file differed considerably. In each of the case studies provided by Royal Insurance, a standard procedure had been adopted by the panel engineer investigating each claim. This entailed an initial report concerning the visible damage. This initial report contained an assessment of the visible damage in the property and suggested possible reasons for the cause of damage and whether or not the movement in the property could be expected to continue. Following this, a more detailed report contained specific details relating to the cause and any progression of the damage. This second and more detailed report included the results of trial hole and geotechnical investigations, and the results of monitoring the property for structural movement. The conclusions emerging from the report identified the cause of the damage and suggested the most appropriate form of remedial action necessary.

The presentation of information in those case studies not provided by Royal Insurance followed no standard format. Where the case study was associated with an insurance claim, the file usually followed a similar format to Royal Insurance case studies. Those case studies that did not involve an insurance claim tended to contain less relevant information. Typically, an initial inspection would be carried out and a report produced indicating the damage evident in the property. If the damage was considered significant enough to warrant further investigations, these would be carried out and reported. However, considering the objective of this chapter and the selection criteria for case studies, only case studies were selected in which it was possible to identify the remedial action and the reason why this was undertaken.

4.3: INFORMATION CONTAINED WITHIN CASE STUDIES

For all 127 case study properties, it has been possible to identify four factors that make up each case. These four factors have been identified as:

- Factor 1) *Visible damage evident in a property.*
- Factor 2) *Cause of damage.*
- Factor 3) *Whether or not movement in a property is progressive.*
- Factor 4) *The form of remedial action recommended.*

The above four factors can each be divided into a number of sub-categories. For example, different classifications of visible damage in a property represent the various sub-categories that make up the factor *visible damage*. The division of each factor into sub-categories is considered below.

4.3.1: Factor One: Visible Damage

It has been possible to identify a number of individual sub-categories that make up the factor *visible damage*.

For each case study property considered in this research, a classification has been made of the visible damage evident in the property. This classification was based on information extracted from the case study file, which usually took the form of a written description of the visible damage, although in some cases, a sketch or photographic details were included. From such details, it has been possible to classify damage evident in the property according to the classification proposed in BRE Digest 251 (1993 edition). As the majority of information in case study files relating to damage was expressed in a qualitative, descriptive format, the BRE classification of damage was used in this research because this classification best fit the data available in case studies. The use of this classification enabled the factor _visible damage_ to be assessed on a consistent basis in all case study properties.

The BRE classification of damage has been considered in Chapter Three. It will be recalled that the BRE classification has received much criticism, but that perhaps this criticism depended, to a large extent, upon the manner in which the classification was interpreted. Therefore, it is important to set the use of this classification into context. When attempting to place a case study property into the BRE classification, this was done, as suggested in BRE Digest 251 (1993 edition), by considering the visible damage evident in the walls of a property and the work required to repair this visible damage. It should be noted that the BRE classification of damage takes no account of the cause of damage, or whether or not movement causing damage is progressive.

It was found difficult to be consistent when attempting to classify damage in case study properties according to the six categories contained in the BRE classification. The reason for this being that in some of the case studies collected, information recording the visible damage to the property was not available in sufficient detail to accurately place a case study property into one of the six categories of damage suggested by the BRE. However, the six categories of damage can be combined into three broader categories. These being:

- '*aesthetic damage*'
- '*serviceability damage*'
- '*stability damage*'

From the BRE classification, categories of damage 0, 1 and 2 can be grouped together under the heading of '*aesthetic damage*', categories of damage 3 and 4 can be grouped together under the heading of '*serviceability damage*' and category 5 damage can be considered as '*stability damage*'. BRE Digest 251 (1993 edition) made reference to combining classifications of damage in this way. Therefore, '*aesthetic damage*', '*serviceability damage*' and '*stability damage*' are used as the sub-categories that make up the factor _visible damage_. It has been found that by combining categories of damage in this way enables the visible damage in case studies to be classified more accurately.

A sub-category of '*non applicable*' is included where it has not been possible to make an accurate or reliable classification of visible damage. There were two main reasons why it was not possible to make a classification of damage. One reason was because of a lack of detail in this aspect of the case study records. The second reason was because the BRE classification was not applicable to the damage described in the case study.

One consequence of reducing the number of sub-categories of the factor *visible damage* to three is that each sub-category is wide-ranging. Potential for errors exist when using a descriptive assessment of damage and attempting to fit this information into the BRE classification of damage. The greatest potential for error exists when distinguishing between case studies falling into BRE classifications of damage 2 or 3, as this forms the distinction between '*aesthetic damage*' and '*serviceability damage*'. Therefore, to ensure accuracy and consistency, each case study placed into the same sub-category of visible damage was carefully compared with all other case studies placed into the same sub-category to compare internal consistency. Any case study demonstrating inconsistencies was meticulously scrutinised and subsequently placed into what was considered to be the most appropriate sub-category. Table 4.1 indicates the results of classifying each of the 127 case studies into the sub-categories of *visible damage* identified above.

Classification of *visible damage*	**Number of case study properties**
Aesthetic	79
Serviceability	34
Structural	3
Not known	11
Total	127

Table 4.1: Classification of *visible damage* within case study properties

4.3.2: Factor Two: Cause Of Damage

Through scrutiny of the case study details, it has been possible to identify the cause of damage in each of the 127 case study properties used in this chapter. The following 9 main causes of damage have been identified as sub-categories of the factor *cause of damage* and each case study can be placed into one of these 9 sub-categories.

1. *'Clay subsoil, tree roots, shallow foundations, subsoil desiccation'*
2. *'Clay subsoil, tree roots, shallow foundations'*
3. *'Clay subsoil, tree roots, subsoil desiccation'*
4. *'Clay subsoil, tree roots'*
5. *'Clay subsoil, shallow foundations'*
6. *'Defective drains'*
7. *'Presence of tree roots, subsoil type unknown'*
8. *'Shallow foundations'*
9. *'No details available'*

The above sub-categories of the factor *cause of damage* that involve clay subsoil can be further sub-divided to take into account the shrinkage potential of the clay subsoil (low, medium or high shrinkage potential). Table 4.2 highlights the causes of damage in each case study when this information is taken into account, and the number of case studies classified within each cause. Each of the sub-categories that make up the factor *cause of damage* contain terms that require more precise definitions. Appendix B provides the definitions of these terms within the context of this research by drawing upon some of the technical issues that have been considered in Chapters Two and Three.

Ref	**Cause of damage**	**Number of properties**
1.1	Highly shrinkable clay subsoil, tree roots, shallow foundations, desiccation	17
1.2	Medium shrinkable clay subsoil, tree roots, shallow foundations, desiccation	6
1.3	Low shrinkable clay subsoil, tree roots, shallow foundations, desiccation	0
1.4	Clay subsoil (shrinkage potential unknown), tree roots, shallow foundations, desiccation	4
2.1	Highly shrinkable clay subsoil, tree roots, shallow foundations	6
2.2	Medium shrinkable clay subsoil, tree roots, shallow foundations	3
2.3	Low shrinkable clay subsoil, tree roots, shallow foundations	3
2.4	Clay subsoil (shrinkage potential unknown), tree roots, shallow foundations	4
3.1	Highly shrinkable clay subsoil, tree roots, desiccation	13
3.2	Medium shrinkable clay subsoil, tree roots, desiccation	4
3.3	Low shrinkable clay subsoil, tree roots, desiccation	2
3.4	Clay subsoil (shrinkage potential unknown), tree roots, desiccation	1
4.1	Highly shrinkable clay subsoil, tree roots	2
4.2	Medium shrinkable clay subsoil, tree roots	0
4.3	Low shrinkable clay subsoil, tree roots	1
4.4	Clay subsoil (shrinkage potential unknown), tree roots	4
5.1	Highly shrinkable clay subsoil, shallow foundations	0
5.2	Medium shrinkable clay subsoil, shallow foundations	1
5.3	Low shrinkable clay subsoil, shallow foundations	2
5.4	Clay subsoil (shrinkage potential unknown), shallow foundations	0
6	Defective drains	31
7	Shallow Foundations	4
8	Tree roots	4
9	No details	15

Table 4.2: Cause of damage (taking into account shrinkage potential of clay subsoil)

4.3.3: Factor Three: Movement

Four sub-categories have been identified that make up the factor movement, these being:

- '*movement long-term progressive*'
- '*seasonal movement*'
- '*movement non-progressive*'
- '*no information*'

In those case studies where it has been possible to establish if movement was '*long-term progressive*', '*seasonal*' or '*non-progressive*', a programme of monitoring had been carried out. A variety of different monitoring techniques were employed by the engineering practice investigating the damage in order to establish this information. These techniques included:

- Crack width monitoring using precise measuring techniques such as digital callipers.
- Precision levelling of a building related to a fixed datum.
- Observing damage and noting any progression or recovery.
- Repairing damage and observing any re-occurrence.

Where monitoring has been carried out, no account has been taken of the monitoring technique used, the rate of movement or the length of the monitoring period. Although it was possible to establish the method of monitoring used, it was found that the rate of movement and the time period of monitoring was difficult to establish. In a majority of cases, a complete set of monitoring results was not contained within the file. Even where the results of monitoring were recorded, the data in case study files was difficult to interpret accurately. Consequently, it was necessary to rely upon the engineer's interpretation of whether movement in a property was considered to be '*non-progressive*', '*seasonal*', or '*long-term progressive*'. A number of the case study files made no reference to any form of monitoring and in these cases, the sub-category '*no information*' was recorded. Table 4.3 indicates the results of classifying the 127 case studies into the sub-categories of movement identified above.

Classification of *movement*	**Number of case study properties**
Non-progressive movement	60
Seasonal movement	4
Long-term progressive movement	23
Movement not known	40
Total	127

Table 4.3: Classification of *movement* within case study properties

4.3.4: Factor Four: Form Of Remedial Action

From the 127 case studies analysed, it has been possible to identify the form of remedial action necessary to rectify damage. The different forms of remedial action identified have been grouped into four sub-categories, these being:

A) '*No remedial action necessary other than routine maintenance.*'
B) '*Cosmetic superstructure repairs*'
C) '*Remedial foundation underpinning*'
D) '*Demolish and re-build structure*'

It can be seen that where sub-categories A and B are combined, and sub-categories C and D are combined, this distinguishes case study properties requiring superstructure repairs only from those requiring remedial substructure repairs, which is the threshold of damage under investigation in this chapter. The results of classifying the 127 case studies into the above sub-categories are indicated below in table 4.5 and figure 4.1.

4.3.5: Summary Of Sub-Category Information

Table 4.4 provides a summary of the sub-categories that have been identified within each of the four component factors to each case study (factor three can be further sub-divided by reference to table 4.2 above).

FACTOR ONE:	**VISIBLE DAMAGE**
	Aesthetic *Serviceability* *Stability* *Not applicable*
FACTOR TWO:	**CAUSE OF DAMAGE**
	Clay subsoil, tree roots, shallow foundations, subsoil desiccation *Clay subsoil, tree roots, shallow foundations* *Clay subsoil, tree roots, subsoil desiccation* *Clay subsoil, tree roots* *Clay subsoil, shallow foundations* *Defective drains* *Presence of tree roots, subsoil type unknown* *Shallow foundations* *No details available*
FACTOR THREE:	**MOVEMENT**
	Long-term progressive movement *Seasonal movement* *Movement non-progressive* *No information*
FACTOR FOUR:	**REMEDIAL ACTION**
	A No remedial action necessary other than routine maintenance *B Cosmetic superstructure repairs* *C Remedial foundation underpinning* *D Demolish and re-build*

Table 4.4: Summary of sub-category information.

Appendix C contains the primary "raw" data for the 127 case study properties analysed in this Chapter. This data is classified so that where a sub-category occurs within a case study a value of 1 is applied. Where a sub-category does not occur, a value of 0 is applied.

4.4: ANALYSIS OF CASE STUDY DATA

The objective of this chapter is to identify, from the 127 case studies analysed, a threshold of damage that can be used to differentiate properties that require remedial substructure repairs from those properties which require superstructure repairs only. Therefore, the case study analysis seeks to establish if there exists any identifiable relationship between the factor ***remedial action*** and any of the factors *visible damage*, *cause of damage* and *movement*.

4.4.1: Classification Of Case Study Properties By Remedial Action Required

Table 4.5 and figure 4.1 indicate the number of case study properties that are classified into the four remedial action groups that have been identified in section 4.3.4.

Remedial Action Group	A	B	C	D	**Total**
Number of Case Study Properties	14	62	39	12	**127**
% of Total	11.0%	48.8%	30.7%	9.4%	**100%**

Table 4.5: Case study properties classified by the factor *remedial action*.

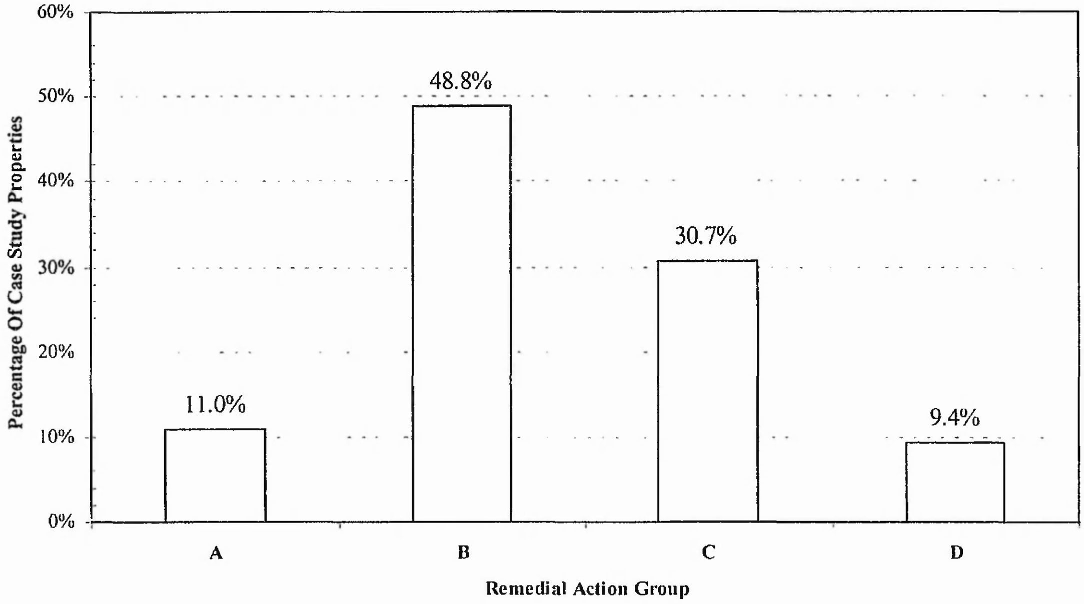

Figure 4.1: Case study properties classified by the factor *remedial action*.

The above information indicates the spread in the number of case study properties that have been classified in each of the four categories of remedial action identified. The majority of case study properties were found to require '*remedial action group B*', the next most common group being '*remedial action group C'*. A small but important, number of case study properties was found to require either '*remedial action group A*' or '*remedial action group D*'.

To first investigate the structure of the data contained within this Chapter, an initial cross-tabulation analysis and chi-square test has been undertaken. This explores any initial relationship between the factor *remedial action* with the factors *visible damage*, *cause of damage* and *movement*. The results of this are included in Appendix D.

The cross tabulation analysis and chi-square test undertaken in Appendix D have indicated some interesting initial results. However, this method of analysis only investigates any relationship between the factor *remedial action* and each of the three other factors (*visible damage*, *cause of damage* and *movement*) on an individual basis only. It is necessary to consider how each of these three factors act in combination to influence the factor *remedial action*.

4.4.2: Methodology Applied To Data Analysis

The primary objective of this chapter is to investigate any threshold of damage that can identify the need for remedial action when a property is damaged by ground subsidence. Therefore, the following analysis considers how the factors *visible damage*, *cause of damage* and *movement* combine to influence the factor *remedial action*. To investigate this, the multivariate statistical technique of multiple regression analysis has been employed. This is a statistical technique that accounts for variation in one dependent variable from a set of predictors.

In order to implement multiple regression analysis, it is necessary to apply an appropriate numerical scale to the factors which form the variables. The factor *remedial action* is the dependent variable with the factors *visible damage*, *cause of damage* and *movement* forming the independent variables. Of the independent variables, applying an appropriate scale to the variable *cause of damage* presents a number of opportunities, and these are discussed below in section 4.4.3.4.

4.4.3: Rational Applied To Rank And Scale The Case Study Data

The individual sub-categories of the data which make up each of the four factors, *visible damage*, *cause of damage*, *movement* and *remedial action* have been ranked in order of importance. Subsequently, what is considered to be an appropriate scale has been applied. The rationale behind the application of an appropriate scale for each factor is discussed below. The general approach to the regression analysis is that the factor *remedial action* is the dependent variable with the factors visible damage, cause of damage and movement forming the independent variables.

4.4.3.1: Ranking And Scaling Of The Dependent Variable - *Remedial Action*

Within the independent variable *remedial action* (*rem_act*), four separate sub-categories have been identified, which are:

- '*remedial action group A*' (repairs as part of routine building maintenance)
- '*remedial action group B*' (cosmetic superstructure repairs)
- '*remedial action group C*' (remedial underpinning)
- '*remedial action group D*' (demolish and rebuild)

The starting point has been to rank the data so that '*remedial action group A*' is considered to be the least important – in terms of damage to the property – with '*remedial action group B*', '*remedial action group C*' and '*remedial action group D*' each being considered progressively more important. After ranking this data a scale has been applied, in the first instance on a linear basis as below:

- '*remedial action group A*' = 1
- '*remedial action group B*' = 2
- '*remedial action group C*' = 3
- '*remedial action group D*' = 4

4.4.3.2: Ranking And Scaling Of The Independent Variable – *Visible Damage*

The data for the independent variable *visible damage* (*vis_dam*) has been ranked in a similar manner to the dependent variable discussed above. Within this, there are four individual sub-categories as listed below:

- '*aesthetic damage*'
- '*serviceability damage*'
- '*structural damage*'
- '*damage not applicable*'

In the first instance, '*aesthetic damage*' is ranked as the least important – again in terms of damage to the property, with '*serviceability damage*' and '*structural damage*' being considered progressively more important. After ranking the data as above, a scale can be applied to the data, again on a linear basis as outlined below:

- '*aesthetic damage*' = 1
- '*serviceability damage*' = 2
- '*structural damage*' = 3
- '*damage not applicable*' = 0

Where it has not been possible to classify the visible damage so that the sub-category '*damage not applicable*' has been recorded – this classification of damage has been assigned a value of 0. The implications of this are considered below in the subsequent regression analysis.

4.4.3.3: Ranking And Scaling Of The Independent Variable – *Movement*

The independent variable *movement* (*build_mvt*) has again been ranked in a similar method to the other variables considered above. The following four sub-categories are contained within this independent variable:

- '*non-progressive movement*'
- '*seasonal movement*'
- '*long-term progressive movement*'
- '*movement unknown*'

In the first instance, '*non-progressive movement*' is ranked as the least important sub-category of this variable, with '*seasonal movement*' and '*movement long-term progressive*' being considered increasingly more important. A scale has again been applied on a linear basis as below:

- '*non-progressive movement*' = 1
- '*seasonal movement*' = 2
- '*long-term progressive movement*' = 3
- '*movement unknown*' = 0

Where it has not been possible to determine how the movement is affecting the property, so that the sub-category of '*movement not known*' is recorded – this has been assigned a value of 0. Again, the implications of this are considered in the following analysis.

4.4.3.4: Ranking And Scaling Of The Independent Variable – *Cause Of Damage*

Ranking and subsequently scaling the various sub-categories of data within the independent variable *cause of damage* (*cause_dam*) presents a number of opportunities. Within each of the other variables - discussed above – it has been possible to identify a clear, objective and unquestionable ranking order and subsequently apply an appropriate scale that reflects appropriate numerical values. It is not possible to follow this method to rank the data within the factor *cause of damage* as there is no obvious order in which to rank the data.

Therefore, ranking of the sub-categories of data within the factor *cause of damage* has been approached by considering the characteristics of each of these sub-categories. Table 4.2 lists the sub-categories of data within the factor *cause of damage* and this takes into account the shrinkage potential of the subsoil.

Considering clay subsoil first, a preliminary ranking order for this can be established based on shrinkage potential. For example, a subsoil with a high shrinkage potential should be ranked more important than a subsoil with a low shrinkage potential. This is demonstrated below:

- '*clay subsoil*' (high shrinkage potential) = 3
- '*clay subsoil*' (medium shrinkage potential) = 2
- '*clay subsoil*' (low shrinkage potential) = 1
- '*clay subsoil*' (unknown shrinkage potential) =1- a conservative estimate based on the fact that as a clay subsoil, it must have a minimum of a low shrinkage potential

This numerical scale can be applied to take into account the shrinkage potential of a clay subsoil. Each property where clay subsoil is found to be involved in the cause of damage can be assigned a numerical value of 3, 2 or 1. Where clay subsoil is not identified as a contributory factor to the cause of damage a value of 0 is applied. Hence, clay subsoil (*clay*) can now be considered as an independent variable in its own right, each property being classified with a numerical value of 3, 2, 1 or 0 as appropriate.

Reference back to table 4.2 indicates that besides clay subsoil, there are a number of further components present in each of the identified causes of damage. However, applying an appropriate scale for these remaining components (as listed below) is difficult. Initially, these components have been assigned a value of 1 if found to occur and 0 where the component does not occur in the cause of damage. This scale is used to initially develop an appropriate scale and this is subsequently considered for refinement.

- '*tree roots*' = 1 (no tree roots = 0)
- '*shallow foundations*' = 1 (no shallow foundations = 0)
- '*subsoil desiccation*' = 1 (no subsoil desiccation = 0)
- '*defective drains*' = 1 (no defective drains = 0)

Within each cause of damage identified in table 4.2, one or more of the above list of components can exist in each case study property. Where a component exists within a cause of damage, it is assigned a numerical value as above. Where a component does not exist within a cause of damage, it can be assigned a value of 0.

From the above discussion, this creates 5 separate independent variables within the factor cause of damage, these being clay subsoil (*clay* = 3,2,1,0) tree roots (*trees* = 1,0) shallow foundations (*shll_fdn* = 1,0) subsoil desiccation (*desiccation* = 1,0) defective drains (*drains* = 1,0). Therefore, as an example, taking a property identified to have cause of damage 1.1 (i.e. highly shrinkable clay subsoil, tree roots, shallow foundations, desiccation), the following numerical values can be applied:

Clay	***Trees***	***Shll_fdn***	***Desiccation***	***Drains***
3	1	1	1	0

Table 4.6: Example classification of independent variables within the factor cause of damage

4.4.3.5: Summary Of Independent Variable Scaling

The various independent variables associated with the factor cause of damage have initially been considered above. The two other independent variables (*vis_dam* and *build_mvt*) and the dependent variable (*rem_act*) can now be added. This then gives a complete picture, from the information available, for each case study property. For information, a selection of the first five case studies is shown below in table 4.7 and the full results of this are shown in Appendix E.

Case No.	*Vis_dam*	*Clay*	*Trees*	*Shll_fdn*	*Desiccation*	*Drains*	*Build_mvt*	*Rem_act*
1	2	3	1	1	1	0	0	**3**
2	2	3	1	1	1	0	0	**3**
3	1	1	0	1	0	0	0	**2**
4	1	3	1	1	1	0	2	**3**
5	1	3	1	1	1	0	1	**2**

Table 4.7: Example classification of all independent variables within case study properties

4.5: RESULTS

After categorising and scaling the independent variables, this information can now be applied to the regression analysis, which is considered below.

4.5.1: Regression Model One

Using the data in Appendix E, a multiple regression analysis has been undertaken using SPSS, and the results of the analysis are also included in this same Appendix. It should be noted that within SPSS, the *enter* method has been used to place the independent variables in to the analysis. Throughout this analysis, various other methods of placing/removing variables into the analysis are also considered. For completeness, a brief discussion of these methods and the interpretation of regression results are included in Appendix H.

Considering the results of the analysis from Appendix E, this indicates some interesting correlations between independent variables. Some of these correlations can be explained. For example, the high correlation between *desiccation* and tree roots in clay soil is obvious. The model summary indicates that the regression model has a relatively poor fit to the data – as demonstrated by the low value of R Square (0.286). The unstandardised coefficients listed in the coefficients table would provide the details of the regression equation. This can then be used to calculate the expected outcome for the dependent variable *rem_act* in cases where this is not known. However, the coefficients table also indicates that some of the independent variables in the model may have a limited use as predictors. Although there is no one test that provides an indication of a "best" model, the *t* statistic in the coefficients table does provide some indication of the relative importance of each variable in the model. As a rough guide, values of *t* well below –2 or above +2 are generally considered to be potentially significant. Using this criteria, it could be suggested that the independent variables *vis_dam* (t = 0.154), *clay* (t = 1.055) *shll_fdn* (t = -1.148) and *desiccation* (t = 0.804) be removed from the model. *(It should be noted that where the stepwise, forward selection or backwards elimination method of entering/removing variables from the model is applied, the independent variables visible damage, clay subsoil and desiccation do not pass the statistical criteria to be entered into the model using the SPSS default settings).*

Although regression model one provides some interesting results, on balance, the statistical significance of this model is not particularly powerful and therefore its use in practice must be questioned. Examination of this model – in particular inspection of the raw data – indicates that some independent variables have "missing" data. This is primarily the case for the two independent variables *vis_dam* and *build_mvt*, and consideration of this leads to refinement of the data for regression model two.

4.5.2: Regression Model Two

For the independent variable *build_mvt*, a scale of 3, 2, 1 or 0 has been applied to represent '*long-term progressive movement*', '*seasonal movement*', '*non-progressive movement*' and '*movement unknown*'. The classification of '*movement unknown*' (value = 0) creates a potential problem. Within the actual case study properties analysed in this Chapter, the engineer investigating the property has not always expressly determined the type of movement in the property. The reason for this is not always clear. For example, the engineer might be applying his or her professional judgement/experience. However, those case study properties in which movement is classified as '*movement unknown*' could potentially be distorting the analysis.

Logically a property classified with '*movement unknown*' **must** fall in to one of the three other categories of '*long-term progressive movement*', '*seasonal movement*' or '*non-progressive movement*'. Therefore, the classification of '*movement unknown*' represents a case study which, for the purpose of this analysis, has incomplete information. Subsequently, to improve the quality of the data, those case studies where '*movement unknown*' occurs are excluded from the analysis. The same rationale applies to the independent variable *vis_dam* so that those case studies classified to have '*visible damage unknown*' are also withdrawn from the analysis.

However, the independent variables associated with the factor *cause of damage* require special consideration. For example, *trees* are either present or not present as a cause of damage – and the scale applied (1 or 0) reflects this. Therefore, where *clay*, *trees*, *shll_fdn*, *desiccation* or *drains* are **not** present in the cause of damage, and hence a scale of 0 is applied, it is legitimate to leave such case studies in the analysis. This assumption holds as long as one or more of these independent variables are found to be present. Where none of these variables exist, then for the purpose of this analysis, it indicates that the cause of damage is unknown (or is outside the causes identified in this analysis). As there has to exist some cause of damage, each case study which is assigned a value of 0 for all independent variables within the factor *cause of damage* is therefore excluded from the analysis.

After undertaking the above refinements, the sample size of case studies is reduced from 127 to 73. The raw data for this analysis is contained in Appendix F. Again, multiple regression has been applied. Initially, the *enter* method of including variables in the analysis has been used. The results of this analysis are contained in Appendix F.

Regression model two again indicates a number of high correlations. In particular, the high correlation (0.874) between the independent variable '*movement*' and the dependent variable *rem_act* is evident. The model summary indicates that regression model two has a much better fit than its predecessor, model one. This is evident in the significantly higher value of R Square (0.834). However, it is necessary to examine the results from this model and look beyond the model fit to consider its significance.

Inspection of the coefficients table provides an indication of the regression equation generated by this model. This equation can be used to predict the form of remedial action, given knowledge of the constituent independent variables. The unstandardised coefficients (B) provide the details of the equation, which can be stated as:

$$\textbf{\textit{Rem\_Act}} = 0.850 + (0.26 * \textit{vis\_dam}) - (0.01 * \textit{clay}) + (0.31 * \textit{trees})$$
$$- (0.07 * \textit{shll\_fdn}) + (0.039 * \textit{desiccation}) + (0.15 * \textit{drains}) + (0.58 * \textit{build\_mvt})$$

However, the results of the analysis indicate that a number of the independent variables are of limited use as predictors of the dependent variable *rem_act*. This is evident through inspection of the *t* statistic in the coefficient table. The variables *clay*, *shll_fdn*, *desiccation* and *drains* all have a value of *t* between –2 and +2. This highlights their potential limitation as useful predictors of the dependent variable. Indeed, where the *stepwise*, *forward selection* or *backwards elimination* method of entering/removing variables from the model is applied, the independent variables *clay*, *shll_fdn*, *desiccation* and *drains* do not pass the statistical criteria to be entered into the model using the SPSS default settings. If these variables were removed from the analysis, it would leave the variables *vis_dam*, *trees* and *build_mvt* as the predictors of the dependent variable remedial action. Of these, the significance of *build_mvt* as a predictor in the regression model is self evident.

If regression model two were accepted at this stage of the analysis, the overriding importance of the independent variable *build_mvt* would be clear. However, after consideration of the results which emerge from this analysis and reflecting upon the classification of the independent variables, it is considered necessary to further explore the analysis. In particular, to ensure a robust analysis is undertaken, scaling of the data within the factor <u>cause of damage</u> is given further consideration. This is considered in regression model three below.

4.5.3: Regression Model Three

As discussed above, classifying and scaling the data within the factor <u>cause of damage</u> presents a number of potential opportunities. In order to examine these more fully, the method of categorising and scaling applied to this data has been discussed with representatives within the Department of Environment Transport and the Regions (DETR) who have extensive experience of this subject matter[1]. This confirmed the approach to ranking and scaling of the shrinkage potential of clay subsoil. However, following discussions, a slightly different approach to the overall ranking and scaling of the data within the factor <u>cause of damage</u> emerged.

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[1] Private communication with the construction research division.

Discussions highlighted the importance of considering the inter-relationships between the individual components which are present within each of the identified causes of damage. For example, a clay subsoil with a high shrinkage potential is not a cause of damage *per se*. It is only when highly shrinkable clay subsoil is present in combination with other components such as tree roots or shallow foundations that its full potential as a cause of damage emerges. Therefore, with reference back to the causes of damage listed in table 4.2 (page 75) it becomes possible to begin development of a more holistic approach of scaling the data contained within the factor cause of damage.

After considering the initial ranking and scaling of the component clay subsoil, discussions highlighted the importance of trees in contributing to causes of domestic subsidence damage. This view is substantiated through the literature review undertaken in Chapter Two.

It was further highlighted that shallow foundations are an important contributory factor – although it was suggested that experience indicates that this is not as important as tree roots. Subsoil desiccation was suggested to be less important – relatively – than both tree roots and shallow foundations, primarily because trees extracting moisture from the soil is the cause of desiccation. Therefore, desiccation can only occur when trees are present. Subsequently, the following numerical values were suggested for the individual components:

- Clay subsoil (high shrinkage potential) = 3
- Clay subsoil (medium shrinkage potential) = 2
- Clay subsoil (low shrinkage potential) = 1
- Clay subsoil (unknown shrinkage potential) =1
- Tree roots = 3
- Shallow foundations = 2
- Subsoil desiccation = 1

To reflect the fact that components within the factor *cause of damage* act in combination, the following method has been used to calculate an alternative numerical value for each of the sub-categories within table 4.2:

Shrinkage potential of clay subsoil * (sum of remaining components)

For example, taking sub-category of damage 2.2 (clay subsoil [medium shrinkage potential], tree roots, shallow foundations), the following value would be calculated:

Medium shrinkable clay subsoil (2) * {tree roots (3) + shallow foundations (2)} = 10

This method has been applied to all sub-categories within table 4.2 and the results are included in table 4.8. Hence there is now only one independent variable associated with the factor cause of damage (*cause*). The numerical scale for this variable is set out in table 4.8 below.

Ref	Cause of damage	Scaled value
1.1	Highly shrinkable clay subsoil, tree roots, shallow foundations, desiccation	18
1.2	Medium shrinkable clay subsoil, tree roots, shallow foundations, desiccation	12
1.3	Low shrinkable clay subsoil, tree roots, shallow foundations, desiccation	6
1.4	Clay subsoil (shrinkage potential unknown), tree roots, shallow foundations, desiccation	6
2.1	Highly shrinkable clay subsoil, tree roots, shallow foundations	15
2.2	Medium shrinkable clay subsoil, tree roots, shallow foundations	10
2.3	Low shrinkable clay subsoil, tree roots, shallow foundations	5
2.4	Clay subsoil (shrinkage potential unknown), tree roots, shallow foundations	5
3.1	Highly shrinkable clay subsoil, tree roots, desiccation	12
3.2	Medium shrinkable clay subsoil, tree roots, desiccation	8
3.3	Low shrinkable clay subsoil, tree roots, desiccation	4
3.4	Clay subsoil (shrinkage potential unknown), tree roots, desiccation	4
4.1	Highly shrinkable clay subsoil, tree roots	9
4.2	Medium shrinkable clay subsoil, tree roots	6
4.3	Low shrinkable clay subsoil, tree roots	3
4.4	Clay subsoil (shrinkage potential unknown), tree roots	3
5.1	Highly shrinkable clay subsoil, shallow foundations	6
5.2	Medium shrinkable clay subsoil, shallow foundations	4
5.3	Low shrinkable clay subsoil, shallow foundations	2
5.4	Clay subsoil (shrinkage potential unknown), shallow foundations	2
6	Defective drains	18
7	Shallow Foundations	2
8	Tree roots	3
9	No details	0

Table 4.8: Cause of damage with scaling factor applied

Cause of damage 6, which is where defective drains have been established as the cause of damage, has been assigned a value of 18. This value has been given to reflect the fact that within the literature review and the interviews conducted in the course of this research, defective drains have been identified as one of the most important causes of damage.

As in the previous regression model, those case study properties where either '*visible damage unknown*', '*cause of damage unknown*' or '*movement unknown*' occur have been removed from the analysis, so the sample size is again 73 case study properties.

After scaling the independent variable *cause of damage* as above, it is possible to perform a regression analysis with *vis_dam*, *cause* and *build_mvt* as three independent variables and *rem_act* as the dependent variable. The raw data used for this, and the subsequent output from SPSS is included in Appendix G. The *enter* method has been used to add the independent variables to regression model three.

The results from regression model three are relatively easy to interpret as there are only three independent variables in the analysis. The high correlation between the independent variable *build_mvt* and the dependent variable *rem_act* is again evident. However, there is also evidence of a reasonable correlation between the independent variable *vis_dam* with remedial action. By comparison, the correlation between *cause* and *rem_act* is poor.

The model summary provides evidence that the model produces a good fit to the data (R Square = 0.815), with the standard error of the estimate being 0.28. The coefficients table provides an indication of the regression equation which could be used to predict the form of remedial action. Using the unstandardised coefficients (B), the regression equation would be:

$$\boldsymbol{Rem\_Act} = 0.967 + (0.299 * vis\_dam) + (0.0058 * cause) + (0.561 * build\_mvt)$$

However, further inspection of this model highlights that the independent variable *cause* has an extremely limited use as a predictor in the regression equation. This is substantiated by both its poor *t* value in the coefficients table (t = 1.038) and its poor correlation with the dependent variable *rem_act* (r = 0.227). Indeed, where stepwise, forward selection or backwards elimination methods of entering/removing variables from the analysis is applied, the variable *cause* fails the SPSS default statistical criteria and is excluded from the analysis. Hence, the results suggest that the independent variable *cause* should be removed from the model as this variable has a negligible influence on the form of remedial action required. The practical implications of this are considered in the discussion of the results below.

4.6: DISCUSSION OF RESULTS

These results have highlighted the strengths and weaknesses of a number of regression models. It is now necessary to consider the statistical results that have emerged in view of the practical aspects of the subject area.

Regression model one can essentially be ignored as it has been highlighted that the constituent raw data for this model is potentially incomplete. This resulted in refinement for regression model two and subsequently the sample size of case studies has been reduced from 127 to 73 for both regression model two and regression model three.

The difference between regression models two and three is in relation to the scaling of the data contained within the variable *cause of damage*. Two different approaches to this have been considered. In both models, it has been clearly demonstrated that the cause of damage has not had a statistically significant influence upon the dependent variable *remedial action*.

What has been found to emerge is the importance of *visible damage* and *movement*. Regression models two and three highlight this. In particular, the overriding significance of *movement* is clear. This is substantiated through reference to the cross-tabulation analysis undertaken in Appendix D. Furthermore, the classification of the variable *visible damage* has some potential limitations which are further considered below. Therefore, returning to the overall objective of this Chapter, which is to investigate a threshold of damage that can be used to establish the need for remedial substructure repairs, it can be tentatively recommended that this be based on a knowledge of whether movement in the property is long term progressive or not.

4.6.1: Results Of Analysis In The Context Of Addressing Non-technical Issues

It has been identified earlier in this Chapter (section 4.1.1) that the threshold of damage being investigated in Research Aim Two is intended primarily to be of relevance to policy makers, in particular, insurance companies. They can then apply this threshold to address some of the contemporary non-technical aspects of subsidence damage.

The emerging conclusions from this chapter (as presented above) **must not** be seen as a simple "rule of thumb" that can replace the professional services of an engineer when investigating technical issues relating to individual cases of subsidence damage. It is imperative to point out that establishing the cause of damage is absolutely essential when investigating damage to a property. However, the way in which the cause of damage is classified in this thesis has highlighted that two properties, classified to have the same cause of damage have been found to require different forms of remedial action. This indicates the complexity of attempting to categorise and classify causes of damage. The cause of damage to any one property is likely to be influenced by a very large number of relatively minor factors, which in isolation appear almost insignificant, but which in combination are crucial. These factors are not always expressly recorded by an engineer investigating damage as these are considered as background knowledge which constitutes professional judgement and experience. Such factors could include, for example, type and quality of construction, age of property, custom and practice etc. To take these important factors into account in a regression model would require a much more detailed approach to collecting case study data which is beyond the resources of this research as discussed further below in section 4.6.2.

It has been highlighted in Chapter One that the focus of this research seeks to address the non-technical issues associated with subsidence and heave damage. It is therefore important to recognise that the threshold of damage emerging from investigation of Research Aim Two is intended primarily to be of use to insurance companies seeking to address the contemporary problems created by the non-technical issues associated with subsidence damage. It is not intended as a replacement for engineering/surveying judgement. Instead it should be seen as an element that can complement the role of an engineer to enable policy makers (principally insurance companies) to address these non-technical issues.

To place the analysis undertaken in this Chapter into context, the 127 case study properties analysed can be thought of as a representative sample of claims made to an insurance company. Looking at this portfolio of claims, a fundamental question that an insurance company would ask is, "*how can those properties requiring relatively minor and inexpensive superstructure repairs be distinguished from properties requiring more expensive substructure repairs*"? The empirical analsysis undertaken has shown that to reliably answer this question it is necessary to base the answer on whether or not movement in the property is long-term progressive. If an insurance company were to then take this knowledge forward and apply it to future claims for subsidence damage, the implications are extremely important. This is investigated later in this work in Chapter Seven.

4.6.2: Reflection On Regression Models

The regression models developed in this work have a number of limitations which need to be explored and considered. The statistical analysis *per se* is of little value unless viewed in the context of the data which has been collected and this subject is considered below.

The regression models developed are subject to the limitations of the data collected in the course of this Chapter. Further work and refinement can be recommended in order to improve and develop the statistical approach.

As discussed at length in the relevant sections of this thesis, a number of compromises have had to be made in order to collect data that is both reliable and valid. This has been the overriding consideration in the research and is seen as a particular strength of this work.

In order to improve the regression models developed, a number of recommendations in relation to data collection would be required. These are discussed below and although this is not intended as a comprehensive discussion it highlights the salient points:

A More Comprehensive Classification Of Visible Damage

Visible damage has been classified according to the classification established in BRE Digest 251 (1993 edition). It has been discussed at length in Chapter Three that this classification of damage has a number of potential limitations and it is not intended to reiterate these again here. However, if the classification of visible damage is to be included in a comprehensive statistical analysis, then it is recommended that a substantially more detailed classification of visible damage than that contained in BRE Digest 251 is used. For example, it would be necessary to consider quantity as well as severity of damage, as well as some of the more subjective elements of damage. To develop a more comprehensive classification of damage and assign values of significance to this to enable this to be used in a statistical analysis would require extensive consultation within the construction consultancy sector, the insurance and lenders sector and consumer representatives. This is a matter for further work which is considered in Chapter Eight.

Consistency In Approach To Establish The Cause Of Damage

To establish the cause of damage, data has been collected "second-hand" through review of engineers' detailed file records. In the course of collecting data in this way, some aspects of detail have been compromised in order to record data on a consistent and reliable basis. The challenges of ranking and scaling this data have been considered previously in this Chapter, and these problems have been addressed in order to produce a potential scale. However, it is clear that a much more accurate ranking and subsequent scaling of the data could be achieved if the cause of damage in all case studies was established according to a common and consistent method. This point, briefly discussed above, would enable the cause of damage in all case studies to be assigned more appropriate values of significance for a statistical analysis than have presently been used. Again, this issue is highlighted in Chapter Eight as an area for potential further work.

To address the issues highlighted above (and hence increase the validity of the data for statistical analysis) would increasingly lead to the conclusion that in order to collect sufficiently detailed information for case studies would require data to be collected through direct investigation. This would involve each case study property being directly physically inspected, the cause of damage investigated and movement monitored, as described in the methodology section in Chapter One. Clearly this approach - although beyond the scope and resources of the research – would address many of the problems highlighted above.

The regression models undertaken in this Chapter provide a number of extremely useful results which have established a threshold of damage to Address Research Aim Two for properties damaged by shallow subsidence. A potentially more refined and powerful model could be developed by consultancies who directly investigate a large number of subsidence or heave cases on a regular basis. In such circumstances, the use of a more detailed – and hence more powerful - regression model could begin to be used to assist (although not replace) engineers and surveyors in their judgements and evaluation. In order to begin to implement this, it would be necessary to address the format and detail required for data collection as highlighted above. However, consultancies dealing with a large number of subsidence cases will be required to evaluate the visible damage, investigate its cause and establish the extent of any ongoing movement and would therefore be in an ideal position to consider implementing such issues.

4.7: REFLECTION ON CASE STUDY DATA

Before summarising the main findings emerging from the case study analysis in this chapter, it is necessary to reflect on the limitations of the case study data.

The reason for investigating this part of the research using case study analysis has been discussed in Chapter One. Having collected and analysed the case study data, the main limitation found was that it is not always possible to identify all of the necessary information in each case study. For example, it has not always been possible to classify the visible damage, or to identify the cause of damage, or even to identify whether or not movement is progressive. However, when collecting case study data it was found that the individual nature of each case study, and the different methods and approaches to investigating damage made it impossible for all case study data to be compatible, even after a rigorous selection criteria was applied. Regardless of these limitations, it was still considered that the methodological approach of collecting data from individual engineering practices represented the best method of data collection for this study.

4.7: CHAPTER SUMMARY

An analysis of 127 case study properties has been carried out to investigate if a threshold of damage exists which can be used to establish the need for substructure repairs in properties damaged by *shallow* subsidence. The 127 case study properties have been analysed and four component factors to each case study have been identified, these being:

- *visible damage*
- *cause of damage*

- *movement*
- *form of remedial action*

Within each factor a number of sub-categories have been identified. The sub-categories that comprise each factor have been summarised in table 4.4. To establish if there exists a threshold of damage that can be used to identify the need for substructure repairs, the factor *remedial action* has first been related individually to each of the factors, *visible damage*, *cause of damage*, and *movement*. These initial relationships (see Appendix D) have been explored by cross-tabulating the sub-categories within factors and applying the chi-square test of statistical association. A more thorough analysis has been considered by examining a number of different multiple regression models. These have used *remedial action* as the dependent variable for prediction. Different approaches have been applied to scale the independent variables used in this analysis.

In relation to the objective of this chapter, it has been established that the most appropriate threshold of damage which can be used to identify the need for substructure repairs in a property damaged by ground subsidence, is to identify if movement in the property is progressive or not. However, this chapter has considered only case study properties damaged by *shallow* subsidence. The following chapter investigates this same threshold of damage, but in relation to case study properties damaged by *deep* coal-mining subsidence.

The analysis in this Chapter has **not** been undertaken with the intention of developing extensive models which can be used to predict remedial action from a set of case specific factors (i.e. independent variables). As previously discussed in this Chapter, the data available for this research is inappropriate to enable development of such a sophisticated refined model. What the analysis has established is a model developed from a representative sample of case studies that can be used to demonstrate **when** sub-structure repairs are required in properties damaged by ground subsidence or heave. It has been clearly demonstrated that the most important consideration is to establish whether or not movement is *long-term progressive*. This forms a threshold of damage for potential implementation by insurance companies who can apply this to address the non-technical issues that cause many of the contemporary problems associated with subsidence and heave damage in low-rise properties. The application in practice of the threshold of damage identified in this Chapter is investigated in detail in Chapter Seven.

CHAPTER FIVE: CASE STUDY ANALYSIS OF PROPERTIES DAMAGED BY COAL-MINING SUBSIDENCE

5.1: INTRODUCTION

This chapter considers Research Aim Two in relation to case study properties damaged by coal-mining subsidence (*deep* subsidence). Therefore, the primary objective of this chapter is to investigate whether a threshold of damage exists which can be used to differentiate between a property that requires remedial substructure repairs from a property that requires remedial superstructure repairs only. A further objective of this chapter is to investigate, through case study analysis of damaged properties, whether any threshold of visible damage exists, which may be used to establish liability for coal-mining subsidence damage.

The objectives of this chapter are investigated through an analysis of 109 case study properties that have allegedly been damaged by coal-mining subsidence. The first section of this chapter considers the collection of case study data and discusses the sources from where this data has been collected and the selection criteria used to identify appropriate case studies. After considering the collection of case studies, the data contained within these case studies is scrutinised. The data is then analysed and the results which emerge are discussed in relation to the objectives of this chapter.

5.2: COLLECTION OF CASE STUDY DATA

5.2.1: Sources Of Case Study Data

Details of 109 claims made to The Coal Authority[1] have been collected and analysed as individual case studies. Each claim represents an individual case study of a privately owned residential low-rise property where the property owner has given notice to The Coal Authority, in accordance with the relevant legislation, for damage that is thought to have been caused by coal-mining subsidence. All 109 case studies were gathered from The Coal Authority because statutory legislation places responsibility for the consequences of coal-mining subsidence with the agency responsible for the coal-mining operations, which until 1994 was exclusively The Coal Authority. The coal industry in Great Britain was privatised in 1994, which has resulted in agencies other than The Coal Authority being responsible for surface subsidence resulting from coal-mining. However, prior to the coal industry privatisation, The Coal Authority was the only agency that handled all claims for coal-mining subsidence. Following privatisation, The Coal Authority has continued to administer claims made to some private coal mine operators. These facts make The Coal Authority the only significant source of primary data in the subject field of coal-mining subsidence damage.

5.2.2: Selection Criteria For Case Studies

Access was made available to all claims made to The Coal Authority and its predecessors, The British Coal Corporation and the National Coal Board (NCB). This access included files dating back to the 1940s. Consequently, a very large number of claims were potentially available to use as case studies and it was necessary to apply a selection criteria.

The Coal Authority has recorded all claims on a computer database. Using this database, claims that were applicable to be used as case studies in this research were identified. First, the selection criterion was applied that all claims must involve only privately owned low-rise residential properties. The second criterion was to consider only claims made after 1st January 1985. This time-scale was selected after advice from The Coal Authority, which suggested that information contained within claims made after the mid 1980s tended to be easier to identify, mainly because information contained within files was processed on computers after this date.

After the above selection criteria were applied, tens of thousands of claims still existed which could potentially have been used as case studies for this research. A sample of approximately 100 case studies was required to enable a sufficient number to be analysed in detail. To allow for any unforeseen problems, a sample of approximately 175 individual claims were selected from The Coal Authority database on a random basis. Not all files of individual claims requested from The Coal Authority were available because they were either in use or had been misplaced. Some of those files available were found after inspection not to be appropriate for use as case studies for this research. Therefore, 91 of the 175 claims requested were selected and used as case studies. This sample was made up of case studies from the following regions of Great Britain.

Regional Location	**Number of Claims**
Yorkshire/East Midlands	54
West Midlands	10
North East (England)	9
South Wales	8
Scotland (Central belt)	10
Total	**91**

The predominance of claims selected in the Yorkshire/East Midlands regions takes into account the fact that this geographical area has sustained the majority of modern longwall coal-mining operations during the 1980s and 1990s. However, several case studies have been collected from other regions of Great Britain where coal-mining operations have been carried out. This helps to

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[1] For convenience throughout this chapter, The Coal Authority is also taken to include its predecessor, The British Coal Corporation and The National Coal Board (NCB).

provide a national overview of coal-mining subsidence damage claims throughout Great Britain. The regions Yorkshire and East Midlands are combined as one area because the majority of all coal-mining operations have been carried out in the South/West Yorkshire region and in the North East Midlands region which are within close proximity to each other.

No selection criterion was applied requiring that liability for coal-mining subsidence damage should be accepted by The Coal Authority. This decision was taken because one of the objectives of this chapter, defined in the chapter introduction, is to establish if a threshold of visible damage exists within a property which can be used to establish where liability for coal-mining subsidence damage exists. Therefore, the collection of case study files included both claims where liability for coal-mining subsidence damage was admitted and claims where liability was denied. This information was not known until each case study file was reviewed and analysed. In those case studies in which liability for coal-mining subsidence damage was admitted, the subsequent case study analysis carried out in this chapter revealed that damage to these properties was restricted to cosmetic or serviceability repairs to the superstructure of properties, and no case studies involved damage that required remedial substructure repairs. Consequently, to investigate the threshold of damage in properties which identifies the requirement for remedial substructure repairs, a sample of claims involving substructure repairs is required.

From The Coal Authority database of claims it was not possible to establish a selection criterion to identify which claims involved substructure repairs. However, the nature of such repairs usually involves significant expense, and it was possible to apply an additional search criterion that remedial action costs exceeded £20,000. This criterion was suggested by The Coal Authority as the best available method to identify properties damaged by coal-mining subsidence that required remedial substructure repairs. After this criterion was applied, within the time-scale of claims used for this research, it was possible to obtain details of a further 18 claims where remedial action costs exceeded £20,000, making the total number of case studies used in this chapter to be 109. Of the 18 case studies in which remedial action costs exceeded £20,000, eight of these properties were found to include substructure repairs. The remaining 10 cases were found to have exceptionally high repair costs because the property was substantially larger than normal, or because of the high quality of finishes that had to be reinstated to their original condition. Each of these 18 claims were from the Yorkshire/East Midlands region.

5.3: INFORMATION CONTAINED WITHIN CASE STUDIES

5.3.1: Claims Procedure

It has been highlighted above that before the coal industry was privatised in 1994, legislation dictated that The Coal Authority was the only agency responsible for handling claims made for alleged coal-mining subsidence damage. Following privatisation, The Coal Authority continued to administer coal-mining subsidence damage claims for some private mine operators. The Coal Authority is therefore the only agency who hold significant amounts of data concerning properties damaged by coal-mining subsidence. As all case study information used in this chapter has been collected from this one source, all case studies follow a standard format because the same procedures are adopted for all claims throughout the country. Consequently, this provides a high level of compatibility and consistency between case studies used in this chapter.

For each alleged claim for coal-mining subsidence damage, a Damage Notice has to be completed by the property owner and this has to be submitted to The Coal Authority. For privately owned low-rise residential properties, the applicable parts of the Damage Notice record:

- The property address
- The person(s) who own the property
- Any other party who may have an interest, such as a mortgage lender
- A brief description of the alleged damage
- The date when the damage first became apparent.

After receiving a Damage Notice, The Coal Authority arrange for a visual inspection of the alleged damage in the property and obtain a coal-mining report for the area within which the property is located. This report establishes whether a property is located within an area of current or past coal-mining operations and provides technical details including the seam thickness, depth below ground level, seam width, precise location and records the dates of all mining operations. Taking into account this information, the application of empirical rules developed by NCB (1975) are used to establish if a property could be affected by any coal-mining operations. These empirical rules have been described in Chapter Two.

Based upon the visible damage evident in the property and the coal-mining report, The Coal Authority decides whether liability exists for damage related to coal-mining subsidence. It is therefore The Coal Authority which is responsible for deciding if any liability exists, and if so, it is The Coal Authority which is responsible for compensation.

Where liability is accepted for coal-mining subsidence damage, The Coal Authority prepares a schedule of repairs which must be agreed with the property owner. The schedule of repairs is a detailed document that identifies and individually prices each item of remedial work. After this schedule has been agreed with the property owner, The Coal Authority arranges and pays for the remedial works to be carried out, or alternatively pays a property owner the equivalent sum to enable him/her to make their own arrangements to carry out the agreed schedule of remedial works. Where no liability is accepted for coal-mining subsidence damage, The Coal Authority identifies what it considers to be the cause of damage. In this situation, because damage is not related to coal-mining subsidence, The Coal Authority has no responsibility to carry out any remedial action or make compensation payments. Therefore, The Coal Authority closes its file on the claim, so that no further details are available for scrutiny.

As all claims for coal-mining subsidence damage follow the same procedure, the file records of each claim contain the same basic information, and for each claim used as a case study, it has been possible to identify three factors that make up each case study, these being:

- Factor One: *The visible damage evident to a property.*
- Factor Two: *Coal-mining operations within the vicinity of the property.*
- Factor Three: *The remedial action required to repair damage* (applicable only in those case studies where liability for coal-mining subsidence damage is admitted).

The information contained within each of these three factors is used to investigate the research objectives of this chapter. To consider in more detail the information contained within each of the above factors, as in the previous chapter, each factor can be divided into a number of sub-categories and these are identified below.

5.3.2: Factor One: *Visible Damage*

Where a Damage Notice is received from a property owner which states that his/her property has been damaged by coal-mining subsidence, The Coal Authority make an initial inspection of the alleged damage. The inspection notes are kept on file and for each case study these inspection notes are used as a basis to consider the visible damage evident in a property.

The quality of recorded information by mining surveyors who noted the visible damage in properties was found to be variable. For example, in approximately 12 case studies the inspection notes are extremely comprehensive describing in detail the condition of every aspect of every room and elevation of a property, including those which show no apparent signs of damage. Some case study files included sketches and photographic records. In contrast, a small number of case study files contained only brief descriptions of damage apparent in a property. The amount of detail in all other case study files falls somewhere in between these two extremes. The severity or extent of damage in a case study property has been found to bear no relationship to the amount of detail in which the damage has been recorded.

Despite the variations in detail of inspection notes between individual case studies making up this sample, the visible damage in the property has always been recorded in sufficient detail to enable an assessment of the visible damage to be made. In order to assess damage in case studies according to a common basis, this research has used a damage classification. As in the previous chapter, the damage in each case study property is assessed by the classification of damage proposed by the BRE in Digest 251 (1993 edition). In this classification, visible damage in a property is divided into six individual categories of damage, from 0 to 5. Each category is described in a descriptive format with references made to crack widths as a guide. The BRE classification of damage, which has been discussed in Chapter Three, was originally developed to classify damage in buildings that were affected by coal-mining subsidence (NCB, 1975) and is commonly referred to in the subject field of damage in low-rise properties caused by mechanisms other than coal-mining subsidence (BRE Digest 251 1993 edition; ISE 1994).

The classification of damage contained within BRE Digest 251 (1993 edition) is used in this research because it is compatible with the data recorded in case study files which is in a descriptive format with some references made to physical measurements such as crack widths. When using this classification to assess the visible damage in a case study property, as stated in BRE Digest 251 (1993 edition), only the visible damage evident in the walls of a property is considered, and no account is taken of the cause of damage or whether or not the damage is expected to get progressively worse.

It has been found difficult to accurately classify each of the 109 case study properties according to the six categories of damage suggested by the BRE in Digest 251 (1993 edition). The reason for this difficulty being that the information contained within some case study files was not sufficiently detailed to accurately enable every case study to be assessed. Therefore, as in Chapter Four, the six categories are combined into three broader categories which make up the sub-categories of the factor <u>visible damage</u>. These three sub-categories are:

- Sub-category A: '*aesthetic damage*'
- Sub-category B: '*serviceability damage*'
- Sub-category C: '*stability damage*'

BRE Digest 251 (1993 edition) made reference to the fact that categories of damage 0, 1 and 2 can be grouped together as '*aesthetic damage*', categories 3 and 4 can be grouped together as '*serviceability damage*' and category 5 can be considered as '*stability damage*'.

By combining categories of damage in this way, the sub-categories of '*aesthetic damage*' and '*serviceability damage*' become wide ranging as they both involve a combination of two or more categories of the BRE classification of damage. However, this modification has been found to provide an increased degree of accuracy in relation to the information available in the case study records and improves the accuracy of the data interpretation. When considering damage in terms of '*aesthetic damage*', '*serviceability damage*' and '*stability damage*', the greatest potential for error exists when distinguishing between case studies classified into the categories of '*aesthetic damage*' or '*serviceability damage*', because this is the same distinction between categories 2 and 3 of the BRE classification of damage. Therefore, to ensure accuracy after initially placing a case study property into a sub-category of damage, the recorded visible damage in each case study was compared with all other case studies in the same sub-category of visible damage to ensure internal consistency. Any case study demonstrating inconsistencies was meticulously reviewed and subsequently placed into what was considered the appropriate sub-category of visible damage.

From the 109 case studies that have been analysed, regardless of whether or not liability for coal-mining subsidence damage was accepted by The Coal Authority, an assessment was made of the visible damage evident in the property. This assessment is based on damage being classified into one of the three sub-categories of the factor <u>*visible damage*</u> which are, '*aesthetic damage*', '*serviceability* damage' or '*stability* damage'. Table 5.1 represents the results for the 109 case studies used.

Classification of damage sub-category	**Number of case studies**	**Percentage**
'*Aesthetic Damage*' (categories 0,1 and 2 of the BRE classification of damage).	88	81%
'*Serviceability Damage*' (categories 3 and 4 of the BRE classification of damage).	21	19%
'*Stability Damage*' (category 5 of the BRE classification of damage).	0	0%
Total	109	100%

Table 5.1: Results of the sub-categories of the factor <u>*visible damage*</u> in the 109 case study properties analysed.

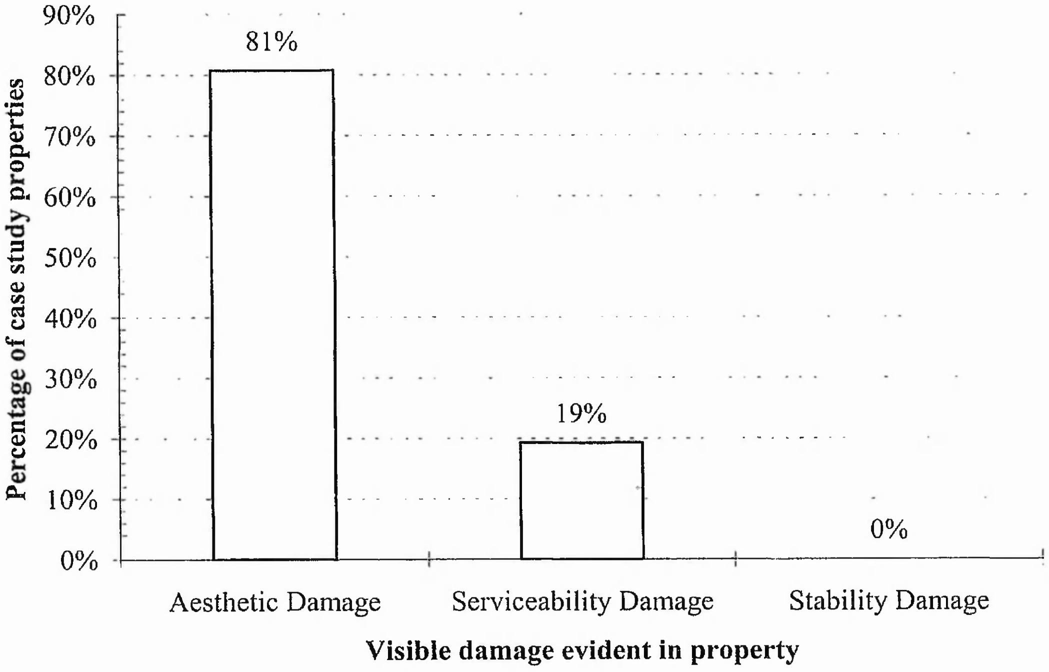

Figure 5.1: **Percentage values of the sub-categories of the factor *visible damage* in the 109 case study properties analysed.**

5.3.3: Factor Two: *The Coal-Mining Situation In Relation To The Case Study Property*

When a property owner submits a Damage Notice for alleged coal-mining subsidence damage, The Coal Authority obtains a detailed report of all recorded coal-mining operations that could theoretically have resulted in surface subsidence damage to the property in question. To determine if a property is considered to be within an area of influence of any coal-mining operations, the methods of surface subsidence prediction developed by the NCB (1975) are used, which have been outlined in Chapter Two. These methods take into account the technical facts relating to coal-mining. It is the mining surveying section of The Coal Authority that provides the details of coal-mining operations and interprets these details to decide if a property is located within an area of influence of any coal-mining operations. It is possible to identify this information in each case study file which has been collected for analysis.

A further important aspect of any coal-mining operations relates to the dates when mining was carried out. It is highlighted in Chapter Two that coal-mining subsidence is almost contemporaneous with the underground coal-mining. Legislation sets a maximum time period in which a claim should be made after damage becomes apparent. The date when damage becomes apparent is usually taken as the same date that coal-mining is completed within an area of influence of the subject property. All case studies used in this research involve claims made to The Coal Authority after 1980, and under the relevant legislation, six years is the stated time period for a claim to be made after the completion of coal-mining operations within an area of influence of a property. Therefore, the factor *coal-mining situation* can be divided into two sub-categories, these being:

- Sub-category A: '*Coal-mining operations may be liable for damage*'.
- Sub-category B: '*Coal-mining operations are not liable for damage*'.

The occurrence of sub-category A does not necessarily lead to the conclusion that coal-mining operations are responsible for visible damage because it is first necessary to eliminate any other potential causes of damage.

In each of the 109 case studies analysed, it has been possible to establish if underground coal-mining operations had taken place within a theoretical area of influence of the property at some time in the six years prior to the claim for damage being made. This information is identified from the coal-mining report contained within each case study. The coal-mining report is prepared by the mining surveying department of The Coal Authority. Hence, the coal-mining situation for the 109 case studies analysed are classified in table 5.2 according to the sub-categories of the factor *coal-mining situation*.

The coal-mining situation in relation to a case study property	**Number of case studies**	**Percentage of case studies**
Coal-mining operations may be liable for damage.	71	65%
Coal-mining operations are not liable for damage.	38	35%
Total.	109	100%

Table 5.2: Results of the sub-categories of the factor *coal-mining situation* for the 109 case studies analysed.

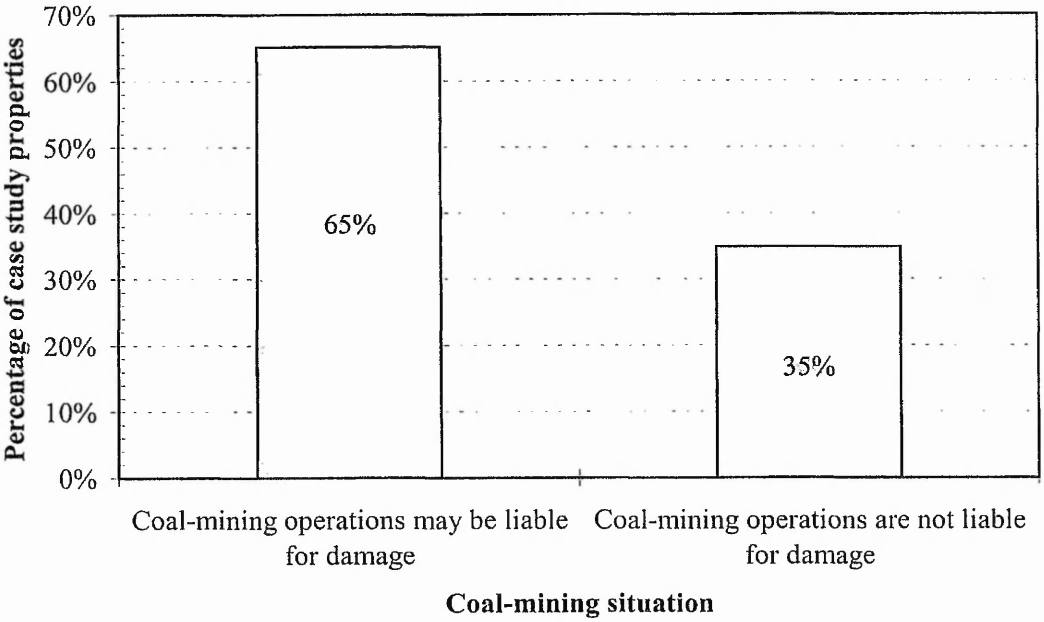

Figure 5.2: **The influence of the factor *coal-mining situation* for the 109 case studies analysed.**

5.3.4: Factor Three: *Form Of Remedial Action*

When selecting case studies for this section of the research, no criterion has been applied requiring that liability for coal-mining subsidence damage must have been accepted by The Coal Authority. In case studies where The Coal Authority accept no liability for damage the file is closed and contains no details about any remedial action. Therefore, it is only possible to identify the form of remedial action in case studies where The Coal Authority has accepted liability for damage.

In those case studies where liability for coal-mining subsidence is admitted, The Coal Authority prepare a detailed schedule of repairs which identifies each item of repair work individually. This schedule of repairs has to be agreed by the property owner. Therefore, in cases where liability for coal-mining subsidence is accepted, the remedial action carried out can be precisely identified from the schedule of repairs.

A total of 12 different forms of remedial action have been identified in the case studies analysed. Several of these forms of remedial action can be grouped together to form three main sub-categories that make up the factor *remedial action*, these being:

- Sub-category A: *'aesthetic repairs'*.
- Sub-category B: *'serviceability and aesthetic repairs'*.
- Sub-category C: *'substructure repairs'*.

Examples of remedial action sub-category A, '*aesthetic damage*' includes repairing internal or external aesthetic cracks, or re-decoration. Examples of remedial action sub-category B, '*serviceability and aesthetic repairs*' includes the replacement of small areas of damaged masonry, or re-fixing damaged flashings in addition to some aesthetic repairs. Sub-category C, '*remedial foundation underpinning*' includes both full or partial underpinning in addition to any superstructure repairs that might be necessary.

Of the total 109 case studies analysed, liability for coal-mining subsidence damage was accepted by The Coal Authority in 67 (61%) case studies. In the 42 case studies where no liability was accepted for damage in the property, The Coal Authority did not consider that coal-mining subsidence had affected the property. In those cases in which liability has been accepted it was possible to identify the form of remedial action carried out by making reference to the schedule of repairs contained within the case study file. Using this information it was possible to consider the remedial action according to the three sub-categories that have been identified within the factor *remedial action*. The results are recorded in table 5.3.

Form of remedial action.	**Number of case studies.**
'aesthetic repairs'	44
'serviceability and aesthetic repairs'	15
'substructure repairs'	8
No liability for damage	42
Total	109

Table 5.3: Results of the sub-categories of the factor *form of remedial action* for the 109 case studies analysed.

5.4: ANALYSIS OF CASE STUDY DATA INFORMATION

The previous sections of this chapter have identified the information that is contained within the 109 case studies collected. After establishing this information, it will be used to investigate the research objectives of this chapter. The first objective is to investigate if a threshold of visible damage in properties exists, which can be used to establish if liability exists for coal-mining subsidence damage. The second objective is to investigate if a threshold of damage exists, which can be used to differentiate a property that requires substructure repairs from a property that requires superstructure repairs.

To investigate the first of these objectives, it is necessary to consider all 109 case studies to take into account both case studies where liability for coal-mining subsidence is accepted, and case studies where liability is denied. The factor, *remedial action* identifies the number of case studies in which liability for damage is either accepted or denied. It is possible to cross-tabulate this information with the factor *coal-mining situation*. The cross-tabulation results are demonstrated in table 5.4.

	Liability for coal-mining subsidence damage.				
Coal-mining situation.	Liability accepted		Liability denied		Total
	Number	%	Number	%	
Recent coal-mining within an area of influence of a case study property.	67	94	4	6	71
No recent coal-mining within an area of influence of a case study property.	0	0	38	100	38

Table 5.4: Results of cross-tabulation between relating liability for coal-mining subsidence damage with the factor *coal-mining situation*.

When considering the issue of liability for coal-mining subsidence damage, it is first necessary to take into account the factor *coal-mining situation*. If the coal-mining report indicates that mining operations are not responsible for damage, then liability is denied, which is clearly demonstrated in Table 5.4 and in all legislation governing the subject.

Only if the coal-mining report indicates that mining operations could be responsible for damage is liability considered. In the 71 case studies where this occurred, the visible damage evident in the property is taken into account. It was possible to identify that the visible damage was not caused by coal-mining subsidence in 4 of these 71 case studies, and that in these 4 case studies The Coal Authority subsequently denied any liability for damage. To eliminate coal-mining subsidence as the cause of damage, the inspection notes from the case study files were used. These notes clearly identified another cause of damage and this information was brought to the attention of the property owner as the reason why The Coal Authority denied liability.

In the remaining 67 of the 71 case studies, liability for damage was accepted by The Coal Authority. Using the inspection notes from these 67 case study files it was possible to either identify damage to be typical of that caused by coal-mining subsidence, **or** it was not possible to identify any other plausible cause for the damage. Consequently The Coal Authority accepted liability for damage. In these 67 case study properties, following meticulous review of the records of visible damage in each property, it has not been possible to identify any threshold of visible damage that could be used to identify where liability for coal-mining subsidence damage exists.

It has been found that, when considering the issue of liability for coal-mining subsidence damage, no account is taken of either the extent or severity of damage in the property. In eight of the 67 case studies where liability was accepted, the visible damage was found to be extremely limited in both the amount, and severity. Typical examples include hairline cracks or wallpaper tears limited to one room or even one wall of a property. In contrast, other case study properties have much more extensive damage which is classified into the sub-category of '*serviceability damage*'.

It can be concluded that when investigating visible damage in properties which are known to be affected by coal-mining subsidence, no threshold of visible damage exists which may be used to identify the existence of any liability. The significance of this is discussed in Chapter Six, which considers Research Aim One of this thesis.

The primary objective of this chapter is to investigate whether a threshold of damage exists, which can be used to identify a property which requires substructure repairs from a property which requires superstructure repairs only. Therefore, to investigate this research objective, only the 67 case studies in which liability for coal-mining subsidence was established are applicable. It has been shown that to establish liability for coal-mining subsidence, it is first necessary to confirm that mining operations have been carried out which could have caused ground subsidence, and that the visible damage in the property has not resulted from any cause other than coal-mining subsidence. In those case studies where liability was accepted by The Coal Authority, the remedial action necessary to rectify the damage has been identified as sub-categories of the factor *form of remedial action*. It is possible to investigate if the visible damage in a case study property can be related to the remedial action required by cross-tabulating sub-categories of the factor *visible damage* with sub-categories of the factor *form of remedial action*. The results of this cross tabulation are presented in table 5.5.

	Remedial Action Group						
Visible Damage	A		B		C		**Total**
	Number	%	Number	%	Number	%	
'*Aesthetic*'	43	82	5	10	4	7	52
'*Serviceability*'	1	6	10	67	4	27	15
'*Stability*'	0	0	0	0	0	0	0

Table 5.5: **Results of cross-tabulation between the factors *visible damage* and *form of remedial action*.**

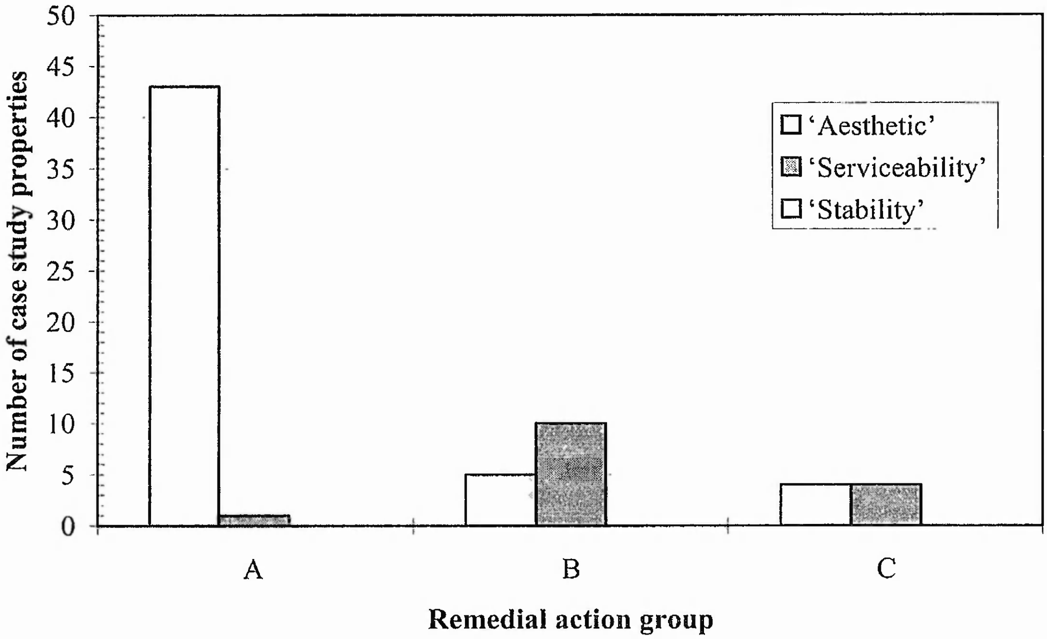

Figure 5.3: **Classification of case study properties by the factors *visible damage* and *remedial action*.**

Table 5.5 highlights that none of the case study properties were found to have damage classified into the sub-category of '*stability damage*'. This was not considered to be of particular importance to this research because, where damage represents a threat to the structural stability of a property, the remedial action necessary is invariably easy to identify and subsequently implemented without delay. However, it is properties which show signs of '*aesthetic*' or '*serviceability damage*' where it can be difficult to identify the most appropriate form of remedial action.

The information depicted in table 5.5 and figure 5.3 indicates that where damage has been classified in the sub-category '*aesthetic damage*', the strongest association exists with the sub-category '*remedial action group A*'. Despite this, it can also be seen that several properties classified to have '*aesthetic damage*' required either '*remedial action group B*' or '*remedial action group C*'. In the case study properties where visible damage has been classified into the sub-category of '*serviceability damage*', it can be seen that no obvious association exists with any of the various sub-categories of the factor remedial action.

Based on the cross-tabulation evidence in table 5.5 and figure 5.3 it would appear that it is not appropriate to develop any firm conclusions about how the factor *visible damage* might influence the factor *remedial action*.

The cross-tabulation results in table 5.5 can be taken to show that no clear relationships emerge between any sub-category of the factor *visible damage* with any sub-category of the factor *form of remedial action*. Therefore, to investigate if a threshold of damage exists which can be used to identify where substructure repairs are required, it is necessary to consider in a more **qualitative** manner those 67 case studies where liability for coal-mining subsidence damage has been admitted.

It has been identified that in eight of these 67 case study properties, remedial action that involved the sub-category of '*substructure repairs*' was required. Detailed analysis of each of these eight case studies revealed that in six case studies '*substructure repairs*' were required because of the presence of a fissure. Fissures are commonly associated with coal-mining subsidence and create a void in the ground which causes ground instability. In the two remaining case studies that required '*substructure repairs*', there existed evidence of cracking below the level of the damp proof course (d.p.c.) which caused the representative of The Coal Authority investigating the damage to suspect that the foundations of the property may have become damaged. Therefore, in all 8 case studies, further below ground investigations were carried out.

In the six case studies that involved fissures, further investigations confirmed that the fissure caused the foundations of the property to become unstable, or that the presence of the fissure represented an imminent cause of damage to the buildings' foundations. In the two case studies where visible damage was evident in the substructure of the property, the further investigations revealed that the foundations of the property had been damaged by subsidence movement. This had caused a weakness in the foundations of the building which was being transmitted to cause damage to the buildings' superstructure.

It appears that the common denominator in each of the eight case studies that required '*substructure repairs*' is the damage to the foundations of the property. In all eight of these case studies, the '*substructure repairs*' involved remedial foundation underpinning to either repair the damaged foundations, or eliminate the risk of future damage. In the six case studies that involved fissures, it was also necessary to "cap" the fissure and in all eight case studies it was necessary to repair the superstructure damage, in addition to carrying out substructure repairs.

Liability for coal-mining subsidence was accepted in 67 case studies, and out of these case studies, eight involved remedial '*substructure* repairs'. The remaining 59 case studies involved '*superstructure*' repairs. In these 59 case studies, from the visible damage evident in the buildings' superstructure, it is clear that the foundations of the buildings were affected by ground movement caused by coal-mining subsidence. However, although movement occurred to the buildings' foundations it can be assumed, from the form of remedial action recommended, that The Coal Authority considered no damage had been caused to the foundations of the property. Therefore, in the absence of any indication that damage existed in the foundations, '*aesthetic repairs*' or '*serviceability and aesthetic repairs*' were carried out.

This highlights, from the analysis of the 67 cases studies where liability for coal-mining subsidence was accepted, that to establish when '*substructure repairs*' are necessary, it is essential to distinguish between the fundamentally different concepts of **foundation movement** and **foundation damage**. From the 67 case study properties used in this part of the research, in each case study, foundation movement has been accommodated as damage in the superstructure of the property. Although all 67 case study properties were subject to foundation movement, in eight of these 67 case studies it was possible to establish that the foundation movement resulted in damage or an imminent threat of potential damage to the foundations of the property, and therefore remedial substructure repairs were considered necessary to rectify this damage.

Therefore, for properties damaged by coal-mining subsidence, the distinction between foundation movement and foundation damage can be suggested as a threshold of damage which may be used to differentiate a property which requires substructure repairs from a property which requires superstructure repairs only.

The preceding section of this chapter has considered the analysis of case study properties. Before summarising the main findings of this analysis, it is necessary to reflect on the case study data employed.

5.4.1: Reflection On Case Study Data

Two main limitations existed in the case study data used for this chapter. The first limitation relates to the high number of case studies which did not involve liability for coal-mining subsidence damage (42 out of 109). The second limitation was the low number of case studies which involved remedial '*substructure repairs*' (8 out of 109).

Considering the 42 case studies in which no liability for coal-mining subsidence damage was accepted, these case studies were used to investigate if a threshold of visible damage existed which could be used to establish liability for coal-mining subsidence damage. When initially selecting case studies on a random basis, it was not anticipated that 38 of these 42 case studies would involve liability for coal-mining subsidence being rejected because of the coal-mining situation. It was anticipated that a higher proportion of case studies would involve other reasons why liability for coal-mining subsidence damage was rejected. When selecting case studies, it was not possible to identify the reason why liability for damage was denied and so, therefore it would not have been possible to make this a selection criterion in case study collection.

The second limitation of the data has been the low number of case studies that involved remedial substructure repairs. In the initial 91 case studies collected, it was found that none involved remedial substructure repairs. Therefore, a further number of case studies were selected in an attempt to collect cases which involved remedial substructure repairs. Using The Coal Authority database of claims it was not possible to identify properties that required remedial substructure repairs as a selection criterion. The best method to identify such claims was to apply a further selection criterion whereby remedial action costs exceeded £20,000, as the high costs would be the best method available to identify where possible remedial substructure repairs were carried out. The Coal Authority identified a number of claims that satisfied this criterion and these were requested from its archives. However, it was only possible to obtain 18 of these claims because many claims were still ongoing at the time requested and the corresponding files were in use. Of these 18 case studies it was found that only eight involved remedial substructure repairs. The remaining 10 case studies involved high remedial action costs for reasons other than the cost of superstructure repairs, such as compensation payments for tilt, or because the property was very large with a high standard of decoration.

5.5: CHAPTER SUMMARY

A total of 109 case studies were collected and analysed in order to investigate the research objectives of this chapter. The first objective has sought to investigate if a threshold of visible damage exists which can be used to identify where liability exists for low-rise properties damaged by coal-mining subsidence. The second objective has sought to investigate if a threshold of damage exists which can be used to identify properties damaged by coal-mining subsidence that require remedial substructure repairs.

To investigate the first objective of this chapter, a cross-tabulation matrix has established, from the 109 case studies analysed, that liability for coal-mining subsidence damage will only be considered where coal-mining operations have been carried out within an area of influence of a property at some time in the six years prior the claim being made. Where this is established, the case study analysis has also shown that liability for coal-mining subsidence damage will not be accepted where it can be demonstrated that damage has resulted from another cause. This is significant because where the cause of damage is not obvious, it has been found that it is not necessary to prove that damage has been caused by coal-mining subsidence, but that it is necessary to eliminate any other potential causes of damage. It has also been shown from the case study analysis that no threshold of visible damage exists which can be used to identify the existence of liability for coal-mining subsidence damage. Where coal-mining subsidence is identified as the cause of damage, The Coal Authority have been found to accept liability no matter how minor the extent or severity of damage.

To investigate the second objective of this chapter it has been necessary only to consider those case study properties in which liability for coal-mining subsidence damage was accepted by The Coal Authority. These case studies have been used to investigate if a threshold of damage exists which can be used to differentiate properties which require substructure repairs from properties which require above ground superstructure repairs only. It has been shown that the visible damage in a property can not be used to identify any threshold of damage.

A threshold of damage identified from the case study analysis which *can* be used to differentiate a property which requires substructure repairs from a property which requires only superstructure repairs is to identify the difference between foundation movement and foundation damage. Foundation movement caused by coal-mining subsidence results in damage to the superstructure of a property. However, where foundations have been subject to movement, after this is complete, if the foundations are undamaged and able to perform their function, then it is only necessary to repair the damage to the superstructure of a property. In the case study properties which required remedial substructure repairs, it was established that coal-mining subsidence had either caused, or represented imminent potential damage to the foundations of the property. This foundation damage was clearly identified in the case study files by reference to the investigations carried out into the damage.

Therefore, in relation to the first objective of this chapter, it has been found that liability for damage caused by coal-mining subsidence will only exist where coal-mining operations have been carried out within an area of influence of the property in the six years prior to the claim being made, and where it is not possible to identify another cause for the damage. This corroborates what is stated in the relevant legislation governing the subject. However, it has been shown that no threshold of visible damage exists which can be used to identify the existence of liability for coal-mining subsidence damage. In relation to the second objective of this chapter, a threshold of damage has emerged which can be used to identify where substructure repairs are necessary in a property damaged by coal-mining subsidence, this threshold being to identify the distinction between foundation movement and foundation damage.

CHAPTER SIX: DAMAGE THRESHOLDS

6.1: INTRODUCTION

The two previous chapters have considered the analysis of case study properties damaged by ground subsidence. This chapter considers the results that have emerged from these chapters in relation to Research Aims One and Two of this thesis. Chapter Four has considered 127 case study properties damaged by *shallow* subsidence, and Chapter Five has considered 109 case study properties damaged by *deep* subsidence.

The first part of the chapter addresses Research Aim One, which investigates the threshold that causes concern about visible damage evident in a property. Regardless of the cause of subsidence, it is possible to consider the visible damage evident in each case study property on the same basis. Therefore, the relevant results from both Chapter Four and Chapter Five are combined and presented, and these are subsequently discussed in relation to Research Aim One.

This chapter also addresses Research Aim Two, which investigates the threshold of damage that can be used to identify the need for substructure repairs. The results of the case study analysis in both Chapter Four and Chapter Five are considered and a threshold of damage is suggested. The strengths and weaknesses of this threshold of damage as a mechanism to identify the appropriate form of remedial action are then discussed. After presenting the main conclusions of the case study analysis carried out to investigate both Research Aims One and Two, the findings of this chapter are summarised.

6.2: INVESTIGATION OF RESEARCH AIM ONE

Research Aim One of this thesis has been stated to be:

> ***To investigate the threshold of visible damage that causes concern to professional advisors acting on behalf of property owners.***

It has been established in Chapter Three that visible damage in a property resulting from ground subsidence is similar, regardless of the cause of subsidence. Therefore, when considering Research Aim One, the 127 case studies relating to *shallow* subsidence in Chapter Four, and the 109 case studies relating to *deep* subsidence in Chapter Five can be combined to form an overall sample of 236 case study properties.

In both Chapter Four and Chapter Five, the visible damage evident in each case study property has been considered. This has involved interpreting the inspection notes of either a chartered civil or structural engineer (for properties damaged by *shallow* subsidence) or a building/mining surveyor (for properties damaged by *deep* coal-mining subsidence). Using this information, an attempt was made to relate the visible damage into one of the six categories contained within the BRE classification of damage in Digest 251 (1993 edition).

6.2.1: Résumé Of Visible Damage Classification In Low-rise Properties

Chapter Three, section 3.3 has reviewed the classification of visible damage presented in relevant literature. However, it is felt that following the case study analysis in previous chapters, a brief résumé of this literature would be appropriate to reacquaint the reader.

The BRE classification of damage has been found to be almost ubiquitous in all relevant literature which considers visible damage caused to low-rise properties by ground subsidence. Indeed, this classification of damage has been used internationally. For example, in America, Boscardin and Cording (1989) used this classification of damage in an attempt to relate predicted amounts of subsidence movement to a category of the BRE classification of damage. More recently, Al-Rawas and Qamaruddin (1998), used the BRE classification of damage to consider damage caused by expansive soils and rocks in Oman. In addition, the BRE classification of damage is based upon refined versions of similar classifications devised by Jennings and Kerrich (1962) and NCB (1975). Relevant literature relating to the subject highlights few other classifications of visible damage. Although other classifications have been proposed, most notably Pryke (1979; 1981), these can be seen as essentially similar to the BRE classification. This matter has been discussed previously in Chapter Three, section 3.2. Consequently, the available options to consider the classification of visible damage in this research were to either use the BRE classification of damage, or devise an alternative method.

Although devising an alternative method was considered, for several reasons this approach was ultimately rejected. The most substantive reasons being the fact that the BRE classification of damage has its origins in damage caused by both shrinking/swelling clays and coal-mining subsidence. The classification has been used, developed and refined over many years by recognised experts working in this field of study (for example, MacLeod and Littlejohn, 1974; NCB, 1975; Tomlinson *et. al.*, 1978; Driscoll, 1983; Hunt *et. al.*, 1991; Burland, 1993; ISE, 1994). This has afforded the BRE classification of damage the opportunity to come under close scrutiny from both the academic and technical community. Indeed, over the years this process led to the classification of damage being amended, for example Hunt *et. al.* (1991) made minor alterations in order to try and make it more objective. This amendment was subsequently adopted by BRE in Digest 251 (1993 edition). In contrast, any new method proposed by this research would be largely untested and open to potential error and misinterpretation. Therefore, as the objective of this research was not to consider proposing methods of visible damage classification, it was subsequently decided to accept and use the BRE classification of damage.

However, before analysing the results emerging from the case study analysis, it is necessary to consider some of the criticisms directed towards the BRE classification of damage. Chapter Three, section 3.2.3 has discussed some of the limitations of visible damage classification. However, during the course of collecting case study information for this research, the opportunity arose to speak informally with several chartered engineers and building/mining surveyors who practice in the field of subsidence damage to low-rise buildings. The general consensus of opinion which existed was that although the BRE classification of damage was ubiquitous in academic literature, its relevance and use in practice was limited; the main reason suggested for this being that this classification of visible damage can lead to confusion and misunderstandings regarding the extent and nature of repair work. However, this potential limitation does not present a problem within the context of this research as the visible damage in a property has been assessed objectively by a chartered engineer or building/mining surveyor, and is considered independently to the remedial action that might be necessary.

6.2.2: Classification Of Visible Damage In Case Study Properties

After establishing the BRE classification as the most appropriate method of assessing the visible damage, an attempt was made to assess the damage in each case study property. The data which emerged from the in-depth analysis of case study properties was found to be in a format that was largely compatible with the BRE classification. Information available on which to make an assessment of visible damage was found to be in the form of written notes describing the damage, with some references to physical measurements such as crack widths. However, as explained in both Chapter Four and Chapter Five, it was found that in most case studies the information describing the damage was not sufficiently detailed to enable damage to be accurately classified into one of the six categories of damage proposed by the BRE. Therefore, these six categories have been grouped together to form three broader sub-categories of visible damage, these being '*aesthetic damage*', '*serviceability damage*', and '*stability damage*'. BRE Digest 251 (1993 edition) made reference to merging categories of damage 0, 1 and 2 together as '*aesthetic damage*', categories 3 and 4 as '*serviceability damage*' and category 5 as '*stability damage*'. Table 6.1 represents both the original classification of damage proposed by the BRE, and relates this to the combined categories of damage used in this research.

Category of damage	**Description of typical damage** *Ease of repair in italic type*	**Sub-category of damage used to assess case study properties**
0	Hairline cracks of less than about 0.1mm which are classed as negligible.	**Aesthetic Damage**
1	Fine cracks of up to 1mm width which can be *treated easily using normal decoration*. Perhaps isolated slight fracturing in building. Cracks rarely visible in external brickwork.	
2	Cracks up to 5mm width which *can be filled easily. Redecoration probably required. Recurrent cracks can be masked by suitable linings*. Cracks not necessarily visible externally; *some external re-pointing may be required to ensure weather-tightness*. Some distortion, so windows and doors may stick slightly.	
3	The cracks, which may be from 5mm to 15mm in width (or several, each up to 3mm), *require some opening up and can be patched by a mason. Re-pointing of external brickwork and possibly a small amount of brickwork to be replaced.* Doors and windows sticking. Service pipes may fracture. Weather-tightness often impaired.	**Serviceability Damage**
4	Extensive repair work to cracks of 15mm to 25mm width (depending on number) which involves *breaking-out and replacing sections of walls, especially over doors and windows*. Windows and door frames distorted, floor sloping noticeably. Walls leaning or bulging noticeably, some loss of bearing in beams. Service pipes disrupted.	
5	Cracks usually greater than 25mm width (depending on number) *require a major repair, involving partial or complete rebuilding*. Beams lose bearing, walls lean badly and require shoring. Windows broken with distortion. Danger of instability.	**Stability Damage**

Table 6.1: Relationship between the BRE classification of damage in Digest 251 (1993 edition) with classification of damage used in this research.

When the six categories of damage in the BRE classification are combined into three, it has been found that the information contained in case studies becomes more compatible with the BRE classification of damage. A significant consequence of having only three categories of visible damage is that these categories of damage become wide-ranging and can restrict the interpretation of any results which emerge. However, it is the accuracy of the damage classification in each of the case study properties analysed that is of paramount importance. This aspect of the data interpretation has received priority in the case study analysis. A further reason to support this combination of visible damage to three categories is that, should a particular trend be associated with any one of these three categories of damage, then this can be subsequently investigated in detail to establish whether classifying visible damage in greater depth would provide useful.

6.2.3: Results Of The Classification Of Visible Damage In Relation To Research Aim One

The visible damage evident in each case study property analysed in both Chapter Four and Chapter Five has been classified according to the three sub-categories of '*aesthetic damage*', '*serviceability damage*' and '*stability damage*'. The results of the classification of visible damage in the 127 case studies analysed in Chapter Four have been recorded in table 4.2, and the results of the classification of visible damage in the 109 case studies analysed in Chapter Five have been recorded in table 5.1. These results are combined in table 6.1 and figure 6.2 for all 236 case studies.

	Number of Case Studies					
Sub-category of visible damage	***Shallow* subsidence**		***Deep* subsidence**		**TOTALS**	
	Number	**%**	**Number**	**%**	**Number**	**%**
'*Aesthetic damage*' (categories 0,1 and 2 of the BRE classification of damage	79	62	88	81	167	71
'*Serviceability damage*' (categories 3 and 4 of the BRE classification of damage)	34	27	21	19	55	23
'*Stability damage*' (category 5 of the BRE classification of damage)	3	2	0	0	3	1
'*Damage not applicable*'	11	9	0	0	11	5
TOTAL	**127**	**100**	**109**	**100**	**236**	**100**

Table 6.2: Classification of visible damage in all 236 case study properties analysed.

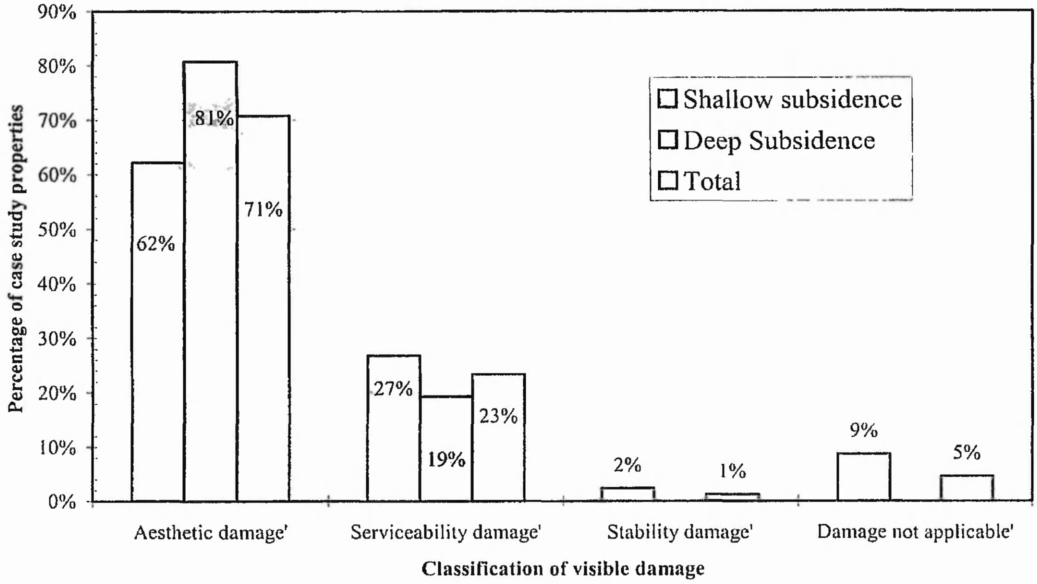

Figure 6.1: Case study properties classified by the factor visible damage.

The sub-category of '*damage not applicable*' has been applied where there existed insufficient details available in a case study to make an accurate assessment of damage or, because the damage evident in the property was not applicable to the classification of damage. This has been fully explained in Chapter Four.

6.2.4: Discussion Of Visible Damage Recorded In Case Study Properties In Relation To Research Aim One

The results in table 6.2 can be compared with similar work by Driscoll (1983), who analysed over 200 low-rise masonry buildings damaged following the drought of 1976. Driscoll recorded that 75% of these buildings fell within or below category 2 of the BRE classification of damage, 20% were classified in category 3 of the BRE classification, and 5% were classified into either category 4 or 5 of the BRE classification. It should be noted that Driscoll combined categories of damage 4 and 5 and considered category 3 individually which can be contrasted with the approach adopted in table 6.1. This discrepancy takes into account some slight modifications and updating of the BRE classification of damage over time. Despite this relatively minor difference, the similarities which exist are still evident. This provides an indication that the sample of cases studies collected in this research is representative of a wider population.

Table 6.2 demonstrates that in over 98% of case study properties analysed, in which it has been possible to make an accurate and reliable classification of visible damage, the damage has been classified to be either '*aesthetic damage*' or '*serviceability damage*'. This high value of 98% can be seen to reflect the fact that, despite frequent press reports depicting the extreme cases where properties become structurally unstable, in the majority of properties subsidence movement does not represent an imminent danger of structural instability or collapse.

From the results in table 6.2, it is possible to suggest two preliminary thresholds of damage, these being threshold T_1 and threshold T_2. Damage threshold T_1 can be defined as:

> **The threshold where damage becomes apparent to a professional advising a property owner <u>and</u> causes concern about the potential consequences of damage.**

Damage threshold T_2 can be defined as:

> **The threshold where damage in a property threatens to impair the structural stability of the property.**

These two thresholds of damage can be related to the six categories of damage suggested by the BRE as shown in the model proposed in figure 6.2. This model makes the assumption that damage category 0 of the BRE classification can be considered as representing '*no visible damage*', as by definition, damage category 0 is defined as, "*hairline cracks of less than about 0.1mm which are classed as negligible*" (BRE Digest 251, 1993 edition).

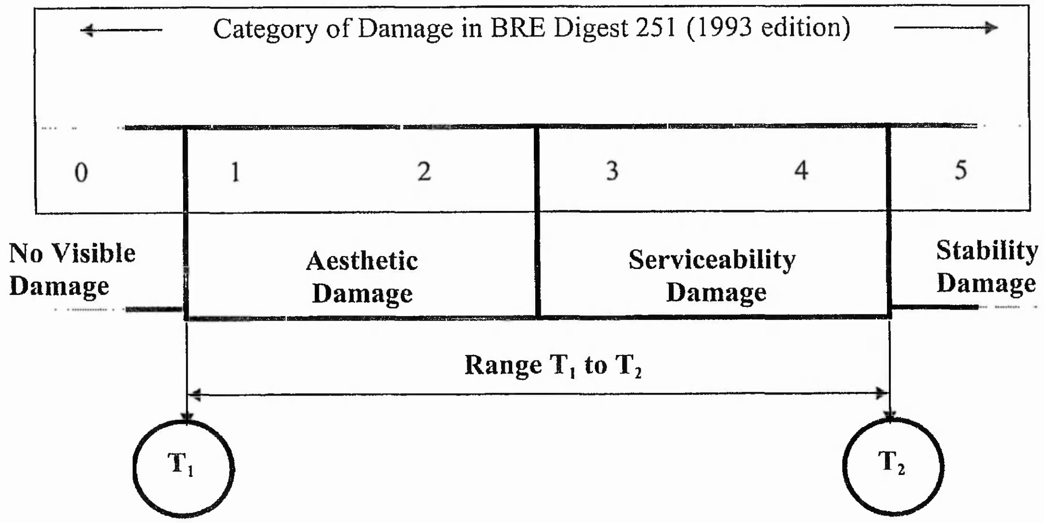

Figure 6.2: Damage thresholds T_1 and T_2 in relation to the BRE classification of damage.

Of the two damage thresholds that have been defined, damage threshold T_2 is the easier to identify. Threshold T_2 defines damage that represents a threat to the structural stability of a property. Because of the nature of such visible damage, identifying damage which threatens the structural stability of a property is usually obvious (Pryke 1992). Where this is established, the nature of the visible damage dictates the remedial action that is necessary and this is usually carried out without delay.

In contrast, damage threshold T_1 is more ambiguous and therefore more difficult to identify than threshold T_2. Threshold T_1 defines damage that is apparent to the property owner or a professional advisor (a surveyor or engineer) and causes concern about the potential consequences. It can be appreciated from the definition of threshold T_1 that property owners are prepared to tolerate damage in their property after this becomes apparent, so long as this damage does not cause them, or where appropriate their professional advisor, concern. The key issue in relation to threshold T_1 is the element of '*concern*'. Whilst one individual might not be prepared to tolerate even minor hairline fractures in his/her property, another individual might be prepared to tolerate significant cracks. Evidence to support this exists empirically in the case study analysis of visible damage in properties. This empirical evidence is demonstrated by considering table 6.2, which shows that in 71% of case studies, visible damage in properties was classified to be '*aesthetic damage*'. Despite being '*aesthetic*', this damage must have caused concern to the property owner as advice about the damage was sought which resulted in investigation. However, in 23% of case studies, visible damage was classified to be '*serviceability damage*', and again this caused concern as the property owners sought advice about the damage. This demonstrates the range of damage that property owners are prepared to tolerate and indicates that because of the highly subjective element of '*concern*' from the case study analysis, no classification of visible damage can be used to attempt to define threshold T_1 in a more detailed quantitative format.

The subject is further complicated by the fact that damage takes time to become visibly obvious. Therefore, although a property owner might be concerned when damage represents, for example category 2 of the BRE classification ('*aesthetic damage*'), by the time this is fully investigated and recorded, it could have progressed to category 3 ('*serviceability damage*').

It is recognised that investigating research aim one through case study analysis of damaged properties only considers one side of this issue. The other side would be to consider this threshold through investigating visible damage that does not cause concern to property owners or professional advisors acting on their behalf. To establish this it would be necessary to consider visible damage which property owners are prepared to tolerate **before** becoming concerned about such damage and seeking advice from construction professionals such as an engineer or surveyor. This is discussed below.

6.2.5: Investigating A Threshold Of Visible Damage In Low-rise Properties That Does Not Cause Concern To Property Owners

In an attempt to investigate Research Aim One by considering damage in low-rise properties which does not cause concern to property owners, a questionnaire survey was considered. An initial pilot survey of this questionnaire was first sent out to a residential area of Nottingham in April 1996. This area was selected because it was known that ground subsidence movement is common to the area. Of the 37 pilot questionnaire forms sent out, 12 responses were received, a response rate of approximately 32%. Modifications were made to the questionnaire design in an attempt to encourage a higher response rate.

The modified questionnaire was sent out to three different locations of the Nottinghamshire area in June 1996. One location was a residential area of Nottinghamshire which was known to have a history of ground subsidence problems. This was established through an initial desk study carried out at the offices of a local building contractor specialising in subsidence remedial work (see appendix A). A second location was a residential area of Mansfield where it was established, through reviewing relevant files from The Coal Authority, that coal-mining subsidence had caused recent damage to properties in the area. A third location was a residential area of Nottinghamshire that was known to have no adverse ground conditions. This information was established from informal communications with construction professionals who have experience of local conditions. These three locations were chosen to take into account the ground conditions in an attempt to establish if any differences towards tolerance of damage existed in areas where it was known that subsidence damage was common.

Of the 306 questionnaires sent out, 108 were sent to the first location, 101 to the second location, and 97 to the third location. However, a total of only 46 responses were received back, a response rate of 15%. This low response rate limits the validity of the questionnaire survey. Although Moser and Kalton (1985) highlighted that postal questionnaires typically have a low response rate, in this case other reasons can be suggested for the low response rate. The primary reason could be that property owners are unwilling to provide details of damage which exists in their property, especially when their home is significantly their largest asset or investment. Essentially, by seeking information about damage, the questionnaire was asking questions which required home-owners to be negative or critical about their own property. This is reflected in the fact that in over 70% of the 46 responses, no damage was reported and in all other cases only very minor damage was reported.

Both the low response rate and the restrictive answers from the questionnaire survey carried out indicated that most home-owners are unlikely to respond well to questions concerning damage in their property. It was considered that the use of a questionnaire survey to ascertain such information would represent a significant methodological weakness. Therefore, the limited information obtained was noted, but not included in the development of the research. Thus, an alternative method was considered.

One alternative approach considered to investigate visible damage which does not cause concern to property owners would be to survey a sample of properties and record any damage. However, this option was unfeasible for the reason that property owners would be unlikely to permit access inside their properties to allow a sufficiently detailed inspection, especially when the very sensitive nature of the subject is taken into account. Therefore, damage threshold T_1 was investigated using the case study properties analysed in Chapter Four and Chapter Five. This was achieved by investigating the visible damage that has caused concern to a construction professional investigating the damage on the instructions of the property owner.

6.2.6: Summary Of Main Findings In Relation To Research Aim One

Considering Research Aim One, it can therefore be concluded from the case study analysis that no universal threshold of visible damage can be identified which causes concern to property owners or professional advisors investigating damage on their instructions. This is because considering damage to a is a subjective matter and depends who is considering the damage. No consensus of opinion or attitude towards visible damage has emerged. An alternative approach to investigate this has been considered by taking into account existing damage which does not cause concern to a property owner. However, it has been highlighted that the methodological approaches necessary to investigate this are problematical.

It has been demonstrated from the case study analysis in Chapter Five, that no account is taken of the amount or severity of damage to a property resulting from coal-mining subsidence. Therefore, where damage is extremely limited, The Coal Authority are still required to carry out a full evaluation of the damage and fund remedial works, even where these might cost less than £100. In contrast, damage caused by shallow subsidence which is covered under the terms of a standard buildings' insurance policy is usually subject to a £1000 policy excess. This policy excess can be seen as an attempt by insurers to impose a financial threshold of damage by discouraging claims that are thought likely to cost less than £1000. However, in most cases, the consequences of subsidence blight to a property are likely to be of substantially more significance than the policy excess sum. This limits the practical implications of an insurance policy excess as a method to discourage minor claims.

An insurance policy excess is defined in precise terms that present no ambiguity. If a similar threshold were applied to coal-mining subsidence claims it could be expected that the number of claims for minor damage would reduce, with such damage being considered as part of routine building maintenance. However, relevant legislation places responsibility for coal-mining subsidence damage with the agency causing the subsidence movement, no matter how minor any damage. Part of the case study analysis carried out in Chapter Five confirms the operation of this legislation in practice.

This research has established no basis on which to suggest a threshold of visible damage that causes concern to a property owner or professional advisors acting on their behalf. If any such threshold of visible damage had been found to emerge, this could have been used as a benchmark to consider in which circumstances it is appropriate to further investigate a suspected case of subsidence, and in which circumstances it is appropriate to repair the damage as part of a program of routine building maintenance. The significance being, that in properties where damage did not exceed a pre-determined threshold of visible damage, such properties could be considered to be free from any form of significant subsidence damage. Where damage did exceed the threshold of visible damage, further investigations would be required to determine the most appropriate form of remedial action (see the investigation of Research Aim Two in section 6.3 below).

Any threshold of visible damage capable of establishing what represents a significant subsidence problem would provide a most useful tool, which would help to overcome many of the contemporary problems caused by subsidence blight. However, the fact that this research has been unable to establish any threshold of visible damage, as discussed above, can be seen to represent a contribution to knowledge. It highlights that considering visible damage in low-rise residential properties is a very subjective issue and, as such, perceptions of visible damage will depend on who is considering the damage. For example, a property owner or a mortgage surveyor concerned with protecting the full market value and saleability of a property will view any damage thought to be associated with ground subsidence as being a significant problem. In contrast, an insurance company liable to pay for subsidence repairs will view damage from a wholly different perspective.

6.3: INVESTIGATION OF RESEARCH AIM TWO

Research Aim Two of this thesis has been stated to be:

> ***To investigate the threshold of damage that can be used to identify the need for substructure repairs.***

6.3.1: Results Of Case Study Analysis In Relation To Research Aim Two

This Research Aim has been investigated through the analysis of case study properties contained in both Chapter Four and Chapter Five. To take into account the different technical factors associated with the different causes of subsidence damage, Chapter Four has investigated Research Aim Two in relation to properties damaged by *shallow* subsidence. Chapter Five has investigated Research Aim Two in relation to properties damaged by *deep* subsidence.

6.3.1.1: Résumé Of Findings In Relation To Case Study Properties Damaged By *Shallow* Subsidence

Each of the 127 case study properties damaged by *shallow* subsidence analysed in Chapter Four had been investigated by a professionally qualified chartered structural or civil engineer. Therefore, the assumption was made that technical issues relating to each case had been objectively investigated by a suitably qualified person. Chapter One, section 1.2.1 has defined **technical issues** as objective factual matters that can usually be accurately established by investigation, measurement or testing, for example, foundation depth or subsoil properties. All relevant technical issues for each case study were evaluated and recorded using the actual file of the engineer investigating the damage. These technical issues were then related to the form of proposed remedial action, in terms of whether or not the property required remedial substructure repairs, to investigate if any relationships had emerged. In reviewing the file of each case study property, after the remedial action had been established, the benefit of hindsight became available.

Cross-tabulation and chi-square tests of association produced some initial evidence that a knowledge of whether or not movement causing damage in the low-rise property is long-term progressive or non-progressive could provide a threshold of damage which can be used to identify whether substructure or superstructure repairs are required. This initial evidence has been further substantiated through the development of multiple regression models. Hence, the relationship between a knowledge of whether or not movement causing damage in the low-rise property is progressive or non-progressive has been shown to be the most reliable threshold of damage which can be used to identify whether substructure or superstructure repairs are required.

Establishing whether or not movement in a property is progressive has been found to be the most appropriate threshold to establish whether or not a property requires remedial substructure repairs. Initially this might appear to an obvious conclusion. However, the significance of this finding and the contribution that it makes to knowledge, is not the relationship between structural movement and remedial action *per-se*, but the fact that from the case study analysis no other relationships or conclusions have emerged. This confirms the significance and importance of assessing whether or not structural movement is progressive as a method to determine remedial action.

6.3.1.2: Résumé Of Findings In Relation To Case Study Properties Damaged By *Deep* Subsidence

Chapter Five has considered case study properties damaged by *deep* subsidence. The main objective has been to investigate if any threshold of damage exists which can be used to identify whether a property damaged by coal-mining subsidence requires substructure repairs or superstructure repairs. A suitable threshold that has emerged is to make a distinction between foundation movement and foundation damage.

All buildings subjected to ground movement are susceptible to some degree of foundation movement. This foundation movement is transmitted to the superstructure of a building where this movement can become accommodated as visible damage. The extent of damage depends primarily on the amount of movement but will also be influenced, to some extent, by other considerations such as the form of building construction. A review of the process of coal-mining subsidence (see Chapter Two, section 2.4) has highlighted that subsidence movement occurs at the same time as the underground coal-mining operations. Therefore, where coal-mining subsidence results in damage to a property, by the time visible damage becomes apparent, the movement causing the damage has usually ceased. Consequently, if the foundations of a property are not damaged and the function of the foundations are not impaired, it is necessary only to repair the visible damage that is evident in the superstructure of a property.

Where the ground movement has damaged the foundations of a property, or has resulted in a potential cause of damage to the foundations so that the function of the foundation is impaired, the structural stability of the property may become compromised. In the case study properties analysed in Chapter Five, this fact was established through analysing the results of detailed 'post-damage' site investigations. Where subsidence movement results in foundation damage it is necessary to carry out substructure repairs to restore the function of the foundations, in addition to repairs to the superstructure of a property to repair the visible damage.

6.3.2: Summary Of Main Findings In Relation To Research Aim Two

In relation to Research Aim Two, for properties damaged by *deep* coal-mining subsidence, the main conclusion to be drawn is that to establish whether or not '*substructure repairs*' are necessary, it is necessary to distinguish between the fundamentally different concepts of foundation movement and foundation damage. Repairs to a building substructure are only necessary where the functions of the foundations are threatened, which in turn represents a threat to the structural stability of a property. This distinction between foundation movement and foundation damage can be identified through a detailed 'post-damage' site investigation.

When considering properties damaged by shallow subsidence, the main conclusion drawn is that a knowledge of whether or not structural movement is progressive provides the only reliable threshold to establish whether or not a low-rise property requires remedial substructure repairs. On reflection, establishing whether or not movement in a building is progressive can be seen in similar terms to distinguishing between foundation movement and foundation damage. This helps to draw together the findings from Chapter Four and Chapter Five when addressing Research Aim Two. Where movement is found to be '*non-progressive*', the damage in the building has been caused by **foundation movement** but, as this movement has ceased, if the structure is stable, it does not represent a threat to the structural stability of the property. In contrast, where movement is found to be '*long-term progressive*', the foundation movement can be expected to continue. This foundation movement will lead to continual aesthetic disruption to building finishes, and potential serviceability or structural damage to the building. Hence, buildings diagnosed as suffering from long-term progressive movement could be considered to have **foundation damage**.

For properties damaged by *deep* coal-mining subsidence, the fact that subsidence movement is directly related to mining operations makes it relatively straightforward to establish between foundation movement and foundation damage, through a 'post-damage' site investigation. However, for properties damaged by *shallow* subsidence, determining whether or not movement is '*long-term progressive*' presents a more difficult obstacle. This must be established through a program of monitoring the building.

Assessing the remedial action required to repair subsidence damage in a low-rise building by solely considering whether or not movement is progressive would be restrictive. Robson (1991) made the point that monitoring a building merely watches the symptoms of damage. However, it should be remembered that this research takes into account the non-technical aspects of subsidence damage.

Establishing whether or not movement is progressive could be seen to provide a clear and unambiguous indication of whether or not the building is free from subsidence blight and hence directly address the non-technical aspects of the problem. This is not intended to detract from the importance of a meticulous 'post-damage' site investigation. These investigations are essential to establish the technical aspects of the damage, the extent of damage, and the technical aspects of the remedial action.

It can therefore be suggested that a property which shows signs of visible damage associated with subsidence or heave movement should be subject to a full 'post-damage' site investigation. In the case of properties damaged by *shallow* subsidence, this investigation should be extended to include a program of monitoring.

The following chapter uses the results that have emerged in this chapter to consider the practical implications of imposing thresholds of damage for low-rise properties damaged by ground subsidence. The preceding discussion has highlighted that imposing thresholds of damage for properties damaged by *deep* coal-mining subsidence would be limited; the reason for this being that the case study analysis and desk study work carried out at The Coal Authority has found that current practice in dealing with coal-mining subsidence damage cases largely follows the main findings emerging from this work. However, continued debate in the academic literature concerning *shallow* subsidence, especially that caused by the shrinkage and expansion of clay soils, confirms the importance of evaluating the impact of imposing thresholds of damage as a method to overcome some of the contemporary problems of subsidence blight. This forms the focus of Research Aim Three which is considered in the next chapter.

6.4: CHAPTER SUMMARY

This Chapter has drawn together the results of the case study analysis carried out in Chapter Four and Chapter Five. These results have been used to investigate Research Aim One and Two.

In relation to Research Aim One, no threshold of visible damage has emerged which can be seen to identify the concerns of property owners. What has been highlighted is that the evaluation of visible damage is a highly subjective issue. Considering Research Aim Two, it has been demonstrated from the case study analysis that the most appropriate threshold of damage to identify whether or not a low-rise building damaged by ground subsidence requires substructure repairs, is to distinguish between foundation movement and foundation damage. This can be established through a detailed 'post-damage' site investigation. However, for properties damaged by *shallow* subsidence, these investigations should include a program of monitoring to establish whether or not movement is progressive.

The following chapter will reflect on the results that have emerged in order to consider the practical implications of imposing thresholds of damage.

CHAPTER SEVEN: IMPLEMENTING THRESHOLDS OF DAMAGE

7.1: INTRODUCTION

This chapter investigates Research Aim Three, the objective of which is to assess how the non-technical problems caused by subsidence or heave damage in low-rise residential buildings would be influenced by the application of any thresholds of damage identified through the investigation of Research Aims One and Two. Research Aim One has investigated thresholds of visible damage that cause concern to a property owner. Research Aim Two has investigated thresholds of damage that can be used to identify the nature of remedial action required.

The results from the case study analysis carried out in previous chapters have demonstrated that no threshold of visible damage has emerged in relation to Research Aim One. What has emerged is that the evaluation of visible damage is a highly subjective issue dependant on many wide ranging influences. Consequently, it is not possible to evaluate how the non-technical issues created by subsidence and heave damage in low-rise residential properties would be influenced by the introduction of a threshold of visible damage.

In relation to Research Aim Two, a discernible damage threshold has emerged from the analysis of case study properties in previous chapters. This threshold has been identified to be; where movement is found to be *'long-term progressive'*, remedial superstructure repairs will be necessary. Similarly, where movement is found to be '*non-progressive*', then cosmetic superstructure repairs only are required.

It has been explained in the previous chapter that it is not appropriate to consider introducing this threshold of damage for claims caused by *deep* coal-mining subsidence. Therefore, this chapter evaluates how the non-technical problems relating to subsidence or heave claims for *shallow* subsidence would be influenced by the introduction of the threshold of damage described above.

Research Aim Three is investigated through the use of a semi-structured interview process. Before the results of this process are presented, the factors underlying the choice of methodology are considered. As the investigation of Research Aim Three is related to the results emerging from Research Aims One and Two, it is necessary to consider the methodology adopted for the investigation of Research Aim Three in this chapter of the thesis. After considering the methodology, the results of the investigation are presented and subsequently discussed. Following this, a reflection on the methodology used is considered and a chapter summary is presented.

7.2: METHODOLOGY EMPLOYED TO INVESTIGATE RESEARCH AIM THREE

Chapter One, section 1.4 considered an overview of the methodology adopted for this research. However, when addressing Research Aim Three, it was stated in section 1.4.5 that to understand the methodological implications in relation to this research aim, a full appreciation of the findings emerging from Research Aims One and Two is required. These findings have been presented and fully discussed in the previous chapter and consequently at this stage of the thesis it is appropriate to discuss the methodology used to investigate Research Aim Three.

Research Aim Three of this thesis has been stated to be:

> ***To consider how the thresholds of damage identified in Research Aims One and Two, if implemented in practice, would impact upon the non-technical problems relating to subsidence and heave damage in low-rise residential properties.***

Methodological considerations in Chapter One, section 1.4 have distinguished between data sources and methods of generating data from these sources. Therefore, it is first necessary to identify the potential sources of data available and then consider the methods available to gather and analyse this data.

7.2.1: Sources Of Data To Investigate Research Aim Three

The opportunity to investigate Research Aim Three through a review of any information published by insurance companies was not available. Insurance companies do not make public any information regarding their policies towards subsidence claims, as this might impact upon any commercial advantage which has been developed in a very competitive market. Similarly, the Association of British Insurers (ABI), which acts in some matters as a common voice for the majority of British insurance companies, also regards information concerning subsidence claims to be strictly confidential and publishes only very general statistics.

Despite the commercially sensitive manner in which insurance companies treat the subject of low-rise residential properties damaged by ground subsidence movement, it is clear that insurance companies would be able to provide the best source of data to investigate Research Aim Three. The reasoning behind this assumption is that insurance companies are the agency who are financially responsible for remedial works to properties damaged by ground subsidence. Therefore, insurance companies will have collected and analysed detailed information relating to past claims and will therefore be in the best position to provide information which could be used to assess the impact of applying thresholds of damage. From informal discussions at conference presentations (see Appendix A) it was established that certain insurance companies compile information relating to past claims in great detail. This confirmed the importance of insurance companies as the primary source of information to investigate Research Aim Three.

Other than insurance companies, there exists no other significant sources of data available that can be used to investigate Research Aim Three. Although agencies such as engineers, loss adjusters, building surveyors and building contractors become involved in cases of subsidence damage, these agencies usually work within a framework set out by an insurance company which fund remedial repairs.

A potential disadvantage of attempting to gather data from insurance companies is the commercially sensitive nature of the information. One of the principal reasons for insurance companies to hold detailed information on this subject is that experience and knowledge accumulated from past claims can be used as a commercial advantage for the future. As a result of this, insurance companies regard much of this information to be highly confidential. The confidential nature of information held by insurance companies could be suggested as one of the primary reasons that has restricted the use of this data in any previous research in this subject field. Therefore, the collection and analysis of data from this source, which does not compromise confidentiality, will form an original contribution to knowledge.

7.2.2: Methodology Adopted To Investigate Research Aim Three

The above discussion has highlighted that insurance companies are the agency that hold the primary and most relevant source of information to investigate Research Aim Three. After establishing this, it is necessary to consider the information required and identify an appropriate method to collect this information.

In order to address Research Aim Three, it is necessary to obtain information that will reveal the policies employed by insurance companies which indemnify subsidence and heave damage to residential low-rise buildings. The use of interview techniques and a postal questionnaire survey were considered as potential methodological strategies to obtain this information. After considering the strengths and weaknesses of these two methodological strategies in relation to Research Aim Three, an interview approach was adopted. The justification for this is considered below.

The use of interview techniques to collect data to investigate research aim three was employed for the following three reasons:

- Barriers of confidentiality can be minimised as a result of the personal approach adopted during an interview.

- Complex questions can be asked during an interview, with an opportunity to provide a detailed explanation of the questions. This helps to ensure to ensure that the meaning of questions is understood.
- Full answers to questions can be discussed, with *probes* (see below) to answers being employed where appropriate.

Fellows and Liu (1997) explained how interviews can vary in nature between:

- structured
- semi-structured
- unstructured

The major differences between the three types of interview lie in the constraints placed on the respondent and the interviewer. A structured interview technique involves the interviewer administering a series of questions and recording the responses, with little scope for probing the responses by asking supplementary questions or seeking further detail. In contrast, the unstructured interview involves the interviewer introducing the topic briefly and recording the replies of the respondent. Semi-structured interviews lie between these extremes. In this research, to investigate Research Aim Three, a semi-structured interview approach was adopted, the details of which are considered below in section 7.3. The use of a structured interview technique was considered too restrictive as this technique would limit the opportunity to explore or probe responses further. Unstructured interviews were also rejected because this method could result in a lack of focus on the issues seeking to be addressed.

Considering the potential limitations of the interview techniques, Fellows and Liu (1997) and Moser and Kalton (1985) have highlighted that these techniques may be subject to various sources and types of error and bias. Interviewing is a human, social process, however it is executed, and as such, it is important to be objective. In an effort to make all questions and responses as objective as possible, interview questions based on factual information and knowledge were used as far as possible. Opinion based questions were avoided apart from where these occurred in probing answers.

An alternative methodological approach considered to enable data to be collected from insurance companies was the use of a postal questionnaire survey. This would have the potential advantage of being able to collect information from a large number of different insurance companies. However, the use of this technique was rejected in favour of a semi-structured interview approach described above for three primary reasons. Firstly, it was felt that the confidentiality of the subject would result in a very low response rate. Secondly, unlike the semi-structured interview technique, a postal questionnaire would not allow any opportunity to further explore or probe a particular issue arising out of an answer. Thirdly, the nature of the information being sought by the questionnaire would require clear and unambiguous questions that could be easily answered by a respondent. This particular problem could be approached through the use of pilot study exercises. However, as the overall population of respondents (insurance companies) is relatively small, and the response rate expected to be low because of confidentiality, the opportunity to pilot the questionnaire would be limited. It might have proved possible to improve response rates by making questions simpler and asking questions which would not be commercially sensitive. However, this would inevitably compromise the reliability and validity of the questionnaire results and subsequent analysis.

A combination of a semi-structured interview followed up by a postal questionnaire to triangulate the findings from the interview was also considered. The postal questionnaire would allow the general validity of the interview findings to be appreciated. However, this approach was rejected because of the limitations of questionnaires discussed above.

7.2.3: Collection Of Data

Before considering the actual structure of the interview in greater detail, it is necessary to identify precisely where to collect the information from. Fellows and Liu (1997) highlighted three conditions necessary for successful interviews:

- *Accessibility* to the interviewee of the information required.
- *Cognition*; the interviewee's understanding of what is required.
- *Motivation* of the interviewee to answer questions correctly.

There exists many different insurance companies, and the major insurance companies known to offer domestic buildings' indemnity were contacted by letter which was subsequently followed up by telephone, to establish whether or not they would provide data. It was clear from the lack of responses that insurance companies were not prepared to discuss this matter. This highlighted the problematical nature of attempting to collect data from insurance companies. Therefore, it was necessary to establish a point of contact within an insurance company which has experience of dealing with subsidence claims.

The first point of contact to collect the necessary data from insurance companies came through attendance at conference presentations (see Appendix A) where the opportunity arose to arrange an interview with the person responsible for co-ordinating domestic subsidence and heave claims at Royal Insurance. This person would clearly be able to meet the first two conditions necessary for a successful interview that are outlined above and in the absence of any evidence to the contrary, would also be able to meet the third condition.

The scope of the information available from this source was extended as Royal Insurance had recently merged with Sun Alliance Insurance to form a combined company, Royal and Sun Alliance Insurance. This merger extended the scope of the interview as it was established that the combined Royal and Sun Alliance Insurance group insure approximately 40% of the United Kingdom market for private domestic buildings' insurance.

The collection of data that covers approximately 40% of the subject under investigation can be seen to represent a significant volume of information. A response rate of 40% could have been considered reasonable if achieved through a postal questionnaire survey. However, to rely on only one source of data could be misleading. Consequently, further data was sought from other insurance companies which operate in the domestic buildings' insurance market.

It had been established that contacting members of insurance companies directly to discuss the subject of subsidence or heave damage in low-rise residential buildings was unsuccessful. Perhaps one of the main reasons for this, which transpired in the subsequent interviews detailed below, was because the operation of an insurance company deals with the commercial realities of insurance provision rather than considering specific points of building technology. In order to obtain the information required to execute this research, it was necessary to establish a point of contact within an insurance company that understands both the fundamentals of insurance provision **and** the building/technical issues relating to subsidence or heave damage. Within each insurance company, there are very few persons who have expertise in both areas. Therefore, the strategy adopted in the research was to first identify appropriate individuals working within an insurance company who would be willing to provide information and then to arrange the semi-structured interview process.

As a result of the lack of response from contacting insurance companies directly, it was necessary to consider an alternative approach to gain information. During attendance at a Chartered Institute Of Building (CIOB) presentation on insurance matters (see appendix A), a director of a large international insurance broking organisation agreed to assist this research by providing contact names of persons responsible for overseeing claims in some of the large insurance companies. As insurance brokers sell the policies of insurance companies and hence aid insurers business operations, the assistance of an insurance broker who is acquainted with the claims manager of an insurance company provided the opportunity to establish an introduction to a very useful point of contact within an insurance company. After being introduced to the claims manager and outlining the nature of the research, it was possible to arrange an interview with an appropriate person within the insurance company who was knowledgeable of both insurance matters and building/technical matters.

The approach outlined above facilitated further semi-structured interviews that enabled data to be collected from two additional insurance companies. One of these semi-structured interviews was with the technical claims manager of the Commercial General Union. This insurance company was formed by the merger of Commercial Union Insurance and General Accident Insurance, and this company estimated that it accounted for between 7.5% to 10% of the United Kingdom domestic buildings' insurance market. The other semi-structured interview was with the person responsible for all subsidence claims at Direct Line Insurance. Direct Line Insurance estimate that it accounts for approximately 5% of the United Kingdom domestic buildings' insurance market.

Royal and Sun Alliance Insurance and Commercial General Union both represent *traditional* insurance companies. These companies can trace their origins back well into the last century and historically such companies have had very close ties with building societies, as outlined in the introduction of this thesis. Both of these insurance companies insure a large portfolio of risks extending well beyond the standard domestic policies. In contrast, Direct Line Insurance is a *new* insurance company, established in 1980. This company insures only the standard domestic risks of motor and household insurance (including buildings' insurance) and virtually all of its business selling policies is conducted over the telephone. Whilst insuring complicated commercial risks requires detailed assessments of the risk to be made, insuring domestic risks can be handled through a pro-forma checklist which can be administered over the telephone. The ease of this system has made the *new* telephone based insurance companies a significant competitor to the *traditional* insurance companies in the area of domestic risk. Therefore, considering the presence of these *new* telephone based insurance companies in the domestic buildings' insurance market, it was considered important to include these in this research.

After conducting three interviews which covered approximately 55% of the United Kingdom domestic buildings' insurance market it was considered that sufficient data had been collected to enable the research to proceed. Royal and Sun Alliance and Commercial General Union represent two of the largest *traditional* insurance companies operating in the United Kingdom, whilst Direct Line Insurance represents the largest independent telephone based *new* insurance company.

7.3: APPROACH ADOPTED DURING SEMI-STRUCTURED INTERVIEW

The previous discussion in this chapter has considered the methodology necessary to investigate Research Aim Three. The use of the semi-structured interview is the method adopted, and appropriate interview subjects have been determined. After establishing this, it is necessary to consider the approach adopted during the semi-structured interviews.

A framework of questions and potential question probes were formulated under a number of different subject headings. These subject headings and questions were identified through considering the objective of Research Aim Three in relation to existing knowledge that had been built up from conference attendance and previous interviews (see Appendix A). Whilst very little published information exists regarding the policies that insurance companies employ in relation to subsidence and heave claims, conferences and interviews enabled some prior knowledge to be established.

The approach adopted during the actual process of the semi-structured interviews was that the interview was divided into a number of different parts. Each part formed a distinct section of the overall interview and all relevant information from each part was collected before moving on. Some areas of overlap were however inevitable. The subject matter of each part of the interview was first outlined, after which a series of questions were asked. For each question the interviewee was encouraged to discuss the subject as fully as possible with answers being probed for further information where relevant. During the actual interview process, it was found that several proposed questions were pre-empted and that a variety of un-planned question probes were used to expand the interview.

7.3.1: Interview Structure

The interview was divided into five parts as listed below:

Part One:	General information relating to insurance cover for subsidence and heave damage.
Part Two:	Claims administration.
Part Three:	Thresholds to qualify visible damage in low-rise properties.
Part Four:	Thresholds of damage to establish the need for substructure repairs.
Part Five:	Quantitative information.

Part One, general information, was intended to provide an introduction to the interview.

Part Two, considers the claims administration procedures employed. The objective of this is to establish how claims are administered and how responsibility for sanctioning remedial work is delegated from the insurance companies to agencies such as engineers, surveyors or loss adjusters. These agencies are responsible for assessing and investigating damage, recommending remedial action and communicating with the property owners.

Part Three considers the subject of applying a threshold of visible damage as a method to qualify the amount and/or severity of visible damage necessary to distinguish an insurance claim for remedial repairs from visible damage which can be considered to be part of routine building maintenance. This was investigated in Research Aim One where it was established that no such threshold of damage emerged from any of the case study analysis carried out in the previous sections of this research. However, it is considered that the semi-structured interview would provide a good opportunity to discuss and help to triangulate the findings that have emerged from Research Aim One.

Part Four addresses the subject of insurance companies applying a threshold of damage, based on whether or not foundation movement is found to be progressive, as an objective method to establish where remedial substructure repairs are required. This threshold of damage has been established through the investigation of Research Aim Two and the significance of this has been fully discussed in Chapter Six. During the semi-structured interview process, there were two objectives to this part of the interview. The first objective was to establish whether or not this threshold of damage is currently used. It is known that monitoring of structural movement is carried out on many low-rise properties diagnosed to be affected by subsidence or heave movement. However, the significance of this information in terms of determining the necessity to carry out substructure repairs is not known. After determining this information, the second objective of this part of the interview was to assess how the non-technical problems caused by subsidence or heave damage in low-rise residential properties would be influenced if insurers implemented the threshold of damage identified.

Part Five considers quantitative information relating to claims made for subsidence and heave. It is known that insurance companies keep records of past claims made for subsidence and heave damage. The objective of this part of the interview was to consider how the introduction of the thresholds of damage identified could be considered in quantitative terms, especially in relation to the number and value of claims.

7.4: RESULTS EMERGING FROM THE SEMI-STRUCTURED INTERVIEWS

After establishing information through the process of semi-structured interviews, the results of these are presented below.

7.4.1: Part One: General Information

Both Royal and Sun Alliance and Commercial General Union have offered indemnity against damage caused to low-rise residential properties as a result of ground subsidence since 1971. Historically, insurance companies have maintained very close business links with building societies. Building societies lent money to finance the purchase of property, with the value of the property acting as security for the provision of finance. In the early 1970s a small number of properties were adversely affected by subsidence damage. This caused a marked reduction in their capital value. To safeguard the building societies' interests, insurance companies provided cover against subsidence damage. During the early 1970s, the issue of subsidence damage to low-rise properties received very little attention in either the academic, technical or national press. At this period in time most home-owners considered any damage apart from serious serviceability damage or structural damage to be part of routine building maintenance. However, soon after the introduction of indemnity against subsidence damage, a severe period of drought occurred in the United Kingdom causing much publicity about subsidence damage to low-rise properties (see Chapter Three, section 3.5).

Direct Line Insurance was founded in 1982 and did not enter into the domestic buildings' insurance market until 1988. This company has no links with building societies, although a subsidiary company, Direct Line Mortgage, does provide a semi-captive market for some insurance policies. Although Direct Line Insurance has approximately a 5% market share of domestic buildings' insurance, its experience in dealing with claims is relatively limited as it takes several years to develop a portfolio of policies and the number of claims will be related to number of policies.

It was also established that the nature of this insurance market is changing. Traditionally, building societies were the lending institution that provided finance for the purchase of residential properties. In more recent times, agencies other than building societies have become lending institutions. It is now starting to become common for major lending institutions to create their own captive insurance market by offering the option to provide buildings' insurance indemnity as part of a mortgage package. In addition, it is no longer required that buildings' insurance has to be taken out with the same agency that provide a mortgage for a property. This has allowed homeowners freedom to "*shop around*" for their buildings' insurance and has allowed the development of new insurance companies, making this area of insurance highly competitive.

7.4.2: Part Two: Claims Administration

From the three semi-structured interviews carried out, it was found that the insurance companies employed different professionals in various ways to administer subsidence or heave claims on their behalf.

Considering Royal and Sun Alliance Insurance, at the time of the interview (July 1997), the claims procedures of the two merged companies were still operating separately. Prior to the merger, both companies employed a panel of independent experts to administer claims. The panel of experts comprises a number of different business practices which have in-house expertise in the area of subsidence damage to low-rise residential properties. A member of this panel of experts is engaged and paid for by the insurance company to investigate any alleged subsidence or heave damage. Their remit is to act objectively and impartially, despite the relationship to the insurance company. Royal Insurance panel of experts comprised of a number of civil and structural engineering practices, Sun Alliance panel of experts comprised of a number of loss adjusting practices. It was established that Sun Alliance allow its panel of experts full delegated power to sanction any remedial works, whereas Royal Insurance require that where underpinning of a property is recommended, this must first be approved by insurers. However, it was stated that in other matters relating to subsidence the claims administration of these two companies was very similar prior to their merger.

Direct Line Insurance were found to administer claims in a similar manner to that described above, employing a panel of structural and civil engineering practices to administer all claims. This system of claims administration was established in 1994 and prior to this date loss adjusters were employed to administer claims. Direct Line Insurance provides its panel of engineers with full delegated powers to sanction remedial work up to a maximum value of £20,000 per claim. Claims costing more than this sum must be referred back to the insurance company for approval to sanction remedial action.

Commercial General Union were found to administer all subsidence and heave claims through chartered loss adjusting practices. Loss adjusters are appointed and paid by the insurance company. No formal panel of loss adjusters is used by this company and claims are administered on a regional basis by insurers which appoint an appropriate loss adjuster. To investigate the technical facts of a case, the loss adjuster usually appoints a chartered structural or civil engineer. Commercial General Union do not give loss adjusters delegated powers to deal with subsidence or heave claims, and the loss adjuster has to present recommendations for remedial action to the insurance company for approval prior to implementation.

The issue of whether or not an insurance company provides delegated powers to experts employed to administer subsidence or heave claims has far reaching implications. Where an expert is given full delegated powers to administer a subsidence claim, the insurance company is not liable to pay VAT on the experts fees. However, where the expert has no delegated power, the insurance company does have to pay VAT on the experts fees.

Despite the differences in how insurance companies administer claims, one common theme has been found to emerge from each company. Each insurance company indicated that they accept the responsibility of proving that damage was caused by the operation of subsidence or heave. In practical terms this means that where a policy holder makes a claim against his/her insurance policy for subsidence or heave damage, the insurance company will bear all the costs associated with establishing whether or not damage has been caused by one of these perils. Each insurance company facilitates this through appointing and paying for a single professional expert to administer a claim as discussed above.

The use of one expert, who co-ordinates all information and provides all technical guidance, has appeared to reduce many problems associated with subsidence claims in the past. Before the use of a single expert acting in the interests of both insurer and property owner, it was common for both parties to each employ their own experts. This resulted in a property owner appointing his/her own engineer or surveyor and any other specialists as necessary to investigate the damage. The property owner would be responsible to pay for all costs associated with these investigations until it was proved to the insurance company that damage was caused by either subsidence or heave. If the insurance company, or loss adjuster acting on behalf of the insurer did not agree with the advice given by the property owners professional advisors, they would appoint their own engineer, surveyor and/or other expert as necessary. Information tended to flow between the individual parties without being co-ordinated amongst all parties involved. In such circumstances, entrenched positions often arose, where regardless of the technical facts of a claim, those acting in the interests of insurers insisted that the property was stable and required only cosmetic repair. In contrast, the property owner desired substructure repairs (usually underpinning) to provide a safeguard against the property being blighted by subsidence, and consequently ensure full market value and saleability. These entrenched positions inevitably caused delays in settling claims often resulting in complex disputes and referrals to the Insurance Ombudsman Bureau (IOB) or even legal action. Additionally, the expense incurred in employing so many experts increased the total costs of each claim.

The system outlined above created many problems for both policy holders and insurance companies in relation to domestic subsidence and heave damage claims, especially during the late 1980s and early 1990s when hot dry weather resulted in a substantial increase in the number of claims. It was found that in the case of both Royal and Sun Alliance and Commercial General Union, the problems created during this period caused a change in the administration of subsidence claims. One of the significant consequences of this was that insurers accepted the responsibility and costs associated with proving that damage was caused by either subsidence or heave, rather than some other non-insured peril. In accepting this responsibility, insurance companies take on a higher standard of care than is strictly required in the details of the insurance policy. However, both insurance companies acknowledged that by instructing either a chartered engineer or loss adjuster to investigate damage objectively, and by keeping the property owner/claimant fully informed, this provided a greater mechanism of control over a claim. Direct Line Insurance was found to employ the same principle of claims administration as Royal and Sun Alliance and Commercial General Union. However, Direct Line was not significantly affected by the high number of claims experienced during the hot dry summers experienced in the late 1980s and early 1990s as this is a *new* insurance company which had only a small presence in the domestic buildings' insurance market at that time.

7.4.3: Part Three: Thresholds To Qualify Visible Damage In Low-rise Properties

This part of the research considers thresholds of visible damage that could be used to distinguish between a claim for subsidence damage repairs and damage which can be considered as part of routine building maintenance. Insurance policies are extremely vague[1] and contain no information to qualify either the amount or severity of damage necessary to make a claim. A threshold of visible damage that causes concern to property owners has been investigated in Research Aim One. Any threshold which was found to emerge could be used as a benchmark to suggest where it is appropriate to further investigate a suspected case of subsidence, and where it is appropriate to repair the damage as part of a program of routine building maintenance at the expense of the property owner. The purpose of seeking to establish what causes concern to property owners is that although they are not technical experts in the subject, it is arguably their perception of damage which is the most significant. This is because it is property owners who initiate and pursue claims for damage, usually to make sure that the value of their property is not at risk.

No obvious threshold of visible damage has emerged from previous chapters that have investigated Research Aim One through the case study analysis. It was shown that the evaluation of visible damage is a highly subjective issue and it has not been possible to quantify any thresholds in this research. Therefore, it is not possible to consider how the non-technical problems caused by subsidence or heave damage in low-rise residential buildings would be influenced by the application of any thresholds of visible damage.

During each of the three semi-structured interviews, the subject of providing qualification of the amount and/or severity of damage necessary to establish a valid insurance claim was considered. At each semi-structured interview it emerged that assessing visible damage evident in a property was a highly subjective problem. For each of the three insurance companies, as explained in the previous section, it was found that where a policy holder reports damage thought to have been caused by subsidence or heave, the insurance company will investigate the damage at its own expense to establish the exact cause. Regardless of the cause of damage, the insurance company will pay all investigation costs. Where subsidence or heave is found to be the cause of damage the policy holder is liable to pay the policy excess. This indicates that when assessing visible damage in a property, insurance companies place most emphasis on establishing the cause of the damage rather than placing emphasis on the symptoms.

Direct Line Insurance were the only company that indicated the approximate costs of investigating the cause of damage to prove whether or not it resulted from the occurrence of the insured peril of subsidence or heave. It was estimated that the average cost of establishing this was in the order of between £800 to £1,000 for each claim (Brett-Pitt, 1998).

7.4.4: Part Four: A Threshold Of Damage To Establish The Need For Substructure Repairs

This part of the chapter investigates how the introduction of a threshold of damage established through the investigation of Research Aim Two could potentially influence the non-technical problems caused by subsidence or heave damage in low-rise residential buildings. The threshold of damage emerging from Research Aim Two was that a knowledge of whether or not foundation movement causing damage is '*long-term progressive*' is the most reliable method to establish if a property requires remedial substructure repairs.

Before considering the potential consequences of implementing this threshold of damage, it was first necessary to determine whether or not this, or any other thresholds of damage were applied in practice, and if so the extent of their use. It emerged that the threshold of damage established in Research Aim Two has, to a large extent, been established in procedures adopted by two of the three insurance companies studied, as explained below.

In addition to the semi-structured interview with Royal and Sun Alliance, it was also possible to review the written guidelines provided by Royal Insurance to their panel of engineers which administers claims (Royal Insurance, 1996). These guidelines indicate that where an initial visual appraisal of a property indicates subsidence as a possible cause of damage, then further investigations, including monitoring, should be carried out. Remedial action without recourse to monitoring is only recommended where ongoing movement is both obvious and severe. The guidelines state:

> "*.....the objective in all subsidence cases is to ensure that a property has stabilised prior to superstructure repairs being carried out. In most cases stability will be achieved by removing the cause of subsidence and proving stability through monitoring. Monitoring should not be delayed until after tree removal or drain repairs have been carried out, since it is important to obtain a view both before and after action has been taken. However, in cases where stability can only be achieved through underpinning, the principle of underpinning must be approved by insurers prior to designing the underpinning scheme.*"

It is also recommended in these guidelines that crack monitoring be carried out for a maximum period of thirteen months[2]. Consequently, the fact that monitoring is recommended to be carried out over a prescribed time period to establish if movement is '*long-term progressive*' or not, clearly

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[1] Typical wording of an insurance policy being, "*cover is provided for damage caused by Subsidence or Heave of the site beneath the Buildings or Landslip, less the policy excess.*"

addresses two major criticisms of monitoring that were highlighted in Chapter Three, section 3.3, which has reviewed the subject literature. The first criticism related to the fact that monitoring can be used as a delaying tactic by insurance companies to avoid or delay settling a claim. This issue is clearly addressed by stating a maximum period of monitoring, which is long enough to take into account a full seasonal weather pattern. A further criticism of monitoring is that it should be carried out for a purpose and should not simply monitor the symptoms of damage and ignore the cause. This criticism can be seen to be addressed as investigations to establish the cause of damage are carried out complementary to monitoring. Where applicable, any potential causes of damage such as trees or leaking drains are removed or reduced, with the purpose of monitoring being to establish if a property has stabilised. However, it was found in the guidelines that no defining thresholds or amounts of movement are suggested to distinguish '*long-term progressive*' movement from '*seasonal movement*', or movement associated with normal thermal, moisture or climatic conditions. The interview highlighted that this is a matter for professional judgement of the engineer handling the case, who in all cases is a professionally qualified chartered civil or structural engineer.

Direct Line Insurance were found to employ a very similar procedure to that outlined above. The approach adopted by this insurance company when dealing with a subsidence or heave claim is to investigate as much as possible as early as possible. After damage in a property is reported, an engineer visits the property with two technicians and carries out both a visual inspection and further investigations including trial holes, boreholes and soil samples in one visit. Direct Line insist that the engineer monitors the damage after any obvious cause of damage such as trees or drains have been eliminated or minimised. It is recommended that monitoring take no longer than twelve months if trees are suspected to be the cause of damage, or six months in the case of leaking drains. The results of the monitoring are a major factor, in conjunction with the findings from the further investigations (trial holes, soils samples etc.), used to establish whether or not the property requires remedial substructure repairs.

All subsidence and heave claims made to Commercial General Union are administered through loss adjusters. To consider the technical facts of each case, an engineer is usually appointed and after considering the advice of the engineer, the loss adjuster makes recommendations for remedial action to the insurance company. However, Commercial General Union do not insist that monitoring is carried out as this is a matter of professional judgement of the loss adjuster and engineer administering a claim.

The semi-structured interview process and the review of the Royal Insurance guidelines have highlighted the method employed to establish the need or otherwise to carry out substructure repairs

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[2] Seven months if the cause is identified to be drains.

to a property. In all cases of suspected subsidence or heave damage involving Royal and Sun Alliance and Direct Line Insurance, except where ongoing movement is both obvious and severe, then monitoring of damage should be carried out complementary to investigations in order to establish the precise cause of damage.

The semi-structured interview process established that it is unnecessary to expressly state in an insurance policy a threshold of damage linking '*long-term progressive*' movement with the need to carry out substructure repairs. What emerged from the insurance companies considered in this research was that the insurance policy states that damage associated with an insured peril will be repaired and it is a matter for insurers to determine what repairs should be carried out. However, it is evident that some insurance companies do employ this threshold of damage when instructing agents, such as engineers, who administer claims.

It was further established that regardless of what form of remedial action (if any) is carried out, at the conclusion of any subsidence or heave damage claim, Royal and Sun Alliance Insurance and Direct Line Insurance both offer a **Certificate of Structural Adequacy** to the property owner. The principle of issuing a Certificate of Structural Adequacy was suggested by ISE (1994). This certificate is issued by the expert employed to administer the claim and provides the insured property owner with evidence that his/her property is free from any significant subsidence or heave related defects. This helps to ensure the market value and saleability of a property. Commercial General Union did not offer such a certificate, but suggested that continuity of insurance, as discussed below, helps to ensure the long term value and saleability of a property that has been the subject of a subsidence or heave claim.

If no major remedial works are found to be necessary, a Certificate of Structural Adequacy can be issued following a full investigation of the cause of damage (including monitoring). Alternatively, the Certificate can be issued following completion of remedial works that are deemed satisfactory by the engineer investigating the case. This certificate does not provide a guarantee, but provides a professional assurance, backed by the engineer investigating the damage, that the property is structurally sound. ISE (1994) suggested that a Certificate of Structural Adequacy should result in a more meaningful assurance than a guarantee issued by a building contractor which carries out repairs to a damaged property. A guarantee issued by a contractor will usually only remain valid where the contractor remains in business. In such cases, the risk of the contractor going into liquidation restricts the backing of any guarantee. Although some specialist underpinning contractors have attempted to obtain insurance backing for their guarantees, ISE (1994) reported that the details of such schemes have not been positively proved.

It was established that each of the three insurance companies considered in this research offer continuity of insurance cover between different owners on properties offered for sale, even where a claim for subsidence or heave damage has been made against the property for sale, or where a past history of subsidence claims in the location is known. In the case of both Royal and Sun Alliance Insurance and Direct Line Insurance, the interview process also highlighted that the monitoring results can be used to provide objective evidence about the structural stability of a property.

Considering the above results from semi-structured interviews, it can be seen that to a large extent, two of the three insurance companies considered have implemented a threshold of damage, linking '*long-term progressive*' foundation movement with a requirement to carry out remedial substructure repairs. The interviews revealed that this threshold has not been expressly implemented through any qualification contained in insurance policies. Instead, it has been applied through a policy of improving customer (policy holder) care, centred around using a panel of quasi-independent professional experts to administer claims.

In the case of Commercial General Union, all claims are administered through loss adjusters and there is no requirement to monitor all claims for subsidence or heave. However, the information provided by Commercial General Union suggested that this insurance company recognised that many mistakes had been made by all parties involved in administering subsidence claims in the late 1980s and early 1990s. Emphasis was placed on dealing with the problem rather than addressing the cause. Hence, as reported in the literature (Hunt *et. al.*, 1991), many properties were underpinned in order to address the problem, rather than establishing and addressing the precise cause of damage. Commercial General Union considered that professionals such as loss adjusters, engineers and surveyors had experienced a learning curve since the high number of claims experienced in the late 1980s and early 1990s. These professionals were now much more aware of the necessity to firstly establish and control the cause of subsidence damage rather than placing too much emphasis on repairing the symptoms of damage. The effects of this learning curve and the better understanding of this subject gained by professionals administering claims over recent years is the primary reason why Commercial General Union feel confident to administer subsidence claims through loss adjusters.

It was estimated by Royal Insurance, prior to its merger with Sun Alliance (Biller, 1997) that before the establishment of independent panel engineers in 1991, more than 80% of all subsidence claims required either full or partial underpinning. Following the introduction of panel engineers and the transitional period, in 1997 less than 10% of all subsidence claims required underpinning. Direct Line Insurance, which also uses a panel of engineers to administer subsidence claims, estimated that in 1998, approximately 5% of subsidence or heave claims required underpinning (Brett-Pitt, 1998).

Commercial General Union did not provide any indication of the approximate number of claims requiring underpinning.

The obvious consequences of reducing the number of properties underpinned is the impact on the cost of settling claims. It has been estimated (Biller, 1997) that for Royal Insurance in 1991, the average cost of settling each subsidence claim cost between £13,500 to £14,500. After the introduction of a system of panel engineers to administer claims, by 1997 this figure had been reduced to £6,500 to £7,000. Direct Line insurance estimate that in 1998 the average cost of a subsidence claim which does not require underpinning is in the region of £5,000. The average cost of a claim involving underpinning costs in the region of £15,000. It was also stated that these costs represented a reduction in the order of 50% since 1991, when this company first started to keep detailed records of the costs associated with subsidence or heave claims. This was also before Direct Line Insurance employed a system of panel engineers. No information on this subject was available from Commercial General Union. The interview process also highlighted that consideration of past records of quantitative information held by insurance companies is not a straightforward process. This subject is considered in section 7.4.5 below.

The system of claims administration employed by both Royal and Sun Alliance Insurance, and Direct Line Insurance embraces the principle established in Research Aim Two. This principle has been combined with other measures, including accepting the costs involved in investigating the cause of damage and issuing a Certificate of Structural Adequacy, as outlined earlier in this chapter. The consequences of this have been demonstrated in the discussion above, where it has been shown that the number of subsidence claims requiring underpinning has been substantially reduced. Consequently the costs associated with subsidence and heave claims, for these two insurance companies, have been significantly reduced. The evidence from the semi-structured interviews also suggests that the insurance companies consider that this has been achieved without compromising the level of service to their policy holders.

7.4.5: Part Five: Quantitative Information

One of the objectives of the semi-structured interview process was to gather quantitative information which related to the number and value of claims for subsidence and heave damage in order to assess how the introduction of thresholds of damage might impact upon this data. Insurance companies gather detailed information relating to past claims and this information is used to assess future risks. Consequently, this information is classified to be confidential and for internal use only. However, it was explained that this information, even if not classified as confidential, would be of limited use to this research. The principal reason for this is because insurance companies collect data to take into account their business operations and this fact would compromise the validity of such data for the purposes of this research. For example, in some instances, buildings' insurance cover can be divided between more than one insurance company. This occurs where building societies maintain a panel of different insurance companies and spread out insurance between these companies to off-set risks. This is known as co-insurance.

It was also highlighted how data relating to the financial costs of settling subsidence and heave damage claims can be misinterpreted. An insurance claim can take several years to conclude between damage first being reported and remedial action being completed and paid for. Therefore, at the time each claim is received by an insurance company it is not known precisely how much the total cost of the claim will be and therefore an estimated cost of settling the claim is allocated. As a result of this, insurers are able to account accurately for the number of claims received in any period of time, but accounting for the actual value of claims is not an accurate reflection of the real value as this information is based on estimated costs.

The above discussion serves to highlight the complications of considering the commercial operations of insurance companies, which is an issue that is beyond the scope of this research.

7.5: REFLECTION ON DATA SOURCES USED TO INVESTIGATE RESEARCH AIM THREE

This chapter has employed the semi-structured interview process to investigate Research Aim Three through collecting data from insurance companies. After collecting data in this way and presenting the results, at this stage of the research it is appropriate to reflect on the data employed.

The discussion in the first part of this chapter has highlighted that collecting data from insurance companies will provide the most suitable source of information to investigate Research Aim Three. Taking into account the nature of the information that has been collected from the semi-structured interviews, and the confidentiality of the subject area, it can be appreciated that a postal questionnaire (considered earlier in this chapter as a potential method to collect data) would have been an inappropriate strategy.

Following the employment of a semi-structured interview process to collect data, it is necessary to consider the measures that have been taken to overcome any potential weaknesses of this data. Information for this part of the research came from three separate insurance companies. This information reflects approximately 55% of the United Kingdom domestic buildings' insurance market. To ensure that the information collected was both objective and representative, interview questions sought factual and knowledge based information, as opposed to opinions.

Reflecting on the quality of the data obtained through the semi-structured interview process, it is possible to be confident of the reliability and validity of the information collected. The reasons for this are that during each interview process it was possible to clearly explain questions and ensure that their meanings were correctly interpreted. It was also possible to ensure that all answers arising from questions were fully explained and understood.

The above findings in this chapter that consider the expenditure on subsidence claims have emerged through considering the limited quantitative information provided by two insurance companies. No quantitative information was provided by the third insurance company considered in this chapter. The difficulties and limitations of collecting data on subsidence and heave claims from insurance companies are discussed earlier in this chapter. Consequently, it has not been possible to provide a comparative assessment between different insurance companies which employ different technical guidelines for claims administration.

7.6: CHAPTER SUMMARY

This chapter has investigated Research Aim Three, the objective of which is to assess how the non-technical problems caused by subsidence or heave damage in low-rise residential buildings would be influenced by the application of any thresholds of damage. The first part of this chapter has considered the methodological implications of investigating Research Aim Three. It was established that the most appropriate method to collect data would be through the process of semi-structured interviews with insurance companies. Relevant information to investigate this has been established from three separate insurance companies, each one having a significant presence in the domestic buildings' insurance market.

The first two parts of the interview process considered the general claims operational matters and highlighted the framework for claims administration. The semi-structured interview process has investigated the impact of applying the threshold of damage which has emerged from the investigation of Research Aim Two. This threshold was established to be that only properties displaying evidence of '*long-term progressive*' movement require sub-structure repairs. It has been found that although this threshold of damage is not expressly stated in the insurance policy, to a large extent, two of the three insurance companies considered have implemented this threshold of damage in practice through the claims administration and guidance procedures involved in administering claims.

Considering the evidence from these two insurance companies, the impact of this threshold of damage has been demonstrated in terms of the reduced number of claims requiring substructure repairs. The obvious consequence being the reduction in the number of claims requiring remedial substructure repairs and hence a reduction in the average cost of settling claims. It is not possible to assert that imposing this threshold of damage in isolation has resulted in a reduction in the number of subsidence claims requiring underpinning, but the evidence suggests it has made a significant impact. All parties involved in subsidence damage cases have learnt valuable lessons following the peak of claims experienced in the late 1980s and early 1990s. It would appear that the reduction in the number of claims requiring sub-structure repairs has been brought about as part of an overall system of improving claims administration. One of the underlying principles of this system is the recognition that in properties where movement is found to be '*long-term progressive*', even after the removal of any obvious causes of damage, remedial substructure repairs will be required. In properties where movement is found to be '*non-progressive*', then repairs will be limited to the superstructure of the property only. This principle would appear to be implemented in a manner that addresses some of the fundamental non-technical issues of subsidence damage. The primary non-technical issue which has been addressed is the issue of a Certificate of Structural Adequacy. This provides a property owner (and significantly where appropriate, a potential purchaser) with evidence that a property is free from any significant subsidence or heave related damage, and hence helps to ensure the market value and saleability of a property, alleviating the problem of subsidence blight. It has further been established that the relationship between '*long-term progressive*' movement and substructure repairs is used as evidence to re-assure a property owner about the stability of his/her property. This is achieved by using the monitoring results as evidence of the stability of the property.

A final point to consider is that establishing an objective threshold of damage to identify the need for substructure repairs is not only in the interests of the insurers, but also the property owner. For example, owners of a property wanting to sell their home can use the monitoring results, supported by a Certificate of Structural Adequacy, to provide evidence of the stability of their property. Consequently, there should be no basis for insurers to refuse to offer continuity of insurance cover and therefore reassure potential purchasers of the market value. Although all three insurance companies stated unequivocally that it is company policy to offer continuity of insurance cover on a property, a Certificate of Structural Adequacy provides a property owner or potential purchaser with tangible evidence of the structural stability of a property in relation to any subsidence or heave problem.

After summarising above the main findings that have emerged from this chapter, the next and final chapter of this thesis will present and discuss the overall conclusions that can be drawn from this research and will indicate areas where future research could be directed.

CHAPTER EIGHT: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

8.1: INTRODUCTION

This research has investigated thresholds of damage for low-rise residential properties subjected to subsidence or heave movement. The research has been investigated through the employment of data collected and analysed from 236 individual low-rise residential properties damaged by ground subsidence or heave. In addition, the research has employed interviews and a review of relevant literature.

8.2: AIMS AND OBJECTIVES

As stated in Chapter One, the overall objective of this research is to investigate the problems caused by subsidence damage in low-rise residential properties, with particular emphasis placed upon the non-technical aspects of subsidence damage. This has been achieved by addressing the following three main research aims:

> **RESEARCH AIM ONE:**
>
> *To investigate the threshold of visible damage that cause concern to professional advisors acting on behalf of a property owner.*
>
> **RESEARCH AIM TWO:**
>
> *To investigate the threshold of damage that can be used to identify the need for substructure repairs.*
>
> **RESEARCH AIM THREE:**
>
> *To consider how the thresholds of damage identified in Research Aims One and Two, if implemented in practice, would impact upon the non-technical problems relating to subsidence and heave damage in low-rise residential properties.*

Previous research has been carried out which investigates low-rise residential properties damaged by ground subsidence or heave movement. However, this previous work does not address the contemporary problems caused by subsidence blight. Subsidence blight is largely caused by the non-technical issues that have been discussed at the start of this thesis in Chapter One, section 1.2.1. Therefore, the aims of this research were formulated to address these issues and this was seen to be a field that would allow the thesis to contribute to knowledge.

The technical and engineering problems caused by ground subsidence have been extensively addressed in previous research and this forms a well-established body of knowledge. This body of knowledge has been extensively reviewed in Chapters Two and Three. The established technical and engineering issues that have emerged from this review have been used as knowledge to underpin the research aims investigated in this thesis.

8.3: CONCLUSIONS

The aims and objectives of this research have been investigated in the preceding chapters of this thesis. The main points established in each chapter can now be summarised and following this the findings and conclusions emerging from the investigation of the research aims are presented.

8.3.1: Chapter Summaries

Chapter One introduced the background and context of the research undertaken and has defined the aims and objectives of the research. The chapter also provided an overview of the methodology and highlighted the importance of the research methodology in relation to the reliability and validity of data within the context of this study.

Chapters Two and Three examined the relevant literature relating to the subject of subsidence or heave damage to low-rise residential properties. Chapter Two considers the causes of damage and Chapter Three considers the consequences.

In relation to the causes of damage considered in Chapter Two, the chapter distinguished between damage caused by *shallow* subsidence and damage caused by *deep* coal-mining subsidence. Considering *shallow* subsidence, in the absence of any definitive guidelines concerning 'post-damage' site investigations for properties damaged by subsidence or heave movement, a number of key issues were identified to be important. These key issues are summarised below:

- The classification of clay soil in terms of its volume change potential.
- The relationship between the proximity of trees and buildings.
- Depth of building foundations below ground level.
- The assessment of the moisture content of clay soils to define the onset of desiccation.
- The effect of leaking drains causing subsidence or heave movement (unlike the other points listed above, little published literature was available on this issue).

In relation to *deep* coal-mining subsidence, empirical methods of predicting surface subsidence have been developed and refined from observation of actual subsidence, and these methods are able to predict subsidence with a high level of accuracy.

After considering the causes of subsidence in Chapter Two, Chapter Three has highlighted its consequences. This chapter has considered visible damage to a property, whether or not movement is progressive and the remedial action required to rectify damage. In addition, Chapter Three discussed the non-technical subject of building value depreciation resulting from damage and has also considered the subject of liability for subsidence damage in terms of those agencies which are responsible for funding remedial action.

After considering the literature, the research progressed to specifically address the aims and objectives of this thesis. Chapter Four considered an analysis of 127 case study properties damaged by *shallow* subsidence. The analysis in Chapter four employed multiple regression analysis to investigate a threshold of damage that can be used to identify the need – or otherwise – for properties requiring substructure repairs. Through the use of multiple regression analysis it has been clearly demonstrated that the most important consideration is to establish whether or not movement is long-term progressive. The results of the analysis in Chapter Four should not be seen as a process or tool that is aimed replacing the professional experience/judgement of a chartered engineer who investigates specific technical issues. The threshold of damage is an element which insurance companies can use to complement the role of the engineer in order to address the non-technical issues associated with subsidence damage which cause many of the contemporary problems. The application of this knowledge in practice is considered in Chapter Seven.

Chapter Five considered an analysis of 109 case study properties damaged by *deep* coal-mining subsidence. The main finding emerging from this chapter is that in order to differentiate a property that requires substructure repairs from a property that requires only superstructure repairs, it is necessary to distinguish between foundation movement and foundation damage. All buildings affected by coal-mining subsidence are subject to foundation movement. Where foundations are subject to movement, after this is complete, if the foundations are undamaged and able to perform their function, then it is only necessary to repair the damage to the superstructure of a property. However, foundation damage can be defined where movement has either caused, or represents imminent potential damage to the foundations of the property. In order to identify foundation damage it is necessary to carry out a thorough 'post-damage' site investigation.

Chapter Six has drawn together the results of the case study analysis carried out in both Chapter Four and Chapter Five to specifically address both Research Aims One and Two. In relation to Research Aim One, no threshold of visible damage has emerged that can be seen to identify the concerns of either property owners or professional advisors acting on their behalf. It has been highlighted that the evaluation of visible damage is a highly subjective issue. In relation to

Research Aim Two, the case study analysis has demonstrated that the most appropriate threshold of damage to identify whether or not a low-rise building damaged by ground subsidence requires substructure repairs, is to distinguish between foundation movement and foundation damage. This can be established through a detailed 'post-damage' site investigation. In the case of properties damaged by *shallow* subsidence, these investigations should include a program of monitoring the building to establish whether or not movement is progressive.

Chapter Seven has specifically investigated Research Aim Three. The objective of this is to assess how the non-technical problems caused by subsidence or heave damage in low-rise residential properties would be influenced by the application of the threshold of damage that has been established through the investigation of Research Aim Two. This has been investigated through considering data from insurance companies that represent approximately 55% of the United Kingdom domestic buildings' insurance market. It has emerged that the threshold of damage which was identified in Research Aim Two has, to an extent, been implemented in practice through the claims administration procedures adopted.

8.3.2: Findings

This research has addressed three clearly defined research aims and the following section will present the main findings:

RESEARCH AIM ONE:

Thresholds of visible damage that cause concern to professional advisors acting on behalf of a property owner

> **No threshold of visible damage that causes concern has emerged from the analysis carried out in this research. What has been established is that the evaluation of visible damage caused by ground subsidence or heave movement in low-rise residential properties is a highly subjective issue.**
>
> The object of investigating this threshold of damage has been to establish in which circumstances it is appropriate to further investigate a suspected case of subsidence as opposed to where it is appropriate to repair any damage as part of a program of routine building maintenance. The fact that Research Aim One has been unable to establish any threshold of visible damage because of the highly subjective issue of damage perception can in itself be seen to represent a contribution to knowledge.
>
> In both Chapter Four and Chapter Five it has been shown, from the case study analysis, that the evaluation of visible damage cannot be used as a reliable method to establish the

form of remedial action required. This demonstrates the limitations of using an assessment of visible damage for any purpose other than assessing the actual building work necessary to repair superstructure damage. For example, it has been shown that properties displaying evidence of minor aesthetic damage have been found to require extensive substructure repairs. Conversely, properties with damage classified to represent extensive serviceability damage have been found to require only superstructure repairs. Therefore, the limitation of employing an assessment of visible damage is clearly evident.

The evaluation of visible damage is further complicated by the fact that the manifestation of damage will occur at different rates and in different ways, depending on the unique nature of an individual building. This fact can also be seen to limit the practical use of existing classifications of visible damage, such as that published by BRE in Digest 251 (1993 edition).

The main conclusion emerging from the investigation of Research Aim One is that an assessment of visible damage caused by subsidence or heave movement provides only an indication of the remedial superstructure repairs required at the time of assessment. It is not possible to draw any conclusions with regard to whether or not a property requires remedial substructure repairs from an assessment of visible damage.

RESEARCH AIM TWO

Thresholds of damage that can be used to identify the need for substructure repairs

In relation to Research Aim Two, from the case study analysis, a threshold of damage has emerged that can be used to identify the need for substructure repairs in low-rise residential properties damaged by ground subsidence or heave movement. This threshold has been identified to be the distinction between foundation movement and foundation damage.

All buildings manifesting damage as a result of ground subsidence or heave movement are influenced by some degree of foundation movement. This movement is transmitted from the foundations of the building to its superstructure, where it is accommodated as visible damage. This usually, but not necessarily, takes the form of cracking. Where the foundation movement has ceased and the foundations remain able to adequately perform their function, if this does not represent a threat to the structural integrity of the property, this can be classified as **foundation movement.** However, if the foundation movement is found to be ongoing, or if the movement has rendered the foundations unable to adequately perform their function, this can be considered as **foundation damage**.

For properties damaged by *shallow* subsidence, in order to distinguish between foundation movement and foundation damage, this research has shown that it is necessary to establish whether or not movement is '*long-term progressive*'. This must be established through a process of monitoring the building over a period of time. In properties damaged by *deep* coal-mining subsidence, the contemporaneous nature of mining subsidence makes it reasonably straightforward to distinguish between foundation movement and foundation damage through the process of a 'post-damage' site investigation.

The relationship between long-term foundation movement and the requirement to carry out substructure repairs might appear to be an obvious conclusion. However, this conclusion is intended to be implemented primarily by insurance companies and other parties seeking to address the non-technical issues relating to subsidence damage. It is **not** intended as a "rule" that can replace a detailed investigation of technical issues that establish **why** damage occurred. The significant contribution to knowledge that this finding makes is that through the case study analysis, no other robust relationships have emerged. This can therefore be seen to support the conclusion that establishing whether or not subsidence or heave movement in a property is '*long-term progressive*' is the only objective method to establish whether or not remedial substructure repairs should be carried out. This finding has important considerations for addressing the non-technical issues which cause many of the contemporary problems associated with subsidence and heave damage. The implementation of this knowledge in practice has formed the focus of Research Aim Three.

RESEARCH AIM THREE

Implementing thresholds of damage to address the non-technical problems relating to subsidence and heave damage in low-rise residential properties

In relation to Research Aim One no thresholds of visible damage have been found to emerge. However, a threshold of damage has been found to emerge in relation to Research Aim Two which has been outlined above. Therefore, Research Aim Three has sought to consider how the introduction of this threshold of damage might impact upon the non-technical aspects of subsidence damage. This has been investigated in relation to properties damaged by *shallow* subsidence through considering data which applied to approximately 55% of the United Kingdom domestic buildings' insurance market.

In relation to Research Aim Three, it has been established that a threshold of damage based on establishing whether or not movement is found '*long-term progressive*' can be used to address non-technical aspects of subsidence.

The threshold of damage which was established through the investigation of Research Aim Two has been found to have been applied in practice by two of the three insurance companies considered in this research. However, this threshold of damage is not expressly stated in an insurance policy, but has instead been applied through a claims administration system. This system has been implemented through express instructions provided to the technical experts (chartered engineers) who administer claims on the insurance companies' behalf. Although the expert is employed and paid by the insurance company, their remit is to act objectively to investigate and establish the precise cause of damage, rather than acting in the perceived best interests of any individual party to a claim.

In applying the above system of claims administration, some of the essential non-technical aspects of subsidence or heave damage have been addressed. Firstly, a Certificate of Structural Adequacy is provided for all properties which have been subject to a claim for subsidence or heave damage and is available regardless of whether or not the property has required substructure repairs. This certificate is backed by the insurers and provides evidence that the property is structurally sound, which in theory should help to maintain the full market value and saleability of the property. In addition, it has been established that within the scope of the data examined, continuity of insurance cover is offered to new purchasers of a property, even if the building has a past record of subsidence or heave related problems.

This research has established the impact of the introduction of the system of claims administration which has a threshold of damage similar to that established in Research Aim Two as one of its principal features. The proportion of claims requiring remedial underpinning has been substantially reduced to between 5% to 10% of all subsidence and heave claims. Implementing this system of claims administration procedure has proved costly. Each potential claim is investigated by an expert, usually a chartered engineer or loss adjuster. These investigations are paid for by the insurance company, who bear the costs even where subsidence or heave is not found to be the cause of damage. However, over the long-term it has been found that the costs of employing a single expert who is considered to be independent and objective has replaced and subsequently improved the previous system. This previous system involved each party to an insurance claim employing their own experts who sought to prove their own entrenched and often widely divergent opinions.

8.4: RE-ENGAGEMENT WITH THE CONTEMPORARY DEBATE

This research would appear to be reaching its conclusion at an important time. Considering the number and value of insurance claims for subsidence and heave damage (figure 3.2), it can be seen that immediately following the 'peak' years of the early 1990s, a downward trend emerged. However, during 1995 and 1996 this trend has started to reverse. Unless measures such as imposing thresholds of damage are implemented, insurance companies might once again face losses on scale to that experienced in the early 1990s. In addition, property owners face the continued uncertainty created by the non-technical aspects of subsidence damage, especially in a buoyant property market.

Shabha and Kuhwald (1995) explained that the insurance industry is highly competitive and that major losses incurred through subsidence could contribute to some insurers being forced out of business. Indeed, during the last three years, several major *traditional* insurance companies have merged to streamline operations and reduce operating costs. Although this research has not investigated whether or not subsidence losses have contributed to these mergers, it is clearly an area that insurance companies would wish to 'keep under control'. Implementing thresholds of damage and therefore attempting to address the non-technical problems of subsidence damage would provide an opportunity to achieve this.

During the course of this research, the major insurance companies have implemented a formal agreement relating to the switching of insurance companies by a property owner and this has helped to reduce some of the non-technical problems in relation to continuity of insurance cover. This agreement between insurers states that the original insurer must meet a claim in full if it is within the first eight weeks of change. A claim made after 12 months of changing insurer must be met in full by the new company and for the period following the first eight weeks, but within the first year, the claim should be divided equally. This agreement does demonstrate that insurers can work together to address some of the contemporary subsidence problems.

This research has highlighted the need to establish if building movement is '*long-term progressive*' when deciding whether or not to carry out substructure repairs. Anumba and Scott (1997) conducted a survey into the current trends in the engineering management of subsidence cases through a questionnaire survey sent to consultants and building contractors. It was shown that 91% of consultants address the possibility of progressive movement in all their cases. However, only 13% of these consultants would always monitor a property. Their findings also highlighted the disparity between the extent of investigations carried out when investigating damage, which helps to confirm the need for some form of guidance in relation to a 'post-damage' site investigation. Anumba (1996) also highlighted the difficulties of investigating buildings subject to subsidence damage and discussed the difficulties that can lead to erroneous diagnoses.

This research has clearly identified the need to monitor a property to establish whether or not movement causing damage is '*long-term progressive*'. Robson (1991) identified that where monitoring is used, there may be a temptation to assume that other investigations into the cause of damage can afford to be less rigorous. However, it has been found in this research that monitoring is used to compliment a thorough 'post-damage' site investigation. Numerous case studies in this research have established that monitoring was simultaneously used as a tool to establish whether or not movement was '*long-term progressive*' and to identify the cause of damage. Common examples are where a tree is removed, or a drain repaired, and the property monitored to see if movement continues. This must be an essential element of all investigations, as the priority in any case of subsidence or heave damage must be to address the cause of damage rather than react to the symptoms. It is also significant that this research has found that insurance companies specify a maximum period of time over which monitoring must be carried out. This directly addresses the common criticism that monitoring is used as a 'delaying tactic' by insurers to avoid payment for a claim.

One final point to address in relation to monitoring is that the expense involved in monitoring a property has been suggested as one reason why this technique is not used more frequently (Hunt *et. al.* 1991). However, over the long-term, it is essential that a correct diagnosis of the cause of damage is made. An incorrect diagnosis of damage is likely to result in significantly more expense than a period of monitoring.

Page (1998) suggested that if climatologists are right about global warming, then subsidence damage has become an endemic hazard of home ownership. It is suggested that insurance companies could have a key role to play in educating property owners about the perils of subsidence and hence encourage them to be vigilant for early signs of damage that can be arrested. However, Page (1998) also highlighted that property owners can be ignorant to such factors as trees being allowed to grow too close to a property. Consequently, it seems likely that subsidence claims are going to be a major source of claims payment by insurers, a fact substantiated by reference to figure 3.2. If this assertion is correct, then it is necessary for all insurance companies to embrace the threshold of damage established in this research through the investigation of Research Aim Two (see recommendations for implementation below).

8.5: FURTHER WORK

Following the execution of this research a number of areas where further work could be directed have become apparent.

8.5.1: Recommendations For Implementation

To fully address the non-technical problems created by subsidence damage, it would be necessary for all insurance companies who operate in the domestic buildings' insurance market to apply similar thresholds of damage. As no thresholds of visible damage have been found to emerge in this research, it could be suggested that it is up to insurance companies to consider imposing a threshold of damage (this issue is discussed below in section 8.5.3). However, it is necessary to recognise the highly subjective nature of evaluating visible damage.

The threshold of damage which has emerged through the investigation of Research Aim Two could also be applied in practice by all major insurance companies. Unless an insurance company and a property owner are in agreement about whether or not to carry out remedial substructure repairs, then the building should be monitored to establish if the movement is '*long-term progressive*'. This might create potential problems about the expense involved in monitoring a building. However, it has been pointed out above that the costs associated with an incorrect diagnosis of the problem far outweigh the costs of monitoring. In addition, the findings that have emerged in Chapter Seven have shown that if insurers are prepared to adopt a system of claims administration that focuses on objectively assessing the cause of building damage and support this assessment with a Certificate of Structural Adequacy, in the long-term, this will benefit all parties to a claim. This leads to the recommendation that all insurance companies should offer both continuity of insurance cover and a Certificate of Structural Adequacy on all properties affected by subsidence or heave movement. These measures would provide a measure of confidence to help eliminate the non-technical problems of subsidence faced by both existing homeowners and all parties involved in the buying, selling and insuring of low-rise residential properties.

Insurance companies have no legal or formal obligations to provide subsidence and heave indemnity. This is undertaken for commercial reasons. If individual insurance companies are to remain competitive in this area, it is essential that they maximise their efficiency. Through adopting the principles that have been established in the investigation of Research Aim Two, this demonstrates how subsidence and heave claims can be efficiently dealt with. At the same time, it is important in a competitive market place that insurers are sympathetic to the needs of their policyholders. In this respect it is essential that any subsidence or heave claim has a minimal effect on the value and saleability of a property. It has been shown that this important aspect can be addressed through the issue of a Certificate of Structural Adequacy and through offering continuity of insurance cover. Although the evidence from this research has highlighted that some individual insurance companies have employed parts of the above practice, this information would need to be fully adopted by all parties involved in the buying, selling and insuring of properties if it is to have a maximum impact.

Whilst the subject of subsidence and heave damage to low-rise residential properties is a subject of primary importance to insurance companies and property owners, it also forms an important aspect of the professional lives of other parties. These are principally engineers, surveyors and loss adjusters. It is important that these professions remain informed of developments in this subject area.

8.5.2: Limitations Of The Study

Perhaps the major limitation and constraint imposed upon this research has been the confidentiality of the data required to execute the research. Agencies which are in possession of appropriate data for this research have a primary obligation of confidentiality to their client, the property owner. This relationship has been fully respected throughout this research. In order to achieve this, it was necessary to delete references to any individual names or addresses of individual case study properties. More significantly, several agencies have not responded to requests to allow access to data. These have included:

Engineering practices

Although several engineering practices have supplied the case study data used in Chapter Four, not all engineers contacted were willing to allow access to this sort of data. The criteria used to collect case study data has been discussed in the relevant chapters. However, a number of visits were arranged at engineering practices where access to collect any specific data relating to individual properties was subsequently not permitted and hence the visit proved ‘un-fruitful’.

Loss adjusters

An attempt to collect data from loss adjusters proved to be unsuccessful. Individual loss adjusting practices were contacted through letters followed up by telephone conversations. However, it was suggested from the replies received that engineers, rather than loss adjusters would hold the kind of data required to execute the research. Loss adjusters tended to handle the insurance aspects of subsidence cases, rather than considering in detail the technical, engineering and surveying aspects.

The National House Building Council (NHBC)

The NHBC provide a ten year warranty for the majority of all new houses built in Great Britain. Problems created by subsidence or heave damage usually occur at least several years after a property is built as the property matures and trees develop or drainage pipes bed down. However, where subsidence or heave damage occurs within the ten year NHBC warranty, this organisation is usually the agency that property owners contact for repairs or compensation.

NHBC was contacted, but were unwilling to supply any specific information relating to individual cases of properties damaged by ground subsidence or heave.

Insurance Companies

It has been discussed in Chapter Seven, that in general, insurance companies were unwilling to make any data available in relation to subsidence or heave damage to domestic buildings because of the commercially sensitive nature of this information.

Building Contractors

Visits were arranged at several building contractors who specialised in subsidence repair works. Contractors were found to place least emphasis on confidentiality of their work probably because the information required for the research related to technical matters rather than the financial or the business side of their operations. However, the information that these organisations held usually related only to details of the repair works rather than the investigative works and was not suitable for this research.

After identifying the available sources of information, and collecting the data required to execute this research, it is possible to reflect on this data. The Chapters of this thesis which have presented the results and analysis of the data collected in this research have considered a reflection on the data employed and highlighted any limitations in each relevant chapter.

In relation to the methodology employed to collect case study data of individual properties, with the benefit of hindsight, collecting data through direct access can be seen to be supported over the alternative methodology considered, which involved collecting data through the use of a questionnaire. The principal reasons for this are that the complex nature and individual interpretation of each individual case study property would limit the validity of data collected through the use of a questionnaire. Collecting data through direct access has allowed a consistent approach and interpretation to data collection being applied. The principal limitation has been the smaller sample of data collected through direct access.

8.5.3: Recommendations For Further Research

Given the knowledge gained through the execution of this research, the following areas for further research can be suggested:

Establishing A Threshold Of Visible Damage

It is clear from this research that the evaluation of visible damage caused by ground subsidence or heave is a highly subjective issue which will depend on a large number of mainly un-quantifiable variables. No threshold of visible damage has been found to exist. Such a threshold of visible damage would differentiate between damage which could be considered to be part of routine building maintenance, and damage which necessitates a full 'post-damage' site investigation.

To establish a suitable threshold of damage, it would be necessary to consult widely with representatives of all parties involved in the buying, selling and insuring of residential properties. The exact form that any such threshold would take would require careful consideration. It would need to take into account both the extent and severity of damage and should not necessarily be based on any category of damage suggested in BRE Digest 251 (1993 edition), which would seem to place greater emphasis on severity rather than the amount of damage.

Establish A Uniform Procedure For A 'Post-Damage' Site Investigation

It has been established from the case study analysis that there exists no uniform set of 'post-damage' site investigation procedures that are applied to properties damaged by ground subsidence or heave movement. The level of detail in the investigations analysed in this research has been found to vary enormously. A standard procedure, which attempts to strike a sensible balance between the cost of investigations and level of detail required could prove very useful and ensure that cases of subsidence and heave would be assessed on a more consistent basis.

Establish Monitoring Criteria

One of the major conclusions emerging from this research is that in cases of doubt, to establish whether or not a property requires substructure repairs, it is necessary to monitor the property to establish if movement is '*long-term progressive*'. However, the data available to execute this research has not enabled the following important points to be addressed (the research has relied on the judgement of a professionally qualified chartered structural or civil engineer):

- What form should monitoring take, for example, crack monitoring, precise levelling, repair and observation, or a combination of methods?
- Over what time period should monitoring be undertaken?
- As all buildings will inevitably move to some extent, it is necessary to establish a threshold of movement to clearly establish what constitutes '*long-term progressive*' movement.

These points are particularly pertinent as one of the criticisms of monitoring subsidence damage is that it prolongs the duration of the study and hence delays payments.

8.6: CHAPTER SUMMARY

The research has examined a number of different areas relating to subsidence damage in low-rise residential properties through the investigation of three main aims. This chapter has presented the overall conclusions that can be drawn from the execution of the research and has discussed areas where future work might be directed.

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APPENDIX A

SOURCES OF DATA COLLECTION AND CONFERENCE ATTENDANCE

SOURCES OF DATA COLLECTION

The following organisations/individuals have furnished the information that has contributed to this research:

Civil/Structural Engineering Practices:

- Brian Clancy Partnership, Altrincham, Manchester.
- Cameron Taylor Bedford, Solihull, West Midlands.
- Contest Melbourne Weeks, Maidstone, Kent.
- Engineering Partnership, Leicester.
- ESI Glanville, St. Albans, Herts.
- R C J Page, The Nottingham Trent University.
- Pick Everard, Leicester.
- John Pryke and Partners, London.
- Smithers Purslow, Oakham, Leicestershire.

Coal Mining Subsidence:

- The Coal Authority, Mansfield, Nottinghamshire.

Insurance Companies:

- Commercial General Union.
- Direct Line Insurance.
- Royal and Sun Alliance Insurance (This company was formed following the merger between Royal Insurance and Sun Alliance Insurance, 1997).

Building/Underpinning Contractors:

- Roger Bullivant Ltd., Burton-upon-Trent, Derbyshire.
- McCane Construction Ltd., Nottingham.

CONFERENCE/COURSE ATTENDANCE

Structural Surveys Of Buildings:

Institution of Structural Engineers, Coventry Hotel, Coventry, 1st March 1994.

Subsidence:

Architects and Surveyors Institute, London, 15th March 1994.

Building on Difficult Sites:

Association of Building Engineers, Royal Moat House Hotel, Nottingham, 25th May 1994.

Subsidence of Domestic Property:

Institution of Structural Engineers, London, 15th February 1995.

Seminar on Subsidence:

Institution of Structural Engineers, London, 25th April 1995.

Building Pathology Conference 95:

Hutton and Rostron, Trinity College, Oxford University, 18th - 20th September 1995.

Construction Industry Insurance:

Chartered Institute of Building (CIOB) DMX Course Presentation, The Robert Gordon University, 19th May 1998.

APPENDIX B

DEFINITION OF TERMS USED IN THE ANALYSIS OF CASE STUDIES IN CHAPTER FOUR

DEFINITION OF TERMS USED IN THE ANALYSIS OF CASE STUDIES IN CHAPTER FOUR

B.1: PROPERTIES OF CLAY SUBSOIL

In this research, shrinkable clay soil has been classified according to the classification presented by NHBC (1996). This classification has been adopted to reflect its predominance found in the case studies analysed in Chapter Four. NHBC (1996) defined shrinkable clay soil as those containing more than 35% fine particles (clay and silt) and having a plasticity index of more than 10%. The properties of clay soils, including a definition of plasticity index, have been fully discussed in Chapter Two, section 2.3.1. NHBC (1996) related the shrinkage potential of clay soil to plasticity index as defined in table A.1 below:

Plasticity Index	**Shrinkage Potential**
Greater than 40%	High
20% - 40%	Medium
10% - 20%	Low

Table A.1: Classification of clay soil according to NHBC (1996)

B.2: PRESENCE OF TREE ROOTS

When investigating the cause of damage, it is usual practice to excavate trial pits around the property. The records of trial pits were available in the case study details and from these records it was possible to establish whether or not tree roots were identified in the trial pit within the immediate vicinity of the foundations of the building. In the case study analysis, no attempt was made to be more precise about the influence that the tree had on the property by considering such facts as the tree age, tree type or distance between tree and building. There were two reasons for this as detailed below:

1. It has been shown in Chapter Two (section 2.3.8) that the subject of proximity of trees and low-rise buildings is a much debated and contentious issue and no definitive guidelines on this subject exist.
2. Although some case studies provided information that identified the species of tree root(s) found, this was not common for all case studies involving trees. Even where the tree roots had been identified, several case studies involved the scenario where two or more species of tree roots were found. In such cases it was impossible to apportion blame.

The information available in the case studies which involved tree roots as a cause of damage rarely attempted to identify the age of a tree in relation to the age of the building under consideration.

B.3: SHALLOW FOUNDATIONS

Relevant literature considered in Chapter Two has established that foundations placed at too shallow a depth below ground level are susceptible to movement caused by seasonal variations in rainfall and solarisation. From the records of trial pit investigations found in case studies it has been possible to establish the physical depth of the foundations of a building below ground level. A foundation depth of less than 0.85 metres below ground level was recorded to constitute a '*shallow foundation*'. This depth was assumed to take into account rounding errors as a depth of 0.85 metres might be rounded up to 0.9 metres which is commonly assumed as the minimum foundation depth (see Chapter Two, section 2.3.7).

Only the depth of the foundations below ground level in the vicinity of the visible damage has been considered. For example, consider a property where visible damage was identified in the front of a property, but a rear extension to the property was found to be totally free from any signs of visible damage. If the front part of the property was found to have a foundation depth of 1.2 metres below ground level, even where the rear extension was found to have a foundation depth of 0.45 metres below ground, this scenario would not be recorded to have shallow foundations.

B.4: DESICCATION OF CLAY SUBSOIL

The definition and method of establishing subsoil '*desiccation*' proposed by Driscoll (1983) has invariably been found to be used in the case studies analysed in this research (see Chapter Two, section 2.3.13). This method of establishing whether or not a soil is desiccated relates the moisture content of a clay soil to the its liquid limit (L.L.). The onset of desiccation can be assumed to occur where soil moisture content < 0.5 L.L.

B.5: DEFECTIVE DRAINS

In the investigations into the cause of damage it was possible to establish whether any defects in the drainage system were identified. In the case studies analysed, this information was established through a closed circuit television (CCTV) investigation, pressure test, or a visual inspection.

When considering the effects of a defective drain in relation to a building, it is imperative to establish whether the defective drain is a cause or a consequence of any ground movement resulting in damage. For example, if the drainage system of a property is located at a shallow depth (say less than 450mm) below ground level, because of the effects of any seasonal movement at such a shallow depth, the drainage system could be susceptible to movement and as a consequence moisture leakage may occur. If any leakage from the drainage system adversely effects the properties of the subsoil supporting the foundations of a building in the vicinity, then leaking drains can be classified as the primary cause of ground movement. However, if the foundations of the building were also at a shallow depth and would have been subjected to any movement regardless of the leaking drain, the leaking drain can be classified as an effect of ground movement, rather than a cause.

In the case study properties analysed, it has been clear to identify whether a leaking drain was a cause or an effect of ground movement causing damage in a property. In relation to subsidence or heave damage indemnified against under a domestic buildings' insurance policy, this has very important consequences. Some insurance companies stipulate a much reduced policy excess where leaking drains are established as the cause of ground movement.

APPENDIX C

PRIMARY RAW DATA USED FOR ANALYSIS IN CHAPTER FOUR

Case No.	visible damage				cause of damage																								progressive movement				medial act
	acs.	scr.	str.	no class.	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4	3.1	3.2	3.3	3.4	4.1	4.2	4.3	4.4	5.1	5.2	5.3	5.4	6	7	8	9	no	seasonal	yes	not known	
1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3
2	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3
3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	2
4	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	3
5	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
6	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
7	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	3
8	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3
9	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3
10	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	3
11	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1
12	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	2
13	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1
14	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	2
15	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1
16	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	3
17	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	2
18	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	3
19	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	2
20	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3
21	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
22	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2
23	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1
24	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	3
25	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3
26	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	3
27	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3
28	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3
29	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
30	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
31	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	4
32	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3
33	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	2
34	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3
35	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	3
36	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1
37	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	2
38	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	2
39	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	3
40	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1
41	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	2
42	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1
43	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	2
44	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	3
45	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	3
46	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	3
47	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
48	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	3
49	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	3
50	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	3
51	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3
52	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	3
53	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	3
54	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	3
55	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	2
56	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	3
57	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1
58	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	2
59	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1
60	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	2
61	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	3
62	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3
63	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
64	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
65	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	4
66	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
67	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
68	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	3
69	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
70	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
71	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2

72	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
73	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
74	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
75	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2
76	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	2
77	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
78	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	2
79	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	4
80	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	3
81	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	3
82	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	2
83	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	3
84	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	3
85	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4
86	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4
87	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	4
88	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	4
89	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4
90	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4
91	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	2
92	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	3
93	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4
94	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2
95	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	2
96	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	2
97	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2
98	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	3
99	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	2
100	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	4
101	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
102	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
103	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
104	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
105	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
106	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
107	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	2
108	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	2
109	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1
110	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	4
111	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	2
112	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	2
113	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1
114	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	2
115	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
116	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
117	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	2
118	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	2
119	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	1
120	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	2
121	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	2
122	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	2
123	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	2
124	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
125	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
126	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
127	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	1
Total	79	34	3	11	17	6	0	4	6	3	3	4	13	4	2	1	2	0	1	4	0	1	2	0	31	4	4	15	60	4	23	40	
				127																								127				127	

APPENDIX D

CROSSTABULATION AND CHI-SQUARE ANALYSIS

D1: INTRODUCTION

The objective of the cross-tabulation and chi-squared analysis contained in this Appendix is to investigate – through the case study data contained within Chapter Four - any association between the factor *Remedial Action* with any of the factors *Visible Damage*, *Cause of Damage* and *Movement*.

D2: Association Between *Visible Damage* And *Remedial Action*

Table D1 shows the results obtained by cross-tabulating sub-categories of the factor *Visible Damage* with the sub-categories of the factor *Remedial Action*.

	REMEDIAL ACTION GROUP (REM ACT)				
Visible Damage (VIS DAM)	**A**	**B**	**C**	**D**	**TOTAL**
'Aesthetic'	13	48	18	0	**79**
'Serviceability'	1	13	18	2	**34**
'Stability'	0	0	1	2	**3**
'Not applicable'	0	1	2	8	**11**
TOTAL	**14**	**62**	**39**	**12**	**127**

Table D1: Classification of case study properties by the factors *visible damage* and *remedial action*.

To investigate the information contained within table D1, a cross-tabulation and chi-squared test has been applied using SPSS. To enter the data contained in table D1 in a format to enable analysis in SPSS, a simple code has been applied as outlined below[1]:

Visible Damage (VIS_DAM)	*Remedial Action* (REM_ACT)
'*Aesthetic damage*' = 1	'*Remedial Action Group A*' = 1
'*Serviceability damage*' = 2	'*Remedial Action Group B*' = 2
'*Stability damage*' = 3	'*Remedial Action Group C*' = 3
'*Damage not applicable*' = 4	'*Remedial Action Group D*' = 4

The results of the analysis are presented on the following page in the **Crosstabs** output from SPSS.

---

[1] Please note that the code applied is arbitrary to enable data manipulation in SPSS. This code is not related in any way to the ranking and scaling of data applied in Chapter Four.

Crosstabs

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
VIS_DAM * REM_ACT	127	100.0%	0	.0%	127	100.0%

VIS_DAM * REM_ACT Crosstabulation

			REM_ACT				Total
			1.00	2.00	3.00	4.00	
VIS_DAM	1.00	Count	13	48	18	0	79
		Expected Count	8.7	38.6	24.3	7.5	79.0
		% within VIS_DAM	16.5%	60.8%	22.8%	.0%	100.0%
	2.00	Count	1	13	18	2	34
		Expected Count	3.7	16.6	10.4	3.2	34.0
		% within VIS_DAM	2.9%	38.2%	52.9%	5.9%	100.0%
	3.00	Count	0	0	1	2	3
		Expected Count	.3	1.5	.9	.3	3.0
		% within VIS_DAM	.0%	.0%	33.3%	66.7%	100.0%
	4.00	Count	0	1	2	8	11
		Expected Count	1.2	5.4	3.4	1.0	11.0
		% within VIS_DAM	.0%	9.1%	18.2%	72.7%	100.0%
Total		Count	14	62	39	12	127
		Expected Count	14.0	62.0	39.0	12.0	127.0
		% within VIS_DAM	11.0%	48.8%	30.7%	9.4%	100.0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	86.370[a]	9	.000
Likelihood Ratio	64.567	9	.000
Linear-by-Linear Association	48.115	1	.000
N of Valid Cases	127		

a. 9 cells (56.3%) have expected count less than 5. The minimum expected count is .28.

```
>Warning # 3211
>On at least one case, the value of the weight variable was zero, negative,
>or missing.  Such cases are invisible to statistical procedures and graphs
>which need positively weighted cases, but remain on the file and are
>processed by non-statistical facilities such as LIST and SAVE.


>
```

The results presented on the previous page indicate evidence of a statistical association between visible damage and remedial action. The chi-square value of 86.370 indicates that this association is significant at the 0.1% level. The crosstabulation matrix provides some indication of the nature of this association – with a high proportion of properties classified to have '*aesthetic damage*' requiring '*remedial action group B*' (it can be noted that this cell also indicates the greatest difference between observed and expect count). Evidence of other associations between sub-categories can also be seen in the crosstabulation matrix, but it will be noted that these relate to cells which have low observed counts. This will limit the validity of drawing any conclusions from such information.

In applying the chi-square test it is necessary to check that the prescribed minimum requirements for the valid use of chi-square have been fulfilled. The valid use of chi-square **may** be limited where any of the expected frequencies are less than 1 or more than 20% of cells have expected counts less than 5. The results indicate that the minimum expected frequency is 0.28 and there are 9 cells out of 16 (56.3%) with expected counts of less than 5. Therefore any association must be treated with caution.

To overcome the stricture about small cells it is possible to collapse the 4 x 4 contingency table analysed above into a 2 x 2 contingency table. The rationale underlying this is that the four remedial action groups identified can be sensibly collapsed into two. By combining '*remedial action groups A and B*' and '*remedial action groups C and D*', this distinguishes properties which require above ground super-structure repairs from properties which require below ground sub-structure repairs. In effect this is the threshold of damage being investigated in Research Aim Two. To further overcome the stricture about small cells, the four sub-categories within the factor *visible damage* can also be collapsed into two. First, it is not appropriate to include the 11 properties where visible damage has been classified as '*non-applicable*'. Secondly, as there are only three properties classified to have '*stability damage*' – the effect of removing these from the analysis will be minimal. The result of the above is a 2 x 2 contingency table as presented below.

	REMEDIAL ACTION GROUP (REM_ACT)		
Visible Damage (VIS_DAM)	A + B	C + D	**TOTAL**
'*Aesthetic*'	61	18	79
'*Serviceability*'	14	20	34
TOTAL	**75**	**38**	**113**

Table D2: **Collapsed classification of case study properties by the factors *visible damage* and *remedial action*.**

The information contained within table D2 is evaluated through cross-tabulation and a chi-square test applied in SPSS. The codes applied to enable data manipulation are:

Visible Damage (VIS_DAM)	*Remedial Action* (REM_ACT)
'*Aesthetic damage*' = 1	'*Remedial Action Groups A + B*' = 1
'*Serviceability damage*' = 2	'*Remedial Action Groups C + D*' = 2

The results of the analysis are presented below in the **Crosstabs** output on the following page.

Crosstabs

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
VIS_DAM * REM_ACT	113	100.0%	0	.0%	113	100.0%

VIS_DAM * REM_ACT Crosstabulation

			REM_ACT		Total
			1.00	2.00	
VIS_DAM	1.00	Count	61	18	79
		Expected Count	52.4	26.6	79.0
		% within VIS_DAM	77.2%	22.8%	100.0%
	2.00	Count	14	20	34
		Expected Count	22.6	11.4	34.0
		% within VIS_DAM	41.2%	58.8%	100.0%
Total		Count	75	38	113
		Expected Count	75.0	38.0	113.0
		% within VIS_DAM	66.4%	33.6%	100.0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	13.832[b]	1	.000		
Continuity Correction[a]	12.264	1	.000		
Likelihood Ratio	13.447	1	.000		
Fisher's Exact Test				.000	.000
Linear-by-Linear Association	13.709	1	.000		
N of Valid Cases	113				

a. Computed only for a 2x2 table

b. 0 cells (.0%) have expected count less than 5. The minimum expected count is 11.43.

Considering the results of the above analysis of the 2 x 2 contingency table, there is clear evidence of a statistical association between the factors visible damage and remedial action. The evidence is provided through the chi-square test of association. This indicates that a chi-square value of 13.832 is significant at the 0.1% level. The cross-tabulation analysis provides an indication of the nature of this association. In particular, it is clear that properties classified to have '*aesthetic damage*' are likely to require '*remedial action group A or B*'. Evidence for this is provided from the fact that 77.2% of properties classified to have '*aesthetic damage*' have been found to require '*remedial action group A or B*'. Where properties are classified to have serviceability damage, the required remedial action is more difficult to predict, with 41.2% of cases found to require '*remedial action group A or B*' while 58.8% were found to require '*remedial action group C or D*'.

D3: Association Between *Cause of Damage* And *Remedial Action*

Table D3 shows the results obtained by cross-tabulating sub-categories of the factor *Cause of Damage* with the sub-categories of the factor *Remedial Action*.

	REMEDIAL ACTION GROUP (REM ACT)				
Cause Of Damage (CAUSE)	A	B	C	D	TOTAL
(1) *'Clay subsoil, tree roots, shallow foundations, subsoil desiccation'*	0	13	12	2	**27**
(2) *'Clay subsoil, tree roots, shallow foundations'*	0	10	6	0	**16**
(3) *'Clay subsoil, tree roots, subsoil desiccation'*	1	7	6	6	**20**
(4) *'Clay subsoil, tree roots'*	0	5	0	2	**7**
(5) *'Clay subsoil, shallow foundations'*	2	1	0	0	**3**
(6) *'Defective drains'*	0	17	13	1	**31**
(7) *'Presence of tree roots, subsoil type unknown'*	0	3	1	0	**4**
(8) *'Shallow foundations'*	2	1	0	1	**4**
(9) '*No details available*'	9	5	1	0	**15**
TOTAL	**14**	**62**	**39**	**12**	**127**

Table D3: Classification of case study properties by the factors *cause of damage* and *remedial action*.

To investigate the information contained within table D3, a cross-tabulation and chi-square test has again been applied using SPSS. Before applying the chi-squared test, the structure of the data contained within table D3 can be modified to reduce the incidence of low cell counts. As in the previous analysis, '*remedial action groups A and B*' and '*remedial action groups C and*

D' are combined. In addition, the 15 case studies where no details of the cause of damage are known can be removed. After applying this criteria, this provides eight causes of damage and two forms of remedial action. This results in an 8 x 2 contingency table which has been analysed in SPSS – the results of which are presented below.

Crosstabs

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
CAUSE * REM_ACT	112	100.0%	0	.0%	112	100.0%

CAUSE * REM_ACT Crosstabulation

			REM_ACT		
			1.00	2.00	Total
CAUSE	1.00	Count	13	14	27
		Expected Count	14.9	12.1	27.0
		% within CAUSE	48.1%	51.9%	100.0%
	2.00	Count	10	6	16
		Expected Count	8.9	7.1	16.0
		% within CAUSE	62.5%	37.5%	100.0%
	3.00	Count	8	12	20
		Expected Count	11.1	8.9	20.0
		% within CAUSE	40.0%	60.0%	100.0%
	4.00	Count	5	2	7
		Expected Count	3.9	3.1	7.0
		% within CAUSE	71.4%	28.6%	100.0%
	5.00	Count	3	0	3
		Expected Count	1.7	1.3	3.0
		% within CAUSE	100.0%	.0%	100.0%
	6.00	Count	17	14	31
		Expected Count	17.2	13.8	31.0
		% within CAUSE	54.8%	45.2%	100.0%
	7.00	Count	3	1	4
		Expected Count	2.2	1.8	4.0
		% within CAUSE	75.0%	25.0%	100.0%
	8.00	Count	3	1	4
		Expected Count	2.2	1.8	4.0
		% within CAUSE	75.0%	25.0%	100.0%
Total		Count	62	50	112
		Expected Count	62.0	50.0	112.0
		% within CAUSE	55.4%	44.6%	100.0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	7.210[a]	7	.407
Likelihood Ratio	8.436	7	.296
Linear-by-Linear Association	1.283	1	.257
N of Valid Cases	112		

a. 8 cells (50.0%) have expected count less than 5. The minimum expected count is 1.34.

```
>Warning # 3211
>On at least one case, the value of the weight variable was zero, negative,
>or missing.  Such cases are invisible to statistical procedures and graphs
>which need positively weighted cases, but remain on the file and are
>processed by non-statistical facilities such as LIST and SAVE.
```

The results of the above analysis of the 8 x 2 contingency table indicate very limited evidence that there is any association between cause of damage and remedial action. The chi-square value of 7.210 is only significant at a level of over 40%. Furthermore, the crosstabulation matrix provides no evidence that any of the 8 causes of damage identified (other than cause of damage 5) can be reliably associated with any form of remedial action. Cause of damage 5 relates to only five cases of damage and hence any conclusions drawn from this need to be treated with caution.

D4: Association Between *Movement* And *Remedial Action*

Table D4 shows the results obtained by cross-tabulating sub-categories of the factor *Movement* with the sub-categories of the factor *Remedial Action*.

	REMEDIAL ACTION GROUP (REM_ACT)				
Movement (MVT)	**A**	**B**	**C**	**D**	**TOTAL**
'Movement Long-term Progressive'	0	0	19	4	**23**
'Seasonal Movement'	0	0	4	0	**4**
'Movement Non-Progressive'	12	48	0	0	**60**
'Not Known'	2	14	16	8	**40**
TOTAL	**14**	**62**	**39**	**12**	**127**

Table D4: Classification of case study properties by the factors *progressive movement* and *remedial action*.

To investigate the information contained within table D4, a cross-tabulation and chi-squared test has been applied using SPSS. To enter the data contained in table D4 in a format to enable analysis in SPSS, a simple code has been applied as outlined below:

Movement (MVT)	*Remedial Action* (REM_ACT)
'*Movement long-term progressive*' = 1	'*Remedial Action Group A*' = 1
'*Seasonal movement*' = 2	'*Remedial Action Group B*' = 2
'*Movement non-progressive*' = 3	'*Remedial Action Group C*' = 3
'*Not known*' = 4	'*Remedial Action Group D*' = 4

The results of the analysis are presented on the following page in the **Crosstabs** output from SPSS.

Crosstabs

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
MVT * REM_ACT	127	100.0%	0	.0%	127	100.0%

MVT * REM_ACT Crosstabulation

			REM_ACT				Total
			1.00	2.00	3.00	4.00	
MVT	1.00	Count	0	0	19	4	23
		Expected Count	2.5	11.2	7.1	2.2	23.0
		% within MVT	.0%	.0%	82.6%	17.4%	100.0%
	2.00	Count	0	0	4	0	4
		Expected Count	.4	2.0	1.2	.4	4.0
		% within MVT	.0%	.0%	100.0%	.0%	100.0%
	3.00	Count	12	48	0	0	60
		Expected Count	6.6	29.3	18.4	5.7	60.0
		% within MVT	20.0%	80.0%	.0%	.0%	100.0%
	4.00	Count	2	14	16	8	40
		Expected Count	4.4	19.5	12.3	3.8	40.0
		% within MVT	5.0%	35.0%	40.0%	20.0%	100.0%
Total		Count	14	62	39	12	127
		Expected Count	14.0	62.0	39.0	12.0	127.0
		% within MVT	11.0%	48.8%	30.7%	9.4%	100.0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	93.648[a]	9	.000
Likelihood Ratio	121.617	9	.000
Linear-by-Linear Association	6.616	1	.010
N of Valid Cases	127		

a. 8 cells (50.0%) have expected count less than 5. The minimum expected count is .38.

```
>Warning # 3211
>On at least one case, the value of the weight variable was zero, negative,
>or missing.  Such cases are invisible to statistical procedures and graphs
>which need positively weighted cases, but remain on the file and are
>processed by non-statistical facilities such as LIST and SAVE.
```

Considering the results of the above analysis, a number of initial associations begin to emerge. The crostabulation table indicates the high incidence of properties classified to have '*long-term progressive movement*' which require '*remedial action group C*' (82.6%). A further point to note is the high incidence of properties classified to have '*non-progressive movement*' which require '*remedial action group B*' (80%). Evidence of a statistical association is provided by a chi-square vale of 93.684 which is significant at the 0.1% level. This initial strong evidence needs to be treated with a certain amount of caution as 8 cells out of 16 (50%) have an expected count less than 5 and the minimum expected count is 0.38. To overcome these warnings, the 4 x 4 contingency table can again be collapsed into a 2 x 2 table. '*Remedial action groups A and B*' are combined as are '*Remedial action groups C and D*'. Properties where no information is known about the movement are excluded, as are those where movement has been found to be '*seasonal*'. The result of this is the 2 x 2 contingency table presented below in table D5.

	REMEDIAL ACTION GROUP (REM_ACT)		
Cause Of Damage (MVT)	**A + B**	**C + D**	**Total**
'Movement Long-term Progressive'	0	23	23
'Movement Non-Progressive'	60	0	60
TOTAL	60	23	83

Table D5: Collapsed classification of case study properties by the factors *progressive movement* and *remedial action.*

The information contained within table D2 is evaluated through cross-tabulation and a chi-squared test applied in SPSS. The codes applied to enable data manipulation are:

Movement (MVT)	Remedial Action (REM_ACT)
'*Long term progressive movement*' = 1	'*Remedial Action Groups A + B*' = 1
'*Non progressive movement*' = 2	'*Remedial Action Groups C + D*' = 2

The results of the following analysis are self explanatory.

Crosstabs

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
MVT * REM_ACT	83	100.0%	0	.0%	83	100.0%

MVT * REM_ACT Crosstabulation

			REM_ACT		Total
			1.00	2.00	
MVT	1.00	Count	0	23	23
		Expected Count	16.6	6.4	23.0
		% within MVT	.0%	100.0%	100.0%
	2.00	Count	60	0	60
		Expected Count	43.4	16.6	60.0
		% within MVT	100.0%	.0%	100.0%
Total		Count	60	23	83
		Expected Count	60.0	23.0	83.0
		% within MVT	72.3%	27.7%	100.0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	83.000[b]	1	.000		
Continuity Correction[a]	78.083	1	.000		
Likelihood Ratio	97.973	1	.000		
Fisher's Exact Test				.000	.000
Linear-by-Linear Association	82.000	1	.000		
N of Valid Cases	83				

a. Computed only for a 2x2 table

b. 0 cells (.0%) have expected count less than 5. The minimum expected count is 6.37.

```
>Warning # 3211
>On at least one case, the value of the weight variable was zero, negative,
>or missing.  Such cases are invisible to statistical procedures and graphs
>which need positively weighted cases, but remain on the file and are
>processed by non-statistical facilities such as LIST and SAVE.
```

Discussion Of Cross Tabulation And Chi-square Tests

The results presented above indicate evidence of statistical association between the factor *visible damage* with the factor *remedial action*. These results provide a strong indication that where visible damage is classified as '*aesthetic*' there is a strong – but not categorical – indication that '*remedial action groups A or B*' will be required. However, where visible damage is classified as '*serviceability*' there is no obvious indication of what particular form of remedial action will be required.

There is no evidence of any association between the factor *cause of damage* and the factor *remedial action*.

The most powerful and robust association is evident between *movement* and *remedial action*. This demonstrates a clear relationship between '*non-progressive movement*' and '*remedial action groups A + B*' The relationship between '*progressive movement*' and '*remedial action groups C + D*' is also clearly evident.

It should be noted that the results in this Appendix are intended as an initial exploration of the data. The main analysis undertaken is the multiple regression analysis contained within Chapter Four.

APPENDIX E

REGRESSION MODEL ONE

Case No.	Vis_dam	Clay	Trees	Shall_fdns	Desiccation	Drains	Mvt	Rem_act
1	2	3	1	1	1	0	0	**3**
2	2	3	1	1	1	0	0	**3**
3	1	1	0	1	0	0	0	**2**
4	1	3	1	1	1	0	2	**3**
5	1	3	1	1	1	0	1	**2**
6	1	1	1	1	0	0	1	**2**
7	2	1	1	0	1	0	2	**3**
8	1	3	1	1	1	0	0	**3**
9	3	3	1	1	1	0	0	**3**
10	2	0	0	0	0	0	3	**3**
11	1	0	0	0	0	0	1	**1**
12	2	0	1	1	0	0	0	**2**
13	1	0	0	0	0	0	0	**1**
14	2	0	0	0	0	0	1	**2**
15	1	0	1	1	0	0	0	**1**
16	1	0	0	1	0	0	3	**3**
17	1	0	0	0	0	1	1	**2**
18	2	3	1	1	0	0	2	**3**
19	1	0	0	0	0	1	1	**2**
20	2	3	1	1	1	0	0	**3**
21	1	1	1	1	0	0	1	**2**
22	1	0	1	0	0	0	0	**2**
23	1	0	1	1	0	0	1	**1**
24	1	0	0	0	0	1	3	**3**
25	1	3	1	0	1	0	0	**3**
26	2	3	1	0	1	0	2	**3**
27	2	3	1	0	1	0	0	**3**
28	2	3	1	1	1	0	0	**3**
29	1	3	1	1	1	0	1	**2**
30	1	3	1	0	1	0	1	**2**
31	3	0	1	0	0	0	3	**4**
32	1	3	1	1	1	0	0	**3**
33	1	0	1	0	0	0	1	**2**
34	1	3	1	0	1	0	0	**3**
35	1	1	1	1	0	0	3	**3**
36	1	0	0	0	0	0	1	**1**
37	1	0	1	0	0	0	1	**2**
38	1	0	0	0	0	0	1	**2**
39	2	0	0	0	0	1	3	**3**
40	2	0	0	0	0	0	1	**1**
41	1	0	0	0	0	0	0	**2**
42	1	0	0	0	0	0	1	**1**
43	1	0	0	1	0	0	1	**2**
44	2	0	0	0	0	1	3	**3**
45	1	0	0	0	0	1	3	**3**
46	2	0	0	0	0	1	0	**3**
47	1	3	1	0	1	0	1	**2**
48	1	1	1	1	1	0	3	**3**
49	2	0	0	0	0	1	3	**3**
50	2	0	0	0	0	1	0	**3**
51	1	1	1	1	0	0	0	**3**
52	1	0	0	0	0	1	3	**3**
53	1	0	0	0	0	1	3	**3**
54	0	0	0	0	0	1	0	**3**
55	2	0	0	0	0	1	1	**2**
56	2	0	0	0	0	1	0	**3**
57	1	0	0	0	0	0	1	**1**
58	2	0	0	0	0	0	0	**2**
59	1	0	0	0	0	0	1	**1**
60	2	0	0	0	0	0	0	**2**
61	1	3	1	1	0	0	3	**3**
62	2	2	1	1	0	0	0	**3**
63	1	0	1	1	0	0	1	**2**

64	1	2	1	1	1	0	1	2
65	3	1	1	0	1	0	3	4
66	1	3	1	1	0	0	1	2
67	1	3	1	1	1	0	1	2
68	1	2	1	0	1	0	3	3
69	1	1	1	1	1	0	1	2
70	1	2	1	1	1	0	1	2
71	1	2	1	1	0	0	1	2
72	2	2	1	1	1	0	1	2
73	1	1	1	1	1	0	1	2
74	1	2	1	1	1	0	1	2
75	2	1	1	1	0	0	0	2
76	1	0	0	0	0	1	0	2
77	1	3	1	1	0	0	1	2
78	1	0	0	0	0	1	1	2
79	0	3	1	0	1	0	3	4
80	2	0	0	0	0	1	3	3
81	0	3	1	1	1	0	3	3
82	1	0	0	0	0	1	1	2
83	1	3	1	1	0	0	3	3
84	1	3	1	1	1	0	3	3
85	0	3	1	0	1	0	0	4
86	0	3	1	0	1	0	0	4
87	0	0	1	0	0	0	0	4
88	0	0	0	0	0	1	0	4
89	0	3	1	0	1	0	0	4
90	2	2	1	1	1	0	0	4
91	2	0	0	0	0	1	1	2
92	1	0	0	0	0	1	3	3
93	0	2	1	0	1	0	0	4
94	1	2	1	0	1	0	0	2
95	1	0	0	0	0	1	0	2
96	1	0	0	0	0	1	0	2
97	2	1	1	1	1	0	0	2
98	2	3	1	1	1	0	3	3
99	1	0	0	0	0	1	0	2
100	2	3	1	1	1	0	3	4
101	1	3	1	0	1	0	1	2
102	1	3	1	1	1	0	1	2
103	1	3	1	0	1	0	1	2
104	2	2	1	1	0	0	1	2
105	1	3	1	1	1	0	1	2
106	2	3	1	0	1	0	1	2
107	1	0	0	0	0	1	1	2
108	1	0	1	0	0	0	1	2
109	1	0	0	0	0	0	1	1
110	0	0	1	1	0	0	0	4
111	2	0	0	0	0	1	0	2
112	1	0	0	0	0	1	1	2
113	1	0	0	0	0	0	1	1
114	1	0	0	0	0	1	1	2
115	1	3	1	1	0	0	1	2
116	1	2	1	1	1	0	1	2
117	2	0	0	0	0	1	1	2
118	1	0	0	0	0	1	1	2
119	1	1	0	1	0	0	1	1
120	1	0	0	1	0	0	1	2
121	1	0	0	1	0	0	1	2
122	0	0	1	0	0	0	1	2
123	1	0	0	0	0	1	1	2
124	1	2	1	0	1	0	1	1
125	1	1	1	1	0	0	1	2
126	1	1	1	0	1	0	1	2
127	1	2	0	1	0	0	1	1

Regression

Descriptive Statistics

	Mean	Std. Deviation	N
REM_ACT	2.3858	.8072	127
VIS_DAM	1.2283	.6323	127
CLAY	1.1890	1.3077	127
TREES	.5827	.4951	127
SHAL_FDN	.4252	.4963	127
DISICC	.3701	.4847	127
DRAINS	.2441	.4313	127
MVT	1.0787	1.0359	127

Correlations

		REM_ACT	VIS_DAM	CLAY	TREES	SHAL_ FDN
Pearson Correlation	REM_ACT	1.000	.028	.291	.287	.003
	VIS_DAM	.028	1.000	-.024	-.048	.042
	CLAY	.291	-.024	1.000	.723	.450
	TREES	.287	-.048	.723	1.000	.502
	SHAL_FDN	.003	.042	.450	.502	1.000
	DISICC	.302	.007	.765	.649	.231
	DRAINS	.069	.056	-.519	-.671	-.489
	MVT	.229	.106	-.005	-.044	-.004
Sig. (1-tailed)	REM_ACT	.	.377	.000	.001	.485
	VIS_DAM	.377	.	.395	.296	.319
	CLAY	.000	.395	.	.000	.000
	TREES	.001	.296	.000	.	.000
	SHAL_FDN	.485	.319	.000	.000	.
	DISICC	.000	.469	.000	.000	.004
	DRAINS	.219	.266	.000	.000	.000
	MVT	.005	.119	.477	.313	.483
N	REM_ACT	127	127	127	127	127
	VIS_DAM	127	127	127	127	127
	CLAY	127	127	127	127	127
	TREES	127	127	127	127	127
	SHAL_FDN	127	127	127	127	127
	DISICC	127	127	127	127	127
	DRAINS	127	127	127	127	127
	MVT	127	127	127	127	127

Correlations

		DISICC	DRAINS	MVT
Pearson Correlation	REM_ACT	.302	.069	.229
	VIS_DAM	.007	.056	.106
	CLAY	.765	-.519	-.005
	TREES	.649	-.671	-.044
	SHAL_FDN	.231	-.489	-.004
	DISICC	1.000	-.436	-.027
	DRAINS	-.436	1.000	.099
	MVT	-.027	.099	1.000
Sig. (1-tailed)	REM_ACT	.000	.219	.005
	VIS_DAM	.469	.266	.119
	CLAY	.000	.000	.477
	TREES	.000	.000	.313
	SHAL_FDN	.004	.000	.483
	DISICC	.	.000	.382
	DRAINS	.000	.	.135
	MVT	.382	.135	.
N	REM_ACT	127	127	127
	VIS_DAM	127	127	127
	CLAY	127	127	127
	TREES	127	127	127
	SHAL_FDN	127	127	127
	DISICC	127	127	127
	DRAINS	127	127	127
	MVT	127	127	127

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	MVT, SHAL_FDN, VIS_DAM, DISICC, DRAINS, TREES, CLAY[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: REM_ACT

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.535[a]	.286	.244	.7020

a. Predictors: (Constant), MVT, SHAL_FDN, VIS_DAM, DISICC, DRAINS, TREES, CLAY

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	23.456	7	3.351	6.800	.000[a]
	Residual	58.639	119	.493		
	Total	82.094	126			

a. Predictors: (Constant), MVT, SHAL_FDN, VIS_DAM, DISICC, DRAINS, TREES, CLAY

b. Dependent Variable: REM_ACT

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	1.458	.201		7.235	.000
	VIS_DAM	1.540E-02	.100	.012	.154	.878
	CLAY	9.223E-02	.087	.149	1.055	.293
	TREES	.758	.221	.465	3.429	.001
	SHAL_FDN	-.182	.158	-.112	-1.148	.253
	DISICC	.172	.214	.103	.804	.423
	DRAINS	.802	.203	.428	3.952	.000
	MVT	.163	.061	.209	2.665	.009

a. Dependent Variable: REM_ACT

APPENDIX F

REGRESSION MODEL TWO

Case No.	No.	Vis_dam	Clay	Trees	Shall_fdns	Desiccatio	Drains	Mvt	Rem_act
4	1	1	3	1	1	1	0	2	3
5	2	1	3	1	1	1	0	1	2
6	3	1	1	1	1	0	0	1	2
7	4	2	1	1	0	1	0	2	3
16	5	1	0	0	1	0	0	3	3
17	6	1	0	0	0	0	1	1	2
18	7	2	3	1	1	0	0	2	3
19	8	1	0	0	0	0	1	1	2
21	9	1	1	1	1	0	0	1	2
23	10	1	0	1	1	0	0	1	1
24	11	1	0	0	0	0	1	3	3
26	12	2	3	1	0	1	0	2	3
29	13	1	3	1	1	1	0	1	2
30	14	1	3	1	0	1	0	1	2
31	15	3	0	1	0	0	0	3	4
33	16	1	0	1	0	0	0	1	2
35	17	1	1	1	1	0	0	3	3
37	18	1	0	1	0	0	0	1	2
39	19	2	0	0	0	0	1	3	3
43	20	1	0	0	1	0	0	1	2
44	21	2	0	0	0	0	1	3	3
45	22	1	0	0	0	0	1	3	3
47	23	1	3	1	0	1	0	1	2
48	24	1	1	1	1	1	0	3	3
49	25	2	0	0	0	0	1	3	3
52	26	1	0	0	0	0	1	3	3
53	27	1	0	0	0	0	1	3	3
55	28	2	0	0	0	0	1	1	2
61	29	1	3	1	1	0	0	3	3
63	30	1	0	1	1	0	0	1	2
64	31	1	2	1	1	1	0	1	2
65	32	3	1	1	0	1	0	3	4
66	33	1	3	1	1	0	0	1	2
67	34	1	3	1	1	1	0	1	2
68	35	1	2	1	0	1	0	3	3
69	36	1	1	1	1	1	0	1	2
70	37	1	2	1	1	1	0	1	2
71	38	1	2	1	1	0	0	1	2
72	39	2	2	1	1	1	0	1	2
73	40	1	1	1	1	1	0	1	2
74	41	1	2	1	1	1	0	1	2
77	42	1	3	1	1	0	0	1	2
78	43	1	0	0	0	0	1	1	2
80	44	2	0	0	0	0	1	3	3
82	45	1	0	0	0	0	1	1	2
83	46	1	3	1	1	0	0	3	3
84	47	1	3	1	1	1	0	3	3
91	48	2	0	0	0	0	1	1	2
92	49	1	0	0	0	0	1	3	3
98	50	2	3	1	1	1	0	3	3
100	51	2	3	1	1	1	0	3	4
101	52	1	3	1	0	1	0	1	2
102	53	1	3	1	1	1	0	1	2
103	54	1	3	1	0	1	0	1	2
104	55	2	2	1	1	0	0	1	2
105	56	1	3	1	1	1	0	1	2
106	57	2	3	1	0	1	0	1	2
107	58	1	0	0	0	0	1	1	2
108	59	1	0	1	0	0	0	1	2
112	60	1	0	0	0	0	1	1	2
114	61	1	0	0	0	0	1	1	2
115	62	1	3	1	1	0	0	1	2
116	63	1	2	1	1	1	0	1	2
117	64	2	0	0	0	0	1	1	2
118	65	1	0	0	0	0	1	1	2
119	66	1	1	0	1	0	0	1	1
120	67	1	0	0	0	0	0	1	2
121	68	1	0	0	0	0	0	1	2
123	69	1	0	0	0	0	1	1	2
124	70	1	2	1	0	1	0	1	1
125	71	1	1	1	1	0	0	1	2
126	72	1	1	1	0	1	0	1	2
127	73	1	2	0	1	0	0	1	1

Regression

Descriptive Statistics

	Mean	Std. Deviation	N
REM_ACT	2.3151	.6428	73
VIS_DAM	1.2603	.5008	73
CLAY	1.2877	1.2854	73
TREES	.6301	.4861	73
SHAL_FDN	.4795	.5030	73
DESICC	.3836	.4896	73
DRAINS	.2877	.4558	73
MVT	1.6027	.8935	73

Correlations

		REM_ACT	VIS_DAM	CLAY	TREES	SHAL_ FDN
Pearson Correlation	REM_ACT	1.000	.518	-.010	.023	-.130
	VIS_DAM	.518	1.000	-.053	.002	-.227
	CLAY	-.010	-.053	1.000	.706	.514
	TREES	.023	.002	.706	1.000	.508
	SHAL_FDN	-.130	-.227	.514	.508	1.000
	DESICC	.052	.040	.639	.604	.202
	DRAINS	.113	.093	-.641	-.829	-.610
	MVT	.874	.358	-.081	-.119	-.096
Sig. (1-tailed)	REM_ACT	.	.000	.465	.425	.136
	VIS_DAM	.000	.	.327	.495	.027
	CLAY	.465	.327	.	.000	.000
	TREES	.425	.495	.000	.	.000
	SHAL_FDN	.136	.027	.000	.000	.
	DESICC	.331	.367	.000	.000	.044
	DRAINS	.171	.216	.000	.000	.000
	MVT	.000	.001	.249	.158	.210
N	REM_ACT	73	73	73	73	73
	VIS_DAM	73	73	73	73	73
	CLAY	73	73	73	73	73
	TREES	73	73	73	73	73
	SHAL_FDN	73	73	73	73	73
	DESICC	73	73	73	73	73
	DRAINS	73	73	73	73	73
	MVT	73	73	73	73	73

Correlations

		DESICC	DRAINS	MVT
Pearson Correlation	REM_ACT	.052	.113	.874
	VIS_DAM	.040	.093	.358
	CLAY	.639	-.641	-.081
	TREES	.604	-.829	-.119
	SHAL_FDN	.202	-.610	-.096
	DESICC	1.000	-.501	-.060
	DRAINS	-.501	1.000	.182
	MVT	-.060	.182	1.000
Sig. (1-tailed)	REM_ACT	.331	.171	.000
	VIS_DAM	.367	.216	.001
	CLAY	.000	.000	.249
	TREES	.000	.000	.158
	SHAL_FDN	.044	.000	.210
	DESICC	.	.000	.308
	DRAINS	.000	.	.061
	MVT	.308	.061	.
N	REM_ACT	73	73	73
	VIS_DAM	73	73	73
	CLAY	73	73	73
	TREES	73	73	73
	SHAL_FDN	73	73	73
	DESICC	73	73	73
	DRAINS	73	73	73
	MVT	73	73	73

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	MVT, DESICC, SHAL_FDN, VIS_DAM, TREES, CLAY, DRAINS[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: REM_ACT

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.913[a]	.834	.817	.2753

a. Predictors: (Constant), MVT, DESICC, SHAL_FDN, VIS_DAM, TREES, CLAY, DRAINS

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	24.827	7	3.547	46.797	.000[a]
	Residual	4.926	65	7.579E-02		
	Total	29.753	72			

a. Predictors: (Constant), MVT, DESICC, SHAL_FDN, VIS_DAM, TREES, CLAY, DRAINS

b. Dependent Variable: REM_ACT

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.850	.150		5.676	.000
	VIS_DAM	.264	.072	.206	3.658	.001
	CLAY	-9.931E-03	.041	-.020	-.243	.809
	TREES	.307	.136	.232	2.253	.028
	SHAL_FDN	-6.841E-02	.089	-.054	-.769	.445
	DESICC	3.902E-02	.094	.030	.417	.678
	DRAINS	.154	.140	.109	1.098	.276
	MVT	.578	.040	.803	14.575	.000

a. Dependent Variable: REM_ACT

APPENDIX G

REGRESSION MODEL THREE

Case No.	No.	Vis_Dam	Cause	Mvt	Rem_Act
4	1	1	18	2	3
5	2	1	18	1	2
6	3	1	5	1	2
7	4	2	4	2	3
16	5	1	2	3	3
17	6	1	18	1	2
18	7	2	15	2	3
19	8	1	18	1	2
21	9	1	5	1	2
23	10	1	3	1	1
24	11	1	18	3	3
26	12	2	12	2	3
29	13	1	18	1	2
30	14	1	12	1	2
31	15	3	9	3	4
33	16	1	3	1	2
35	17	1	5	3	3
37	18	1	3	1	2
39	19	2	18	3	3
43	20	1	2	1	2
44	21	2	18	3	3
45	22	1	18	3	3
47	23	1	12	1	2
48	24	1	6	3	3
49	25	2	18	3	3
52	26	1	18	3	3
53	27	1	18	3	3
55	28	2	18	1	2
61	29	1	15	3	3
63	30	1	5	1	2
64	31	1	12	1	2
65	32	3	4	3	4
66	33	1	15	1	2
67	34	1	18	1	2
68	35	1	8	3	3
69	36	1	6	1	2
70	37	1	12	1	2
71	38	1	10	1	2
72	39	2	12	1	2
73	40	1	6	1	2
74	41	1	12	1	2
77	42	1	15	1	2
78	43	1	18	1	2
80	44	2	18	3	3
82	45	1	18	1	2
83	46	1	15	3	3
84	47	1	18	3	3
91	48	2	18	1	2
92	49	1	18	3	3
98	50	2	18	3	3
100	51	2	18	3	4
101	52	1	12	1	2
102	53	1	18	1	2
103	54	1	12	1	2
104	55	2	10	1	2
105	56	1	18	1	2
106	57	2	12	1	2
107	58	1	18	1	2
108	59	1	3	1	2
112	60	1	18	1	2
114	61	1	18	1	2
115	62	1	15	1	2
116	63	1	12	1	2
117	64	2	18	1	2
118	65	1	18	1	2
119	66	1	2	1	1
120	67	1	2	1	2
121	68	1	2	1	2
123	69	1	18	1	2
124	70	1	8	1	1
125	71	1	5	1	2
126	72	1	4	1	2
127	73	1	4	1	1

Regression

Descriptive Statistics

	Mean	Std. Deviation	N
REM_ACT	2.3151	.6428	73
VIS_DAM	1.2603	.5008	73
CAUSE	12.1644	6.0254	73
MOVEMENT	1.6027	.8935	73

Correlations

		REM_ACT	VIS_DAM	CAUSE	MOVEMENT
Pearson Correlation	REM_ACT	1.000	.518	.227	.874
	VIS_DAM	.518	1.000	.101	.358
	CAUSE	.227	.101	1.000	.190
	MOVEMENT	.874	.358	.190	1.000
Sig. (1-tailed)	REM_ACT	.	.000	.027	.000
	VIS_DAM	.000	.	.198	.001
	CAUSE	.027	.198	.	.053
	MOVEMENT	.000	.001	.053	.
N	REM_ACT	73	73	73	73
	VIS_DAM	73	73	73	73
	CAUSE	73	73	73	73
	MOVEMENT	73	73	73	73

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	MOVEMENT, CAUSE, VIS_DAM[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: REM_ACT

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.903[a]	.815	.807	.2826

a. Predictors: (Constant), MOVEMENT, CAUSE, VIS_DAM

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	24.241	3	8.080	101.147	.000[a]
	Residual	5.512	69	7.989E-02		
	Total	29.753	72			

a. Predictors: (Constant), MOVEMENT, CAUSE, VIS_DAM

b. Dependent Variable: REM_ACT

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.967	.110		8.789	.000
	VIS_DAM	.299	.071	.233	4.200	.000
	CAUSE	5.846E-03	.006	.055	1.038	.303
	MOVEMENT	.561	.040	.780	13.854	.000

a. Dependent Variable: REM_ACT

APPENDIX H

REGRESSION MODEL METHODS AND INTERPRETATION

VARIABLE SELECTION METHODS

- **Enter** – all selected variables are entered as independent variables in the model.

- **Forward Selection** - this method constructs a regression model by entering independent variables in order of their statistical significance. No further variables are entered into the analysis when their impact on the model fails to pass the SPSS default criteria. This criteria can be changed to take into account different circumstances.

- **Stepwise Selection** - the third method of constructing a regression model considers entering the variables through stepwise selection. The first variable selected is based on the highest correlation. Subsequent variables are added based on the t statistic in the coefficients table. As each new variable is added a new model is produced. This process continues until no variables pass the SPSS default criteria. Stepwise selection can also result in variables being removed from the analysis. As new variables are added, existing variables may become less significant and are hence removed.

- **Backwards Elimination** - this method constructs regression models initially entering all variables into the model (which initially produces a model identical to the *enter* method above). The least useful predictors in the model are then subsequently removed at each stage to create a number of models. This process continues until no further variables are removed. The removal criteria is again set by SPSS default and this can be adjusted to take into account the circumstances of each model.

The models that result from these methods may differ. However, it is important to be aware that none of these procedures is guaranteed to provide a best model in absolute terms. In order to consider an appropriate model(s) for the data collected in Chapter Four, several methods of entering /removing variables have been considered.

REGRESSION ANALYSIS RESULTS

The results from the various methods of entering variables requires interpretation to consider which is the most appropriate model(s) both statistically and practically.

Interpretation Of Results

The salient points which influence the interpretation of the output are considered.

- **Descriptive Statistics** – provide details of the mean and standard deviation of the variables in the analysis.

- **Correlations** – provide the correlations between each of the variables. In particular, the correlation between the dependent variable remedial action with each of the independent variables is an important consideration for the analysis.

- **Model Summary** – for multiple regression, the correlation between the observed (actual) and predicted (calculated by the regression equation) values of the dependent variables are given by R. R square is the square of this correlation. The sample estimate of R square tends to be an overestimate of the population parameter. Adjusted R square is designed to compensate for the optimistic bias of R square. It is a function of R square adjusted by the number of variables in the model and the sample size. A model with a perfect fit would achieve a value of R square of either +1 or –1 while a model with no fit would achieve a value of 0.

  However, interpreting the usefulness of a regression model requires more than consideration of R in isolation. There is no one test that determines the best model for the data available. Including too many variables in a model can result in **overfitting**. This is where a model which has a high correlation between the predicted and observed values of the dependent variable (R) would provide a much smaller value of R when this model is applied to a different sample drawn from the same population.

- **ANOVA** – the *F* statistic is highly significant and if the associated probability (*sig.*) is small (<0.0005) this does not necessarily imply that an independent variables makes a meaningful contribution to the fit of the model.

- **Coefficients** – provide the regression equation. The constant and unstandardised coefficient (B) provide an estimate of the regression model equation.

  In order to assess the importance of each independent variable in a model, it is not appropriate to simply compare the unstandardised coefficients (B). The standardised coefficients (Beta) attempt to make the regression coefficients more comparable.

  The *t* statistic in the coefficients table does provide some indication of the relative importance of each variable in the model. These are obtained by dividing each coefficient (B) by its standard error (Std. Error). SPSS suggests that as a guide regarding useful predictors, values of *t* well below –2 or above +2 are potentially significant.

- **Excluded variables** – when using stepwise, forward or backwards elimination, variables are added or removed by steps, the SPSS coefficients table reports results at each step for the variables included in the model. The Excluded Variables table presents information about the variables not included in the model.

It is necessary to re-iterate that no one model will provide a best result in absolute terms.