UNIVERSITY OF
NEWCASTLE

SCHOOL OF CIVIL ENGINEERING AND GEOSCIENCES
GEOTECHNICAL ENGINEERING GROUP

The design of a relational database on the geotechnical properties of Northern England Glacial Till

A thesis submitted for the degree of Doctor of Philosophy

By:

Siamak Hashemi

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Dedicated to my parents

Abstract

The landscape of Northern England has been mostly formed by glacial activities during the Quaternary period, and glacial till materials have been deposited over the northern counties of England during these glacial activities. Townships, industrial developments and infrastructure works exist or are planned in these areas. The variable and often complex successions in which glacial tills occur have frequently led to problems on civil and mining engineering projects.

Glacial tills are engineering soils which have been defined as a poorly sorted mixture of clay, silt, sand, gravel, cobble and boulder sized material deposited directly from glacier ice. The glacial tills of the counties in Northern England are the subject of many studies which are carried out in order to determine the properties of the overlying glacial deposits. Ground investigations have been carried out for opencast coal projects. A large number of samples were obtained and extensive laboratory testing has been carried out.

Using the results of these investigations and tests, a geotechnical database is being developed that should provide a useful resource for civil and mining engineers in the northern counties region. Its purpose is the extensive analysis of the parameters that are used to define the geotechnical properties of Northern England glacial tills. This should give a better understanding of the engineering behaviour of glacial tills and parameter selection for engineering design.

In addition to statistical analysis, Neural Networks, a model of Artificial Intelligence, are used to find correlations between the different parameters and to develop new methods of modelling and predicting geotechnical design parameters. Neural technology is an emerging field of artificial intelligence that has attracted the interest of many scientists and engineers. They are information-processing systems that can mimic the biological system of the brain and can be trained to complete and classify input patterns, or to complete a function of their input. In this project the data available from the database are used to train Neural Networks to classify glacial tills according to their geotechnical properties and investigate their potential in predicting geotechnical design parameters.

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Chapter 1

Introduction

1.1 Introduction

The landscape of Northern England (Cumbria, Northumberland, Tyne and Wear, County Durham and Cleveland) has been mostly formed by glacial activities during the Quaternary period and glacial till materials have been deposited over the northern counties of England during these glacial activities. As a result glacial till materials of considerable thickness have been deposited in the lower lying coastal and valley areas. Townships, industrial developments and infrastructure works exist or are planned in these areas. The variable and often complex successions in which glacial tills occur have frequently led to problems on civil and mining engineering projects. Glacial deposits also overlie Coal Measures strata in many of the areas mentioned above, and these deposits are frequently associated with earthworks and slope instability at opencast coal mines (Hughes et al, 1998). Geotechnical investigations were carried out over the last fifty years in connection with opencast coal mining, which has created an opportunity to study the spatial variability of the glacial tills and their properties in detail.

Glacial tills are engineering soils which have been defined as a poorly sorted mixture of clay, silt, sand, gravel, cobble and boulder sized material deposited directly from glacier ice (Hambery, 1994). Tills are more variable than any other sediment known by a single name (Flint, 1971; Goldthwait, 1971; Hambrey, 1994). A proper understanding of the origin, mode of deposition, post-depositional history, and geometry of glacial till materials is required to define convincing models of the ground conditions from the investigations, and to choose suitable geotechnical parameters for design and analysis (Hughes et al, 1998).

Research into the origin and distribution of the glacial tills began in the latter half of the nineteenth century and is still continuing at the present time. A large volume of literature exists on the Quaternary (glacial) geology of England (Hughes et al, 1998), but the majority of that literature which is often contradicting, focuses on geological aspects of glacial till. Many thousands of samples of till material were obtained from opencast mining investigations and extensive laboratory testing has been carried out in order to produce stratigraphic and property profiles of the glacial deposits. These investigations were required following the introduction of Geotechnical Codes of Practice in the opencast mining industry (Anon 1982, 1989 - and subsequently Health and Safety Commission, 1999). Thorough investigations had been routine prior to that in order to design spoil mounds (Hughes and Clarke, 1997).

Assembling a database of geotechnical information would compliment and enhance the geological information. While many ground investigations have been conducted, obtaining access to the data is difficult because they are owned by many organisations. The British Coal Opencast possessed one of the largest collections of geotechnical data on glacial soils for the Northern England region. An opportunity to study an extensive data set gathered over thirty years from sites across the region arose when the University of Newcastle upon Tyne was given access to ground investigation reports produced for the former British Coal Opencast. Most of the data used for this study were found in hardcopies of site investigation reports from various projects although a few of the most recent data were in electronic form.

Using the results of these investigations and tests, a geotechnical database called NETDATA (Northern England Till DATA) is being developed. Its purpose is the extensive analysis of the parameters that are used to define the geotechnical properties of Northern England glacial tills. The results could be used to re-analyse some earthwork failures such as those in excavated slopes, and this should give a better understanding of the engineering behaviour of glacial tills and parameter selection for engineering design. It should provide a useful resource for civil and mining engineers in the northern counties region.

1.2 Objectives

The ultimate aims of the study were the following:

- The design of a database for storing data of geotechnical parameters of Northern England Till.
- Inputting data from Site Investigation reports into the database.
- Analysing the data from various locations of Northern England using statistical methods and empirical equations.
- Investigating a new method for classification and prediction of the geotechnical parameters of glacial tills using Neural Networks.

The structured summary of the work carried out for this project can be seen in Figure 1.1.

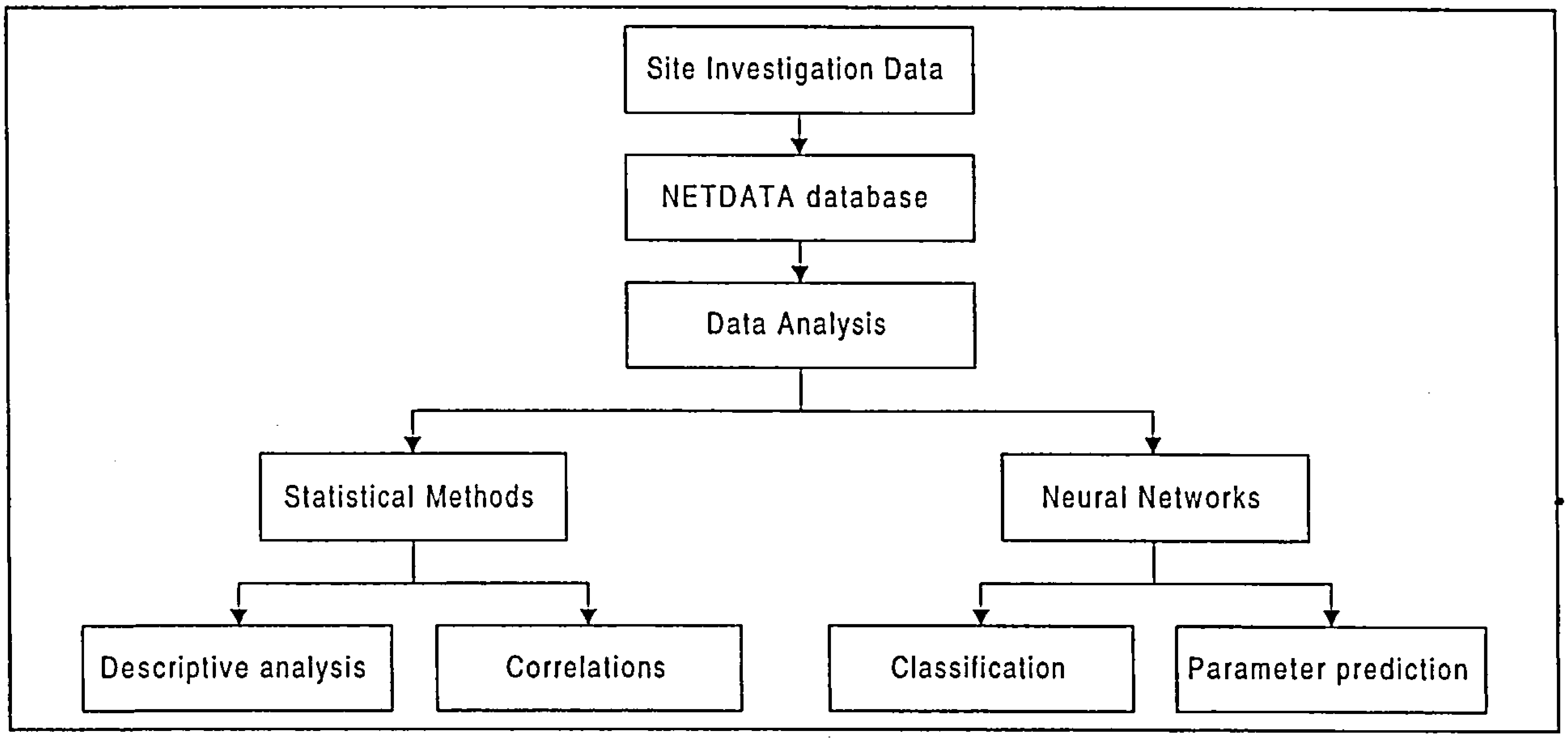


Figure 1.1: Structured summary of thesis.

In order to achieve these objectives, it was necessary to gain an understanding of the geotechnical parameters in order to design a suitable model for the structure of the database. Once the database was designed, data could be stored in one standard format and then be analysed. The aim of the analysis was to produce a concise table of typical values of soil parameters and to find suitable methods for the prediction of these parameters. Some other researchers have attempted similar objectives but have had the primary disadvantage of limited access to data.

As mentioned earlier, tills are the most widespread and variable of all glacial deposits in the UK. Time and effort was spent by many researchers to find the relationship between glacial processes and the geotechnical properties of till to enable a satisfactory classification to be made for geotechnical purposes. A number of classification systems have been developed and some of them meet the needs of geotechnical engineering (Trenter, 1999). For instance till classifications based on modes of deposition were introduced by McGown and Derbyshire (1977).

In this project, the classification of tills using all available geotechnical parameters from the data within the NETDATA database is attempted. For this purpose Neural Networks, a model of Artificial Intelligence, have been used. Artificial Intelligence is a topic that has attracted the interest of many engineers and scientists. In recent years the use of different artificial intelligence models in almost all branches of engineering has been grown significantly. Neural technology is an emerging field of artificial intelligence. It is an information-processing system that can mimic the biological system of the brain. It is the ability to learn that makes neural networks interesting and useful tools. They can be trained to complete input patterns, classify input patterns or to complete a function of its input. In this project the data available from NETDATA are used to train neural networks to complete some incomplete sets of data and to classify glacial tills according to their geotechnical properties.

1.3 Contents of Thesis

The following chapters are included in this report:

Chapter 2 explains the various processes of formation, transportation and deposition of glacial tills. A summary of the properties of glacial tills in Northern England derived from previous research is also included in this chapter. Some examples of engineering problems caused by glacial tills are also reviewed. These are followed by an overview about the history and the use of databases and artificial intelligence, in particular Neural Networks, in the field of geotechnical engineering.

Chapter 3 reviews available methods of data management and techniques for database development. The design and structure of NETDATA database follows a standard format, which is explained in detail. Various objects, which have been included in the database, are also explained.

Chapter 4 reviews methods of site investigations and the British Standard for the description of soils. The geology of glacial tills in the northern counties is reviewed and summaries of the ground conditions of site investigation projects, stored in the database, are given in this chapter.

Chapter 5 describes laboratory testing methods, based on British Standards, which are used in the site investigation projects in order to obtain various geotechnical design parameters. Summaries of test results stored in the database are presented and discussed in detail.

Chapter 6 this chapter reviews the correlation between the various geotechnical parameters of the tills. Comparisons are made to results of research carried out previously by others.

Chapter 7 explains the construction and operation of Neural Networks and also describes how Neural Networks have been used in this project to classify different glacial till units according to their geotechnical properties. Their potential is also investigated for predicting geotechnical strength parameters from their index properties.

Chapter 8 summaries the work carried out during this project and discusses the achieved results. Suggestions for further research are also given in this chapter.

Chapter 2

Literature Review

2.1 Introduction

During the Cenozoic Ice age approximately 30% of the earth's land surface was glaciated, and as a result over 10% of it is now covered by glacial sediments (Bennet and Glasser, 1996). In Great Britain, the area believed covered by Devensian ice amounts to some 60% of the total land area and glacial deposits are particularly well represented in upland parts of the country (Trenter, 1999). Any form of construction on or in these sediments must consider their engineering properties. This requires the determination of the properties of glacial deposits and their variability, which are functions of their depositional and post-depositional processes (Boulton and Paul, 1976).

Studies and observations of glacial phenomena have been undertaken for many decades leading to a number of theories and models for the formation of glacial deposits. A study of the depositional and post-depositional processes should assist in the development of an understanding of the properties of glacial deposits. A summary of the glacial geology and models of the formation of tills, and engineering problems associated when working in such terrain are reviewed in this chapter.

2.2 The glacial geology of Northern England

Several parts of the world were at one time covered with ice due to the variation in temperature and precipitation, as well as astronomical, geographical and meteorological aspects. Ice sheets and glaciers extended over a much larger area than that which is covered at the present time. Glaciers and ice sheets tend to develop on land when local seasonal temperatures are predominantly below freezing point, so that the rates of accumulation of snow exceed the rates of melting and evaporation. In this process, lowering of the temperature is not sufficient and should be accompanied with high precipitation predominantly in the form of snow. Both these conditions are satisfied in mountainous areas, and thus the formation of land-ice generally begins at high latitudes in these areas. This process continues with added snow, and compaction of snow layers under their own weight. They form a solid mass of ice crystals.

Most glacial deposits in Northern England were deposited during the last glaciation of the Quaternary period (Hughes et al, 1998). The Quaternary is a subdivision of geological time that includes the present day (Table 2.1). It is suggested that it comprises the last 1.6 million years (Bowen, 1978) although others have suggested that it should be shorter or longer than this. The Quaternary period comprises of two epochs namely the Pleistocene and the Holocene. The glacial cycles in the Northern Hemisphere involved the growth (during cold glacial periods) and decay (during warmer interglacial periods) of two major ice sheets, which covered North America and Northern Europe.

Table 2.1: Major units of standard chronostratigraphic scale for Cenosoic era.
(after: Bowen, 1978; Harland et al, 1982) - (ka = Thousands of years, Ma = Millions of years)

Erathems and Eras	Systems and Periods		Series and Epochs	Duration of unit	Age of beginning of unit
Cenosoic	Quaternary		Holeocene	0.01 (Ma)	0.01 (10 ka)
			Pleistocene	1.6 (Ma)	1.6 (Ma)
	Tertiary	Neogene	Pliocene	5 (Ma)	7 (Ma)
			Miocene	19 (Ma)	26 (Ma)
		Paleogene	Oligocene	12 (Ma)	38 (Ma)
			Eocene	16 (Ma)	54 (Ma)
			Palaeocene	11 (Ma)	65 (Ma)

During the Pleistocene, several glaciations covered Britain. It was long supposed that the major glaciations were confined to the Quaternary period, so distinguishing this period in terms of climatic changes from its immediate predecessor. However, there is evidence which shows that extensive glaciers had formed in high latitudes of both polar hemispheres before the end of the Miocene period, through the Pleiocene and into the Quaternary. Therefore, it is no longer possible to associate the Quaternary alone with ice ages and glaciation; and hence the term "pre-glacial pleistocene" is used (Bowen, 1978).

Most of Northern Britain was overrun by continental glaciers. There were no fewer than seven centres or groups of centres of radial out flow, each located on a highland region (Flint, 1957).

The seven centres are:

1. The Scottish highlands in central and northern Scotland. These were a cluster of individual centres.
2. The southern uplands of Scotland, south of Edinburgh-Glasgow lowland.
3. The Cumberland highlands (Lake District).
4. The Pennine chain.
5. The mountains of Wales, including several groups stretching from the Bristol Channel to the Irish Sea.
6. Mountain of Connemara and Donegal in western Ireland.
7. Mountains of southern Ireland, including several groups from Kerry on the west to Wicklow on the east.

The centres of outflow are mainly identified on the basis of striations and streamline forms. The north European glaciation and interglaciations, in which the equivalent glacial-interglacial sequences of British Isles are represented, are written below (Bowen, 1978, Lunn, 1995):

1. Devensian glaciation
2. Ipswichian interglaciation
3. Wolstonian glaciation
4. Hoxnian interglaciation
5. Anglian glaciation
6. Cromerian interglaciation

Deposits transported by and released from ice are known as glacial deposits. Those transported by other agents are grouped together as nonglacial sediments. Deposits of these glaciations, which belong to the late Pliocene or early Pleistocene epoch, are widespread in Britain. Figure 2.1 shows the extent of the land surface covered by glacial deposits.

Tills belonging to the late Devensian stage are the best evidence of the last cold stage. They are widespread in Britain and represent the last major ice advance. Most present glacial soils were developed during this period although they have been affected by post-depositional processes (Bowen, 1978).

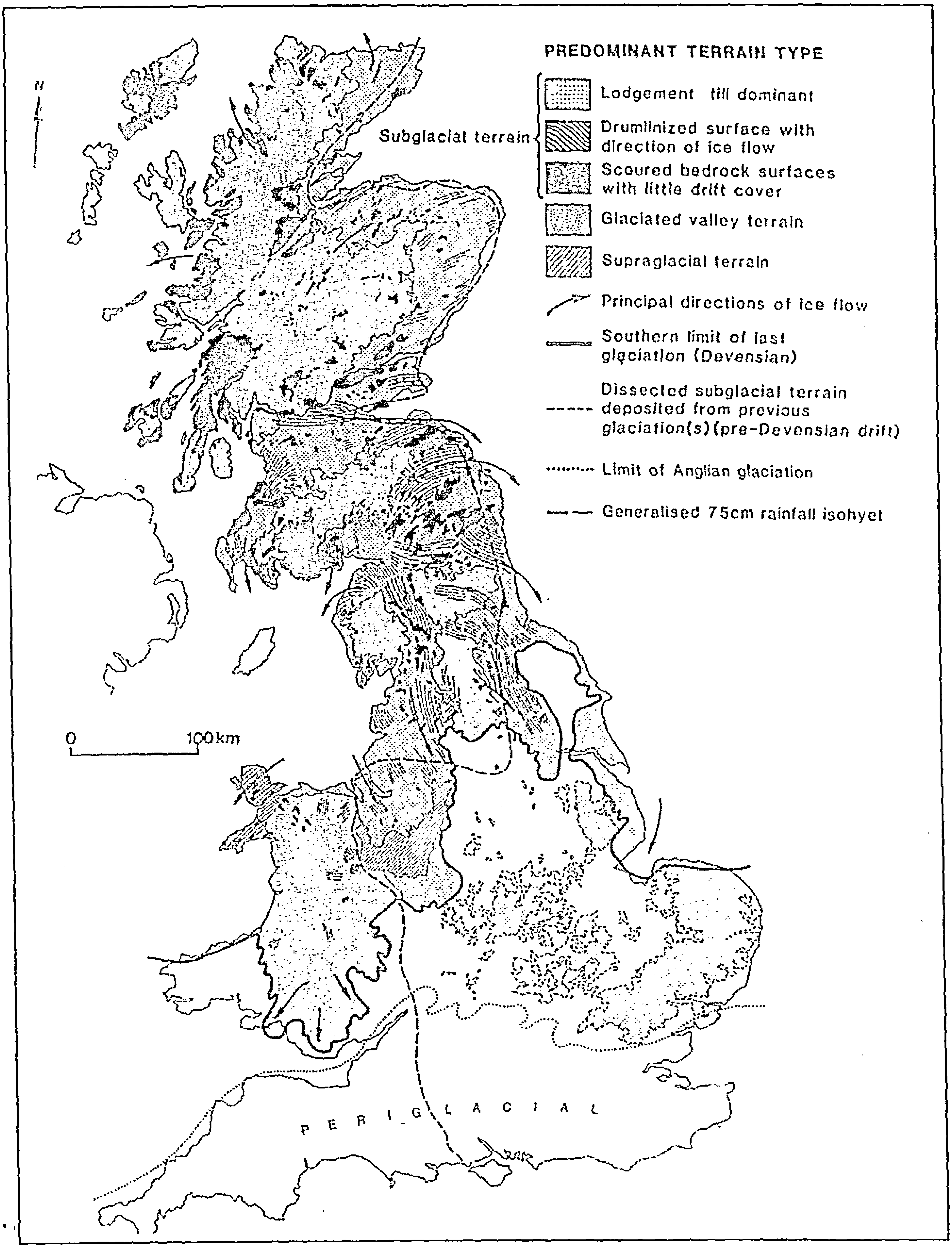


Figure 2.1: Distribution of glacial landsystem in Britain (Eyles and Dearman, 1981)

It has been estimated that about three-quarters of all glacial tills found in Britain are of Devensian age (Derbyshire, 1975). The derivation of debris and mode of deposition control the nature of deposits. In the following section the origin and characteristics of glacial tills and their landforms are discussed.

2.3 Glacial Landsystems

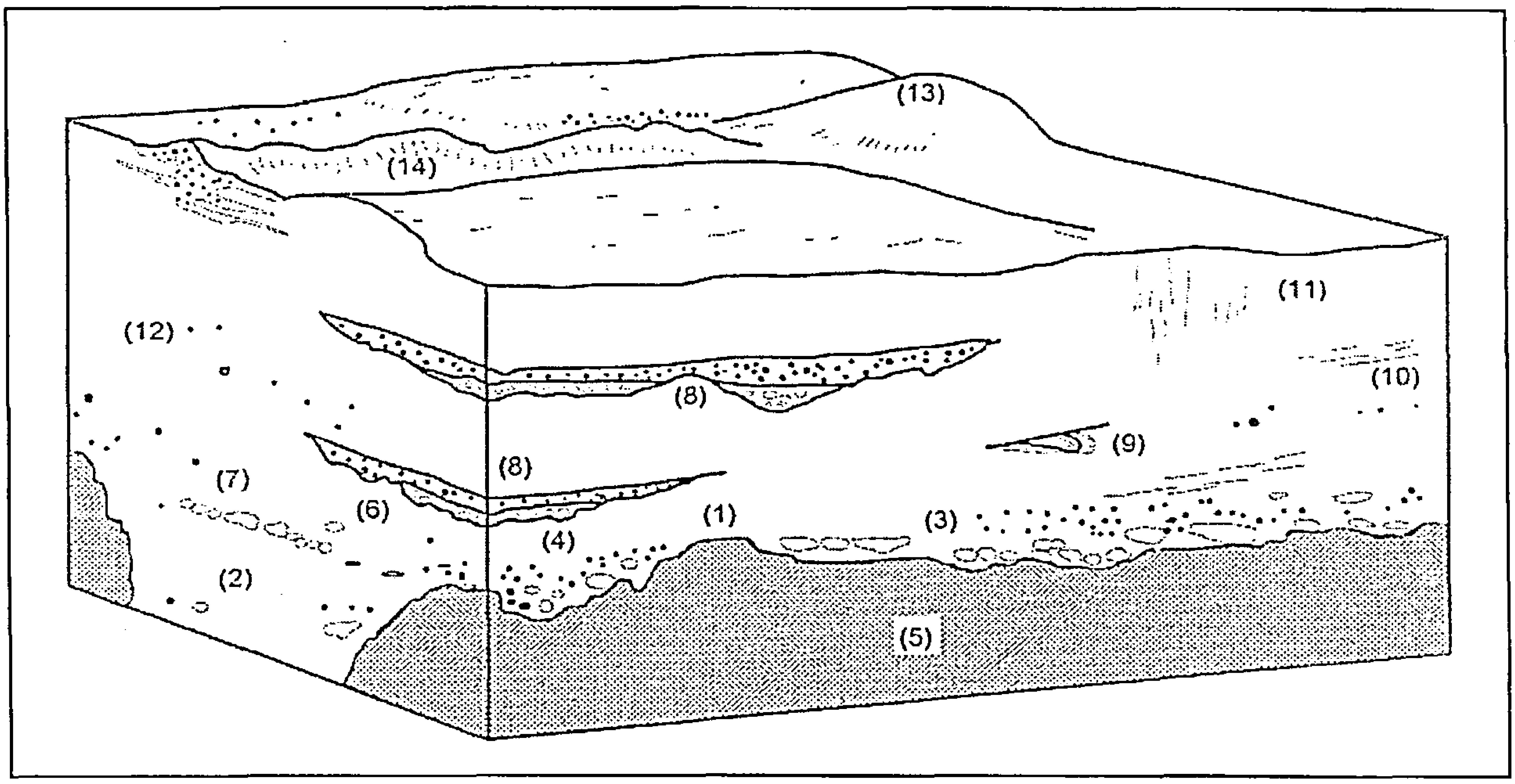
Each glacial cycle produces its own suite of deposits, besides reshaping those deposited during an earlier glacial cycle. As a result very complex glacial sequences can be built up by a series of ice bodies advancing and retreating over a given area. Glacial deposits produce a wide range of deposits and landforms.

A landsystem is a recurrent pattern of genetically linked land facets suitable for mapping. A land facet comprises one or more land elements (which are the simplest part of the landscape) and which can be grouped for practical purposes. A landsystem is also a part of a landscape, which is reasonably homogeneous and distinct from the surrounding terrain. Each landsystem can be defined in terms of the sediment complexes underlying and at the same time controlling surface topography.

The three main landsystems in glaciated terrain are the subglacial landsystem, supraglacial landsystem and the glaciated valley landsystem (Eyles, 1983; Trenter, 1999). These are reviewed in the following sections:

2.3.1 The subglacial landsystem

The definition of the subglacial landsystem recognises that landforms and sediments were deposited at the ice base. The landsystem therefore is the preserved bed over which the ice sheet moved. This model describes the pattern of deposition where the subglacial materials are eroded from the glacier bed and transported in a thin layer of debris due to a high rate of basal ice melt. Subglacial landsystems are typical of glaciated lowlands, such as English lowlands, where sediments were deposited by large ice sheets. This leads to extensive and sometimes deep cover of glacial soil.



Rockhead
1) Striated rockhead surface locally overdeepend by subglacial erosion
2) Buried channel over steepend by subglacial meltwaters and filled with subglacially derived sediments
3) Rock rafts, glaciotectonised rockhead and deformation till depending on bedrock lithology
4) Bouldery unit of debris filling cavities in rockhead surface
5) bedrock

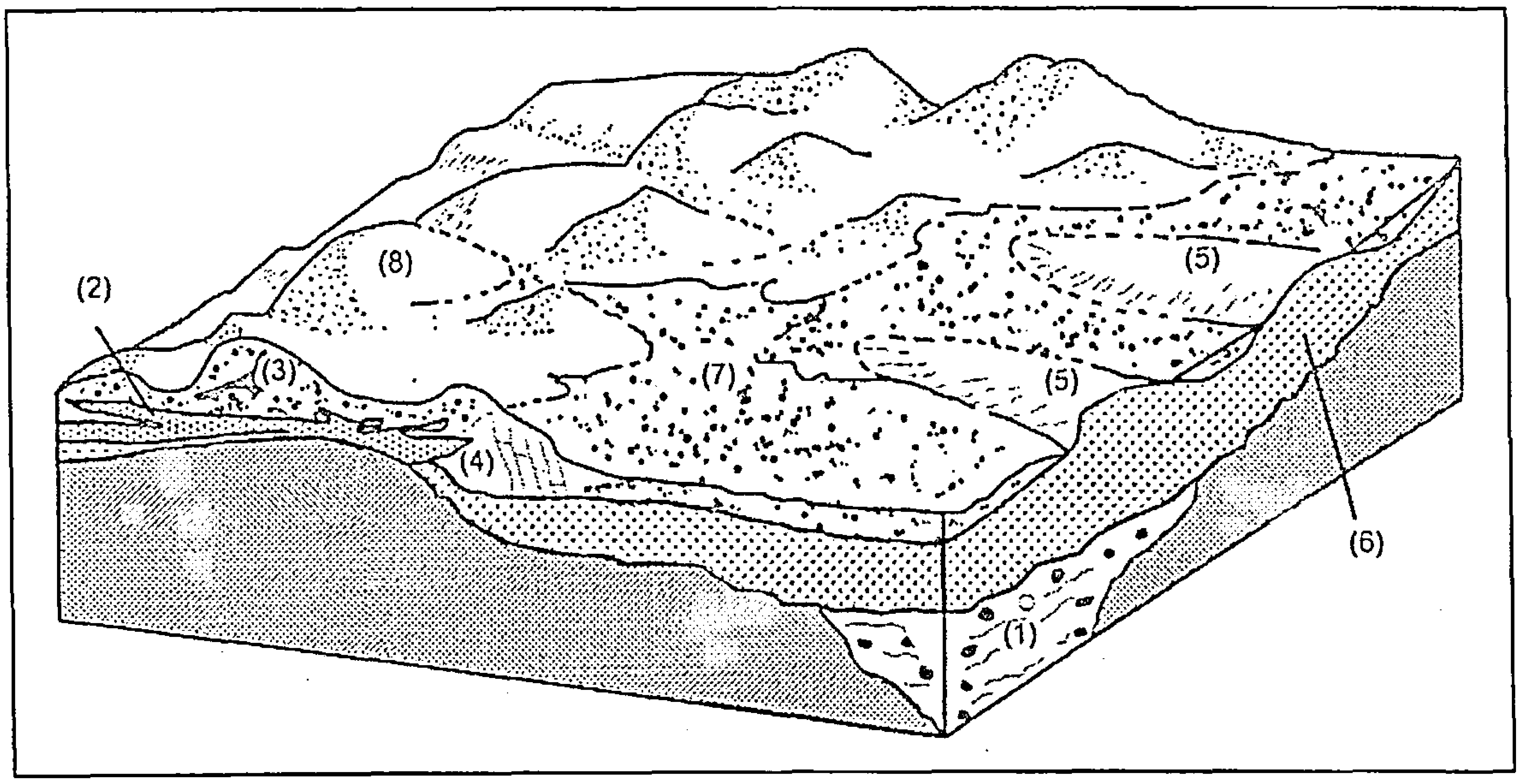
Glacigenic sediments
6) preferentially orientated clast along axis
7) distinct flat iron shaping of clasts composed of fine-grained lithologies; coarse grained lithologies produce clasts of higher sphericity, frequently found as boulder pavements
8) cut and fill fluvial sediments deposited as sand and gravels in interconnected subglacial channels or as laminated clays in subglacial ponds
9) fluvial sediments reworked, deformed and incorporated in subsequent tills
10) slickened bedding plane resulting from subglacial shear
11) near vertical joints oriented with respect to glacier flow direction
12) base of till units maybe fluted

Landform
13) drumlinised, streamlined, low-relief surface
14) a subglacial channel fill that survives as a positive topographic feature not having been shared off and buried by till (esker ridge)

Figure 2.2 : The subglacial landsystem (after Eyles, 1983 and Eyles and Dearman, 1981)

2.3.2 The supraglacial landsystem

In many continental areas, the streamlined bed of the former ice sheet is obscured by other glacial sediments, which were deposited from the ice surface during glacial retreat. These landforms and sediments, superimposed on those deposited subglacially, are collectively referred to as the supraglacial landsystem. This model describes the pattern of deposition and landsystems where the thickness of the basal debris is considerable. In this model a subglacial landsystem is obscured by other deposits, which were deposited during a glacier retreat.



Rockhead
1) subglacially cut buried channel, glacigenic debris filled

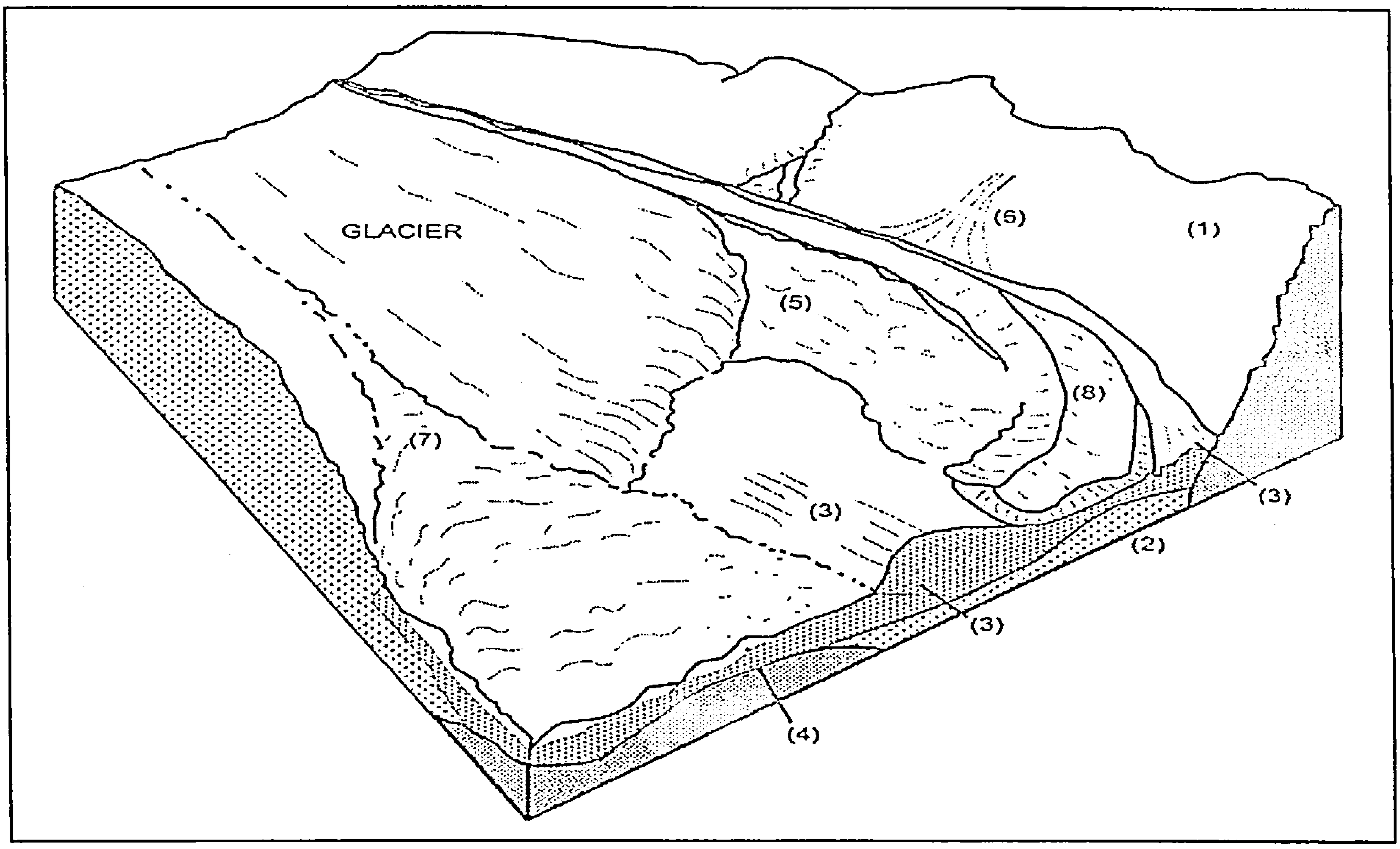
Glacigenic sediments
2) crudely stratified melt-out till formed by meltdown of basal ice with variable preservation of englacial clast orientation, frequently contains cobbles and boulders
3) flow tills
4) strata deforming as a result of meltdown of adjacent ice-cores
5) drumlins
6) buried lodgement till
7) supraglacial melt-out and flow tills

Landform
8) hummocky moraine obscuring streamlined surface of lodgement till

Figure 2.3 : The supraglacial landsystem (after Eyles, 1983 and Eyles and Dearman, 1981)

2.3.3 The glaciated valley landsystem

This terrain type is encountered in highland or mountain areas where mountains break ice sheets up into many separate glaciers that often coalesce on surrounding lowland margins. This model describes the erosion at the base of the glacier and debris deposition by valley glaciers. Coarse angular debris that are derived supraglacially from the valley sides are transported on the glacier surface. The thinning of the ice sheet results in the deposition of the debris by melt-out and flow processes. Glaciated valley landsystems are therefore usually characterised by thin tills and hummocky moraine topography along the valley floor. The Scottish Highlands and the Lake District are examples for this type of landsystem.



Rockhead
1) rocky hillock with a gently inclined, smooth slope facing up-valley resulting from glacial abrasion, and a steep, rough slope facing down-valley resulting from glacial plucking.
2) buried channel filled with glacigenic debris

Glacigenic sediments
3) lodgement till often hard or dense with streamlined drumlinised surface containing cobbles and boulders
4) thick hummocky sequences of supraglacial melt-out straddle valley floor and overlie lodgement tills in places
5) complex glaciofluvial sediments and flow tills deposited in bowl-shaped depressions or against lateral moraines
6) valleyside fans discharging large quantities of coarse debris to lateral moraines

Landform
7) medial moraine
8) lateral moraine ridge

Figure 2.4: The glaciated valley system (after Eyles, 1983 and Eyles and Dearman, 1981)

2.4 Glacial Processes

Sedimentary deposits are the outcome of a series of processes. A comprehensive description of a sediment should include details of its properties, which allows the reconstruction of its erosional, transport and depositional history, its geometry and its position with respect to the adjacent sediments and the land surface (Benn and Evans, 1998).

Any environment that is affected directly or indirectly by glacial activity is called a glacigenic environment. The processes that operate within such environments are reviewed below:

2.4.1 Glacier Flow

Glacial flows may be extensional or compressional depending upon the position within the glacier and the morphology of the underlying glacial bed. Basal sliding is responsible for the bulk of erosion, transport and deposition of glacial debris. Several factors contribute to the movement of ice such as gravity, pressure melting and re-freezing at the ice and glacier bed interface, and sliding on a basal water layer.

2.4.2 Transportation

Glacial debris is generally derived from erosion of the underlying glacier bed or from material that falls on to the glacier surface from valleysides. Glacially transported debris is released before or during ice wastage by a number of different mechanisms that control the type of glacigenic deposits formed (Trenter, 1999; McGown and Derbyshire, 1977). These are briefly reviewed below:

- Supraglacial debris

They are debris that are derived from rockfalls and carried on the glacier surface. They may or may not become incorporated in the glacier and may suffer frost shattering and washing by meltwaters as they are transported on the top of the glacier. These debris may also be transferred to an englacial position by the opening of crevasses in the glacier surface and move through the ice by gravity or differential flow processes.

- Englacial debris

Englacial tills may derive from supraglacial till subsequently buried by accumulating snow or entrained in shear zones and from the uplifting of basal debris by thrusting processes. They are spread throughout a glacier and are transported within the ice mass and are more abundant in polar regions than in temperate zones. Englacial tills can also derive from subglacial debris carried up from the bed along flow lines.

- Subglacial (Basal) debris

Subglacial (Basal) tills are derived from comminution products in the ice-glacier bed contact zones, particularly the lower most regions of a glacier where the glacier bed is eroded due to the movement of the ice sheet. They are generally released and transported in concentrated bands at the base of a glacier but can also be incorporated into the ice by pressure melting and regelation. As re-freezing occurs, debris may become attached to the glacier base. These debris layers can reach several metres in thickness.

2.4.3 Deposition

Glacial debris are released before or after ice wastage. The type of glacigenic deposit depends on the mechanism of release. Tills may be formed if deposition occurs directly from the ice. If debris are carried away by some agent they may deposit in glaciofluvial, glaciolacustrine or glaciomarine systems.

Tills are defined as sediments that have been transported and deposited by or from glacier ice, with little or no sorting by water (Ashley et al, 1985; Trenter, 1999). Tills as glacial deposits have been studied since the 1860s. This material was originally known as boulder clay but at the present day the Scottish word "Till" is preferred.

Glacial tills are complex soils that result from glaciation processes. The genetic term "till" gives no indication of composition. It is commonly known as an unlithified and poorly sorted mixture of fine to coarse sediments that often contain boulders (Flint et al, 1960). This arises mainly because glacier ice does not exhibit the sensitive competence to transport sediment shown by running water and wind (Ashley et al, 1985). Glacial tills are difficult to sample due to the wide particle size range. It is possible to find clay deposits with interbedded sands and coarse-grained soil up to boulder size. Large boulders are a characteristic of glacial deposits. It is also possible to find glacial tills without any boulders. In soil mechanics, the term till is a non-text book material, in that it is characteristically neither sand nor clay and does not conform to the depositional models upon which much of soil mechanics theory is based (Hughes et al, 1998).

The type and composition of till depends on the topographical features of the land mass prior to glaciation, the characteristics of the underlying rockhead, the mode of deposition and the moulding and remoulding which has taken place. Northern England is an area of quite variable bedrock type, and the composition of tills usually varies over short distances. This depends normally on the direction of ice movement. Tills consist of debris that have been transported by a glacier or ice sheet and therefore have a close relationship to the glacier from which they were deposited.

Tills were described as glacial debris deposited with little or no sorting by water. However, further water-borne transport of glacial debris is common and the resulting sediments are frequently associated with tills in preserved glacial sequences. Water-borne transport is usually by melt-water, which may be produced by surface, melting supplemented by rainfall and run-off from melting snow, subglacial melting due to geothermal and frictional heat, or melting due to pressures produced by mass flow. The glaciofluvial system is the drainage for a glacier and in many glaciated areas is the pathway for sediment deposition. Glaciofluvial sediments are therefore widely distributed in formerly glaciated areas and are commonly found as sand, gravel and cobble deposits with variable form and texture. They may be deposited subglacially in channels cut into till or bedrock beneath the ice, or ice marginally where streams of both glacial and non-glacial origin are forced to flow along the ice margins, or proglacially in an ice frontal position or down valley as the meltwater streams spread across the valley floor. A glaciolacustrine system is an extension of the glaciofluvial system and may occur subglacially, supraglacially or proglacially wherever meltwater becomes ponded into lakes where the sediments are deposited.

The processes operating within glacial environments are still not fully understood and information about the origin of tills is under constant review. This complicates the understanding of the geotechnical properties of tills that are characterised by a wide range of behavioural patterns and a high degree of variability. Various geological types of tills have been classified according to their mode of formation, transportation and deposition (McGown and Derbyshire, 1977; Trenter, 1999). Glacial tills have been divided into four genetic types based on their mode of transportation and deposition, which are shortly reviewed below:

- Lodgement tills

Lodgement tills result from the subglacial lodgement of debris in basal traction beneath a glacier. Lodgement is the deposition of till from the sliding base of a moving glacier by pressure melting or other mechanical processes (Ashley et al, 1985).

By pressure melting of the ice, debris are forced to be released and the tills to become lodged through frictional resistance against the glacier bed. If tills are deposited from mechanical processes, they are derived from rock and material debris plucked from the ground by deep shearing actions at the base of moving ice sheets. Lodgement tills may suffer varying degrees of shear and stress relief that may influence their fabric (McGown and Derbyshire, 1977; Bennet and Glasser, 1996). Lodgement tills occur by slow incremental accretion of debris in the basal zone or the lowest englacial part of a glacier (Boulton, 1975). In terrain comprising weak rocks or unlithified sediments the forward movement of the ice may actually be due to sliding within a deforming layer of till where the till itself is transported in a highly fluid state (Boulton et al, 1991). In hard rock terrains, subglacial lodgement till is deposited by the ground being plastered with crushed rock debris at the sliding base of the glacier (Hambrey, 1994). The tills may be deposited on bedrock or other older till surfaces, in some cases they may be reincorporated and reworked by a glacier again elsewhere.

- Melt-out till

Melt-out is the slow release of debris from glacier ice that is not sliding or deforming internally. Melt-out occurs in some places from ice bodies that are wholly stagnant. Elsewhere it occurs from stagnant, basal ice that is separated by a sliding plane from overlying active ice (Ashley et al, 1985). Slow melting of buried ice beneath a layer of supraglacial ice may release debris referred to as melt-out till, and stagnant ice beneath confining overburden ice may release debris which is called subglacial melt-out till. Melt-out tills accumulate as the ice of an ice-debris mixture melts out. Ice inherited fabric may or may not be greatly changed during deposition. These tills usually preserve some of the elements of an englacial till fabric (McGown and Derbyshire, 1977; Boulton, 1976).

- Flow till

Flow tills may be derived from freshly deposited tills released subglacially or supraglacially due to water flowing down the slope by gravitational forces. These are a type of till that have been secondarily transported and emplaced by debris flowage. When debris on the ice surface becomes saturated it may begin to creep, slide and flow. Flow tills may accumulate as a result of either lodgement or melt-out tills deforming by flow due to high porewater pressures, slope instability or imposed stresses (McGown and Derbyshire, 1977).

- Deformation till

Deformation tills consist of weak rocks or unconsolidated sediments that have been detached by the glacier from their sources and tectonically deformed between bedrock and lodgement till by the action of moving subglacial material when the pressure imposed by the glacier exceeds the strength of the glacier bed. They are produced by plucking, thrusting, folding and brecciation of the glacier bed which means that the primary sedimentary structures are distorted or destroyed and may be mixed with foreign material (Trenter, 1999; McGown and Derbyshire, 1977).

The different glacigenic sediments are shown in Figure 2.5.

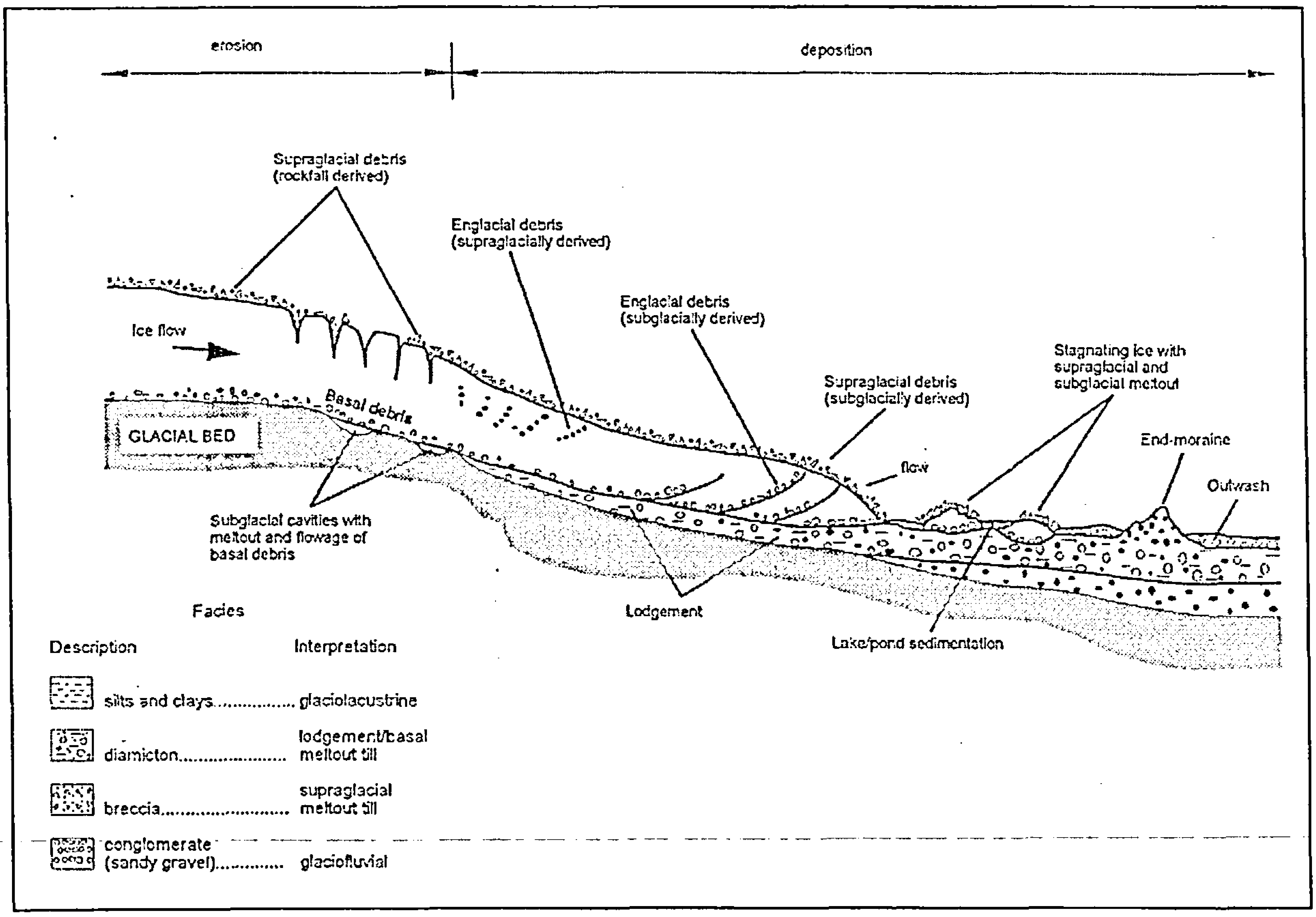


Figure 2.5: Cross section of a typical temperate glacier illustrating the various glacigenic sediments. (after Hambrey, 1994)

These genetic classification systems have been subdivided into smaller groups also based on the criteria mentioned above, and may be used to predict likely engineering properties. The characteristic variability of tills is neither predicted nor accommodated in these systems; hence this problem restricts the usefulness of these classification systems.

The process from which tills are produced are shown in Figure 2.6. This figure only refers to one ice advance and retract.

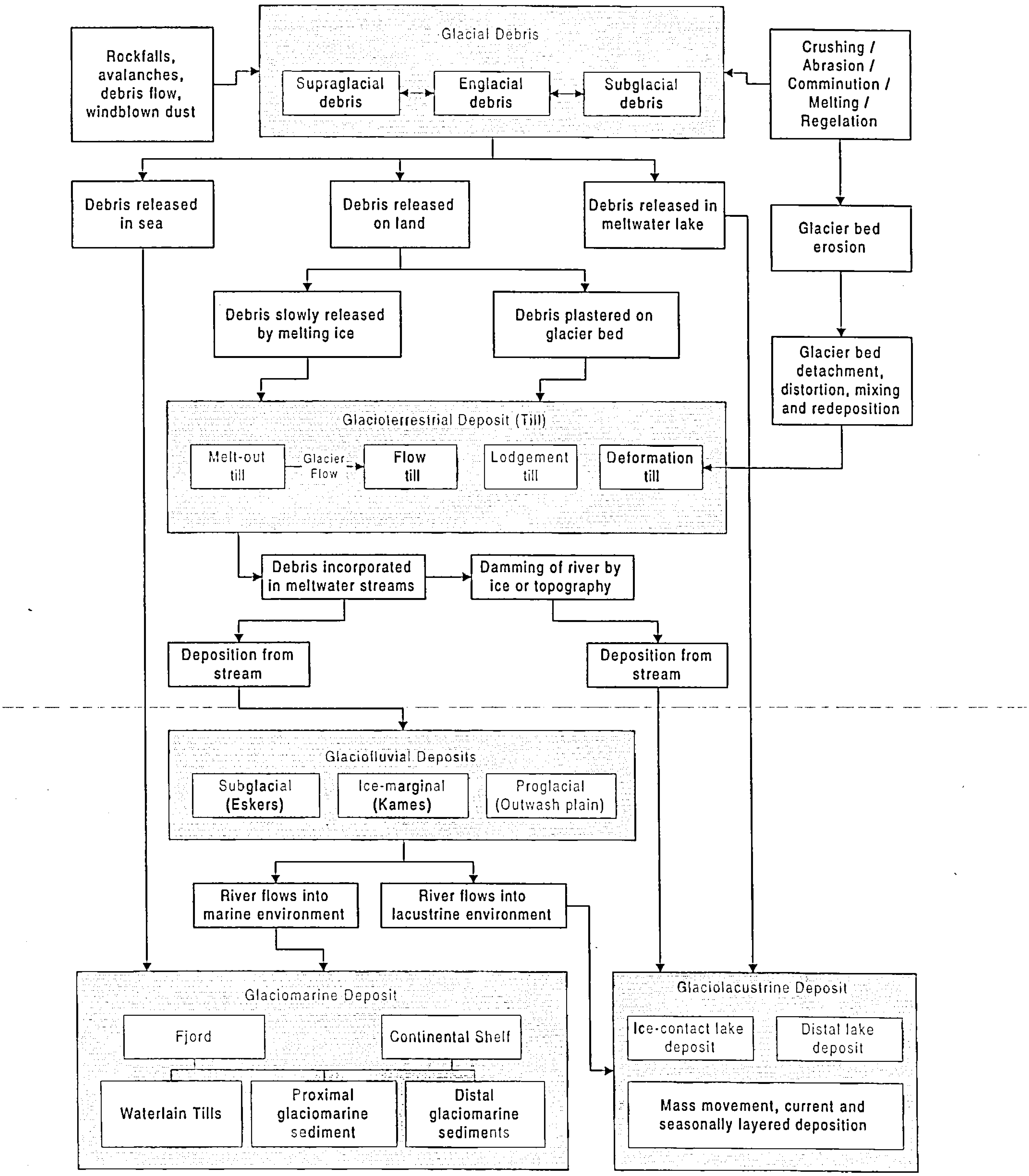


Figure 2.6: Evolution of glacigenic deposits (after Trenter, 1999)

In the classification of glacial sediments a distinction is sometimes made between primary deposits, which are laid down by the glacier, and secondary deposits, which have undergone some form or reworking by non-glacial processes (Dreimanis, 1989). The primary deposits include tills deposited from a subglacial deforming layer, or by lodgement or melt-out, and the secondary deposits are composed of glacial debris that are remobilised and deposited by gravitational flowage, stream flow or other agencies (Benn and Evans, 1998).

However, the boundary between the primary and secondary deposits is arguable and it is not clear at what point sediments loose their unique glacial character. Since some processes explained earlier can be repeated more than once, the tills may contain features of ice re-advances. Most of the classification systems mentioned earlier do not take into account the fact that tills may contain features of previous ice advances and hence do not relate to the properties of the tills. Figure 2.7 demonstrates a model of the glacial sediment system for valley glaciers and also demonstrates such re-advances.

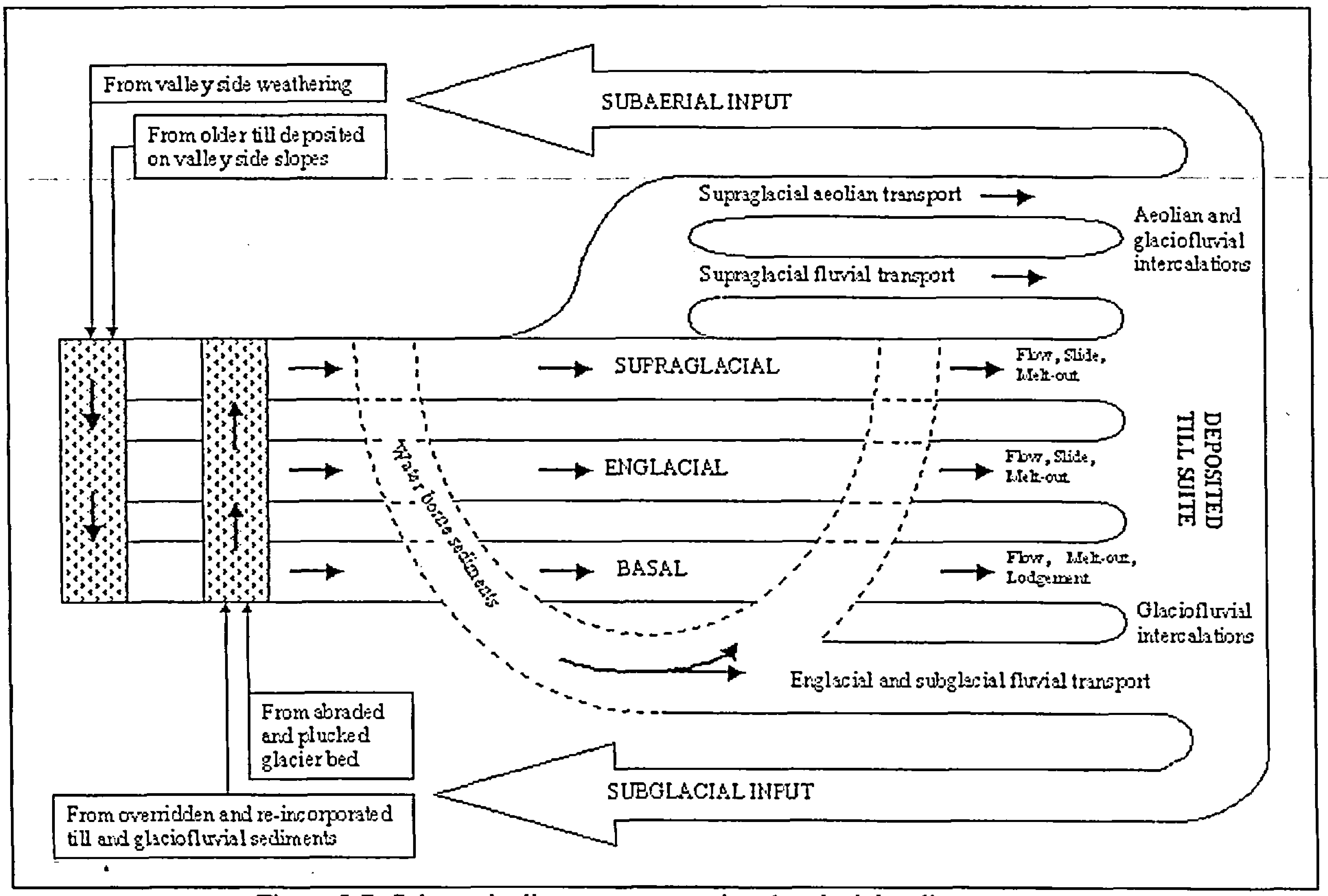


Figure 2.7: Schematic diagram representing the glacial sediment system
(After Derbyshire and Love, 1986; Fookes, 1991)

By selecting the appropriate sampling and testing techniques, and by including other physical features of the tills in the classification, it is possible to further subdivide them and identify the factors contributing to till variability more closely. The difficulty lies in the recognition of the parameters and their manipulation for including them in the system (McGown and Derbyshire, 1977).

2.5 Geotechnical properties of glacial tills

It has been stated that the geotechnical properties of glacial tills depend principally on four factors (Boulton, 1976):

1. The grain size distribution and mineralogy
2. The nature of the sequence within which they occur
3. The stress history which they have undergone
4. The presence, frequency and orientation of joint planes within them.

The variability in the geotechnical properties of glacial tills is mainly due to their depositional and post-depositional history and is the result of three basic processes (Paul and Little, 1991). The first phase is the erosion and transport phase endows the material with its basic composition and grading. The geotechnical character of a till is determined by the substrate that has been eroded during its formation. This leads to the distinction between clast dominant and matrix dominant tills. Clast dominant tills are the result of the erosion of the coarse sedimentary bedrock, and matrix dominant tills are formed by the erosion of fine grained lithologies. The transport process governs the grading of the material which often generates a relationship between the Atterberg limits that causes them to fall on a defined band on a plasticity chart which is referred to as the T-line. The behaviour of glacial deposits with respect to the A-line and T-line depends on the clay minerals, size, shape and grading of the material. If clay minerals were replaced by rock flour, which is typical of the hard rock terrains in northern Britain, the plasticity data would plot further to the left which means that the plasticity will be reduced (Trenter, 1999).

The deposition phase is the second phase that changes the grading and controls the initial water content of the till. During deposition the constituent particles of the till are brought together. Material that has been deposited by subglacial lodgement usually has a packing that gives a high density. Melt-out tills have a more open structure and subsequently a lower density (McGown and Derbyshire, 1977).

The third phase is the post-depositional phase that may alter any or all the above characteristics. Re-sedimentation process causes the grading to be changed during flow and this might change other properties of the tills. Weathering is another process that can further change the geotechnical index properties of the soil. These changes can be summarised as follows (Sladen and Wrigley, 1983):

- increase of clay and silt content due to mechanical disintegration, which results in increased plastic and liquid limits and plasticity index.
- increased clay content and increased activity due to the formation of secondary clay minerals which also results in increased plasticity
- increased moisture contents.

Several studies on the geotechnical properties of Northern England were carried out which are reviewed below:

- The geotechnical properties of glacial deposits in northwest England were investigated by Alderman (1959). A succession comprising of upper glaciofluvial clays and sands, lower glaciofluvial clays and sands have been reported for this area. This succession however can not be compared with the tripartite stratigraphy in Northumberland. In this research the geotechnical properties of the glacial till such as index properties, shear strength and compressibility have been determined from tests carried out on intact soil samples from that area.
- The geology of the Cromer Till between Happisburgh and Cromer was studied by Kazi and Knill (1969). In this study the glacial deposits were divided into Upper Cromer Till, laminated beds and Lower Cromer Till. The sediments studied were reported of being heavily overconsolidated and fissured. Geotechnical properties of classification, strength and consolidation of these sediments have been determined. Due to the presence of boulders and fissures the preparation of adequate samples for triaxial tests was difficult and hence direct shear tests were carried out on undisturbed samples from this area.
- The geological and geotechnical properties of glacial deposits in southeast of Northumberland were studied by Thabet (1973). The glacial deposits in this area consist

mainly from upper and lower tills, which are separated by laminated clays and / or glaciofluvial sand. This research concluded that the three glacial successions were not present at some sites. The link between the geological aspect and mechanical properties was investigated by studying particle size distribution, clay mineralogy, compressibility and strength.

- The glacial till in the coasts of Northumberland were investigated in terms of stratigraphy and geotechnical properties of weathered lodgement till by Eyles and Sladen (1981). This research attempted to explain the mode of deposition and the degree of weathering in the tripartite stratigraphy. It emphasised on the weathering zones and the effect of weathering on the geotechnical parameters of tills. It was suggested that weathering was associated with the increase of fine particles, which would lead to higher moisture content, and plasticity and decreasing shear strength.
- Another study was carried out on the geotechnical properties of a number of sites in Northumberland in order to determine the depth and the properties of the surficial deposits (Robertson et al, 1994). A glacio-litostratigraphic model for the tills of Northumberland based on the study of excavated faces of opencast sites and analysis of site investigations was proposed. This model is consistent with the general patterns of occurrence described as the succession of glacial tills and identifies four discrete units (Figure 2.8).

  In this model the Upper Till is defined as an ablation or melt-out till and is subdivided into an upper weathered layer (Unit 1) and a lower relatively unweathered layer (Unit 2). The Lower Till (Unit 3) lies below the ablation till and is considered to be primarily a basal till. These tills contain lenses of sands/gravels and laminated clay which are grouped together as Unit 4, which occur within Unit 2 or between Unit 2 and 3, but rarely within Unit 3. Boulders are commonly encountered in Unit 3. Laminated clays and sand units frequently show inclusions of irregular till masses having either melted out from the ice roof or been eroded from adjacent till slopes along the sides of subglacial melt-stream ponds.

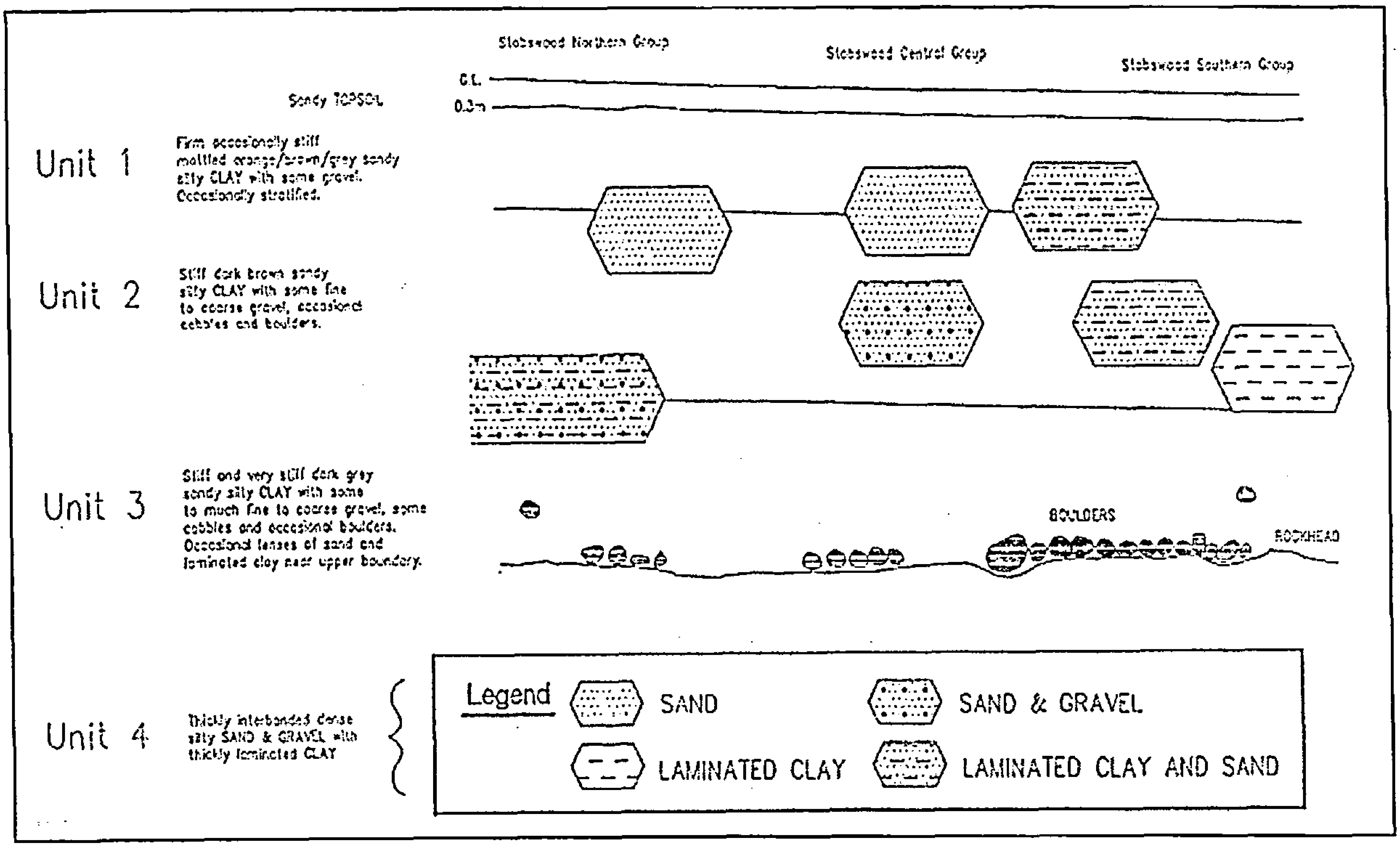


Figure 2.8: A model of the glacial litostratigraphy of Northumberland glacial deposits in Stobswood (after Robertson et al, 1994).

The works reviewed above represent research into the geotechnical properties of glacial tills. These were mainly carried out on undisturbed till samples. A summary of the results derived from the above mentioned research can be found in table 2.2.

Table 2.2: Geotechnical parameters of glacial tills derived from previous research

Researcher	Till Type	% w	LL	PL	ρ_d	c_u	c'	φ'
Alderman (1959)	Upper Till	10-26	22-56	12-24	---	100-159	---	0-17
	Lower Till	10-16	22-35	9-16	---	110-527	---	0-21
Kazi & Knill (1969)	Upper Till	11-13	28-36	15-20	---	28-55	---	---
	Lower Till	11-13	28-36	14-21	---	35-55	---	25-30
Thabet (1973)	Upper Till	20-24	43-51	18-21	1.92-2.09	91-197	---	---
	Lower Till	12-16	29-33	14-18	2.18-2.21	226	---	---
Eyles & Sladen (1981)	Upper Till	12-25	35-60	15-25	1.9-2.2	---	0-25	27-35
	Lower Till	10-15	25-40	12-20	2.15-2.3	---	0-15	32-37
Robertson et al (1994)	Upper Till	9-34	---	---	1.77-2.59	50-410	0-11	22-30
	Lower Till	9-23	---	---	1.92-2.46	65-410	0-20	25-30

2.6 Engineering problems in glaciated terrain

Glacial deposits are frequently associated with earthworks and slope instability. The variable and often complex successions in which glacial tills occur have frequently led to problems. Some of these problems are briefly reviewed below:

Experience in opencast mining and other excavations have shown that the presence of laminated clay layers, even if they are only a few millimetres thick, can have significant effects on slope stability due to their relatively low shear strength and tendency to soften rapidly when unloaded (Hughes et al, 1998). Problems that might occur during excavation in glacial tills can be summarised as follows (Trenter, 1999):

- The possibility of misidentifying cobbles and boulders for rockhead, which needs to be established during site investigation, could lead to problems in the progress planning and costing purposes
- Failure to correctly assess large boulders and cobbles during site investigation can lead to wrong choice of plant during the main works, with delays and disruption in the excavation process
- Excavation in glacial terrain can be interrupted when water-bearing soils are penetrated. Low plasticity tills can rapidly turn into a slurry in the presence of water and it is therefore important to identify the extend of these material during site investigations.

Several cases of slope instability of roadworks during constructions in Northwest England were reported by Arrowsmith (1985). The slips in glacial material in this area were attributed to the presence of laminated clays with low shear strength. Other cases have revealed that some slope failures in glacial tills have occurred due to the use of total shear strength rather than the effective stress parameters during design (Batchelor et al, 1985).

The estimation of shear strength parameters is a necessary pre-requisite to stability analysis and slope design in earth works. It is suggested that granular soils do not posses true cohesion or cement between the particles and thus the conventional linear Mohr-Coloumb failure criterion is misleading in applying an apparent cohesion to exist (Whyte, 1985). Failure envelopes may not be conventionally linear and can be curved, with the degree of curvature depending on soil type, grading, density and mineral composition. Based on shear box tests carried out on glacial tills it is suggested that these material possess non-linear strength properties (Whyte, 1985). The degree of non-linearity generally increases with increasing coarse soil fraction. Soils exhibiting non-linear strength properties have a reducing safety factor with increasing depth below the slope. To establish reliable strength parameters, representative sampling and correct test procedures are required.

The construction of retaining structures is associated with problems like obstruction due to cobbles and boulders, water problems associated with permeable inclusions or random seepage paths (Cocksedge, 1983). Granular tills can be a source of seepage. This can be short-term if the material is a lens of limited extent, or can cause long term problems of ingress of water if of large extent or subject to recharge (Hughes et al, 1998).

Problems also appear while tunnelling in glacial deposits. Unpredictable lateral and vertical variation of material type and troublesome groundwater flow are the main problems. Water-laid sand lenses, which occur randomly within till layers, could create problems in excavation and tunnelling especially if they are water bearing.

Problems that may occur during piling in glacial tills have been reported as follows (Weltman and Healy, 1978; Trenter, 1999):

- Identification of the bedrock, which should not be assumed unless there is some evidence.
- Open-drive sampling, in-situ testing and pile installation becomes more difficult with the increase of coarser material in the till. In these situations it is important to establish the grading of the till with particle size distribution tests on a representative sample.
- The presence of large boulders can obstruct the pile installation. Using robust driven piles capable of penetrating obstacles, the use of heavy chisels and down-the-hole hammer are some methods that could overcome this problem.

Another case with problems associated with glacial deposits was reported when site investigation were carried out in order to investigate the ground conditions for the construction of a nuclear power station in Hartlepool (Fookes et al, 1978). Due to the wide variation in grain size, and shape of the material it is difficult to generalise their engineering properties and behaviour. Therefore it was hard to predict the bearing capacity and settlement characteristics of these glacial deposits. For this reason, the foundations of the reactor had to be taken to the bedrock through water bearing glaciofluvial deposits.

Due to the fabric of tills there is a large range of values for the properties of glacial tills. For a better understanding of the properties and the behaviour of glacial tills it is best to consider the origin, geological history, and the structure of the till in addition to the results of laboratory tests. Analysing available data of the geotechnical properties of tills in areas where engineering problems are encountered or expected can help to prevent or to find solutions to these. Data may be obtained from public or private sources, site investigations, laboratory testing, previous publications, etc. The best way of saving large amounts of data and having easy access to them is the use of databases. The purpose of this study is to analyse the geotechnical design parameters of Northern England glacial till. In order to do this data from various sources were obtained. The most effective way for storing the data for further analysis or modelling was to put them into a database. Database technology has been a part of computing for many years and can provide a tool to extract information from datasets. In the following section the use of databases in geotechnical engineering is briefly reviewed.

2.7 Databases

Geotechnical Engineers are constantly solving new problems. This frequently involves the re-examination and re-interpretation of old data using new theories or new knowledge. That means they are re-using old data in new ways and therefore they need a varied source of data which can be analysed in many different ways. The difficulty arises not with the nature of the data in each record, but with the number of records that are involved, especially in large projects (Finn and Eldred, 1987). Datasets are sometimes so large and of such variety that the information they contain are obscure. Problems that are related to the search of a particular project or difficulties in the search for specific problems, and sometimes the loss of some valuable information, lead to the use of databases in the field of geotechnical engineering. A database is actually nothing more than a computerised record-keeping system or, in other words, a kind of electronic filing cabinet. The initial reason for the development of databases was to centralise all available data in a common format. This immediately simplifies any comparative studies undertaken, and assists in the identification of any problems with existing data, and highlights areas where data are rare and hard to find. The benefit of this system is that the user can perform a variety of operations rapidly. During the course of site investigations large volumes of various data are collected. These data must be judged and analysed to achieve the best engineering solutions. Some examples in which databases have been designed and used to store site investigation data are reviewed below:

- Geoshare is a geotechnical database that was designed to act as a data management tool for site investigation data (Day et al, 1983). The database was used to store and search for geotechnical records and was designed to handle all aspects of data management in a site investigation project from the input of records to the analysis of the retrieved information. A database management system called Codasyl was used for the storage of data. The processing is carried out using Cobol and Fortran codes. A study carried out on this database showed that there were weaknesses in the retrieval system and the management of the site investigation data (Raper and Wainwright, 1987). The retrieval of data was difficult due to the grammatically complex descriptions of borehole logs, which were not following any standard. Searching for various composites that could exist in a soil was a difficult task hence a need was identified to develop a standard for description procedures and to simplify and restrict the range of terminology; also to reduce the overall number of words.
- The National Geological Record Centre (NGRC) in UK which administers the British Geological Survey (BGS) documentary collections of original geological data and the indexes to the data. The NGRC has collected large collections of borehole records, geological maps, site investigation and road reports, information on waste sites and mine plans. In order to centralise and improve access to BGS data they have been indexed and stored on a database, called the "Geoscience database". This database was designed using Oracle, which is a relational database management system (Database management systems are discussed in more detail in the next chapter). An interface was designed using a menu-aided retrieval system called Mars, which is a combination of a Pro-Fortran program and a purpose built Oracle database table. This minimises the involvement of the user with the complexities of the Oracle SQL program language. Selected queries can be run and the results can be produced as lists or graphical plots. The database is linked to Arc/Info, which a Geographic Information System (GIS) that can be used to produce digital maps using the data stored in the database (Bowie, 1995).
- The UK Nuclear Industry Radioactive Waste Executive (Nirex) is responsible for providing and managing facilities for the safe disposal of radioactive waste. The preferred disposal route for such waste is the use of deep underground repositories. Nirex has

carried out extensive investigations in West Cumbria in order to determine if the site around Longlands Farm near Sellafield could be suitable for a deep underground repository. Several deep boreholes were drilled in the Sellafield region in order to understand and describe geological and hydrogeological processes that may influence the post closure safety of a repository. These activities have generated large quantities of data. The Nirex Digital Geoscience Database (NDGD) was developed to facilitate efficient storage and access to the large quantities of data from site characterisation programs. A relational database was designed using Oracle to centralise the data in a controlled and secure environment. The NDGD is managed on behalf of Nirex by the British Geological Survey (BGS). A GIS is operating along with the database to generate geological maps using the data stored in the database (Nirex, 1996).

Some of the problems that were encountered in the use of databases led to further research and the introduction of standard formats and rules to overcome such difficulties mentioned earlier. For instance a format was introduced by the Association of Geotechnical and Geoenvironmental Specialists (AGS) for the storage and electronic transfer of data (AGS, 1999). This format, which has been completed and updated over several years, introduces a dictionary for the use in the geotechnical industry. The AGS format is discussed in more detail in Chapter 3.

Due to the rapid growth in the use of personal computers large numbers of databases have been developed and techniques have also been improved. Several commercial database packages have been especially designed for the storage of geotechnical parameters. Some of these software packages are briefly introduced below:

- GEODASY (GEOtechnical DAtabase SYstem) is a program designed for geotechnical data management in a Microsoft Windows platform. It produces reports and carries out dataprocessing with graphical output such as borehole logs, moisture content and Atterberg Limit plots, grading curves, and also permits AGS data export. (Geodasy, 2002).
- gINT for Windows (gEOTECHNICAL INTegrator) is a database manager and report generator for geotechnical and geo-environmental investigations. It includes logs, graphs, histograms, tables, and data summaries. Output can be to a printer, AutoCAD DXF file, Windows Bitmap file, or gINT Drawing file. Text tables can be output to a variety of

ASCII file formats and to a spreadsheet file. The program supports both export and import of ASCII format and the AGS data interchange format files. Each project is stored in one Microsoft Access compatible file (gINT, 2002).

- SID (Site Investigation Database) is used to enter, store and output geotechnical data from site investigation fieldwork and laboratory testing. It produces borehole and trial pit logs and plots field and laboratory test result graphs. Data can be imported and exported in AGS format to and from spreadsheets. Site plan and geological section plotting and calculation of derived parameters from test results are possible; as are links to AutoSketch or AutoCAD for log, plan and section drawing, and to Grapher and Surfer for plotting (SID, 2002).
- HoleBASE II is a database application dedicated to the storage, manipulation, and presentation of geotechnical and geo-environmental data from ground investigations. Features include Site Plan and Geological Sections, batch printing of multiple forms and borehole logs, and query and report facilities. This package includes: Multiple Project Relational Database, Geotechnical and In situ Test Tables, Data Entry Screens with on-line Help and Spell Checking, Form Designer for Borehole Logs, Data Charts, and Header Sheets, Import/Export of Borehole and In situ Test Data (HoleBASE II, 2002).
- TECHBASE is a software package for the Mining, Environmental and Geotechnical industries. Based around a relational database for exploration geology and engineering information provides facilities for database management, statistics, graphics and graphical analysis, 2D and 3D modelling, groundwater, slope stability, co-ordinate conversions, data and graphical transfer to and from most other programs. It handles AGS format data. The software also produces cross-sections with modelled soil layers, and borehole logs (Techbase, 2002).

Other commercial software such as Oracle or Microsoft Access are also available for the design of specific databases. Unlike the purpose written geotechnical database packages, these software platforms make it possible to design the structure of a database according to the needs of a project, and have the advantage of being more flexible for applying structural changes to the design of a database if required. It was therefore decided to design a database for this study, which would be especially tailored according to available data and the requirements of this project. The software and its file format needed to be compatible with the format of other software such as Microsoft Excel, which was going to be used for the analysis of the data. A stable and consistent platform was required that would allow the complex relationships between diverse datasets to be modelled effectively; and would also allow design modifications to be made without affecting the integrity of the data. Microsoft Access was found to be appropriate for the aims of this project and was chosen for the design. Further details about the capabilities of this software and the design of NETDATA database will be given in Chapter 3.

Results of several site investigation reports from various companies are stored in the database. Details of the site investigations, their data and the geology of the sites will be discussed in later chapters. The available data sets where then used for further analysis and modelling of various parameters related to tills. One of the methods for modelling data, and finding correlations between the different parameters, is by using artificial intelligence, which is reviewed, in the following section.

2.8 Artificial Intelligence

Artificial intelligence refers to the use of computers to imitate or supplement the activities of intelligent human beings. Various types of artificial intelligence exist. Two types which are frequently used in the field of geotechnical engineering are Expert Systems and Neural Networks (Toll, 1996). They are explained briefly in the following sections, and some of their applications are also reviewed.

2.8.1 Expert Systems

Knowledge-Based Expert Systems (KBES) are a model of artificial intelligence that have become very popular for their use in solving several engineering problems. They can be developed in general programming languages or in special artificial intelligence languages. Expert systems are described as computer programs that can advise, analyse, categorise, consult, design, diagnose, explain, explore, identify, interpret, justify, manage, monitor, plan, present, retrieve, schedule, test and tutor (Adeli, 1988). They use artificial intelligence techniques, which involve human knowledge and experience in solving problems that would otherwise be solved by an expert in a larger amount of time. They can embody organised knowledge concerning a variety of tasks and inference procedures to solve problems.

A KBES comprises several components as shown in Figure 2.9. These are: a factual database, a knowledge base, an inference mechanism and a working memory (McCracken and Cate, 1986; Adeli, 1988). The factual database contains real case data. The Knowledge Base is the repository of information relating to a particular task or application derived from a human expert and it comprises documented definitions, facts, rules, procedures and objects. The inference mechanism, also known as the inference engine, carries out the reasoning process to solve definite problems using question-and-answer consultations with factors relating to the application. The inference mechanism is a kind of interface between the knowledge base and the database that matches the conditional clauses of the rules with the case data. The working memory of the Expert System is used as temporary storage for facts discovered during a consultation. Its content alters dynamically and comprises information provided by the user about the specific problem and information derived by the system.

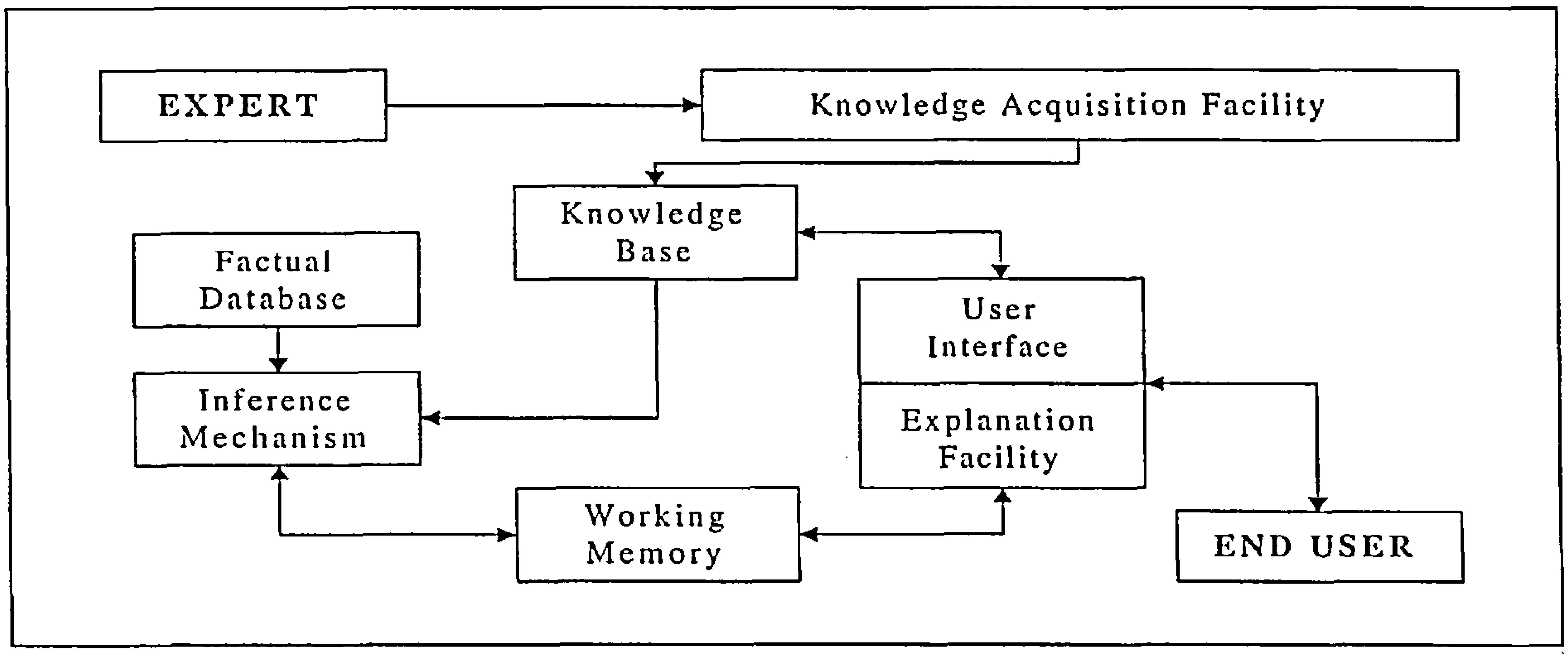


Figure 2.9: Components of a Knowledge-Based Expert system.

An Expert System is based on two fundamental principles, being the appropriate representation of domain knowledge and the control of this domain knowledge. A database management system which is used to access and manipulate data stored in a database, acts as the interface between the users, the application program and the database; and it shares the same overall objectives as knowledge representation schemes for Expert Systems. Expert Systems provide a useful reasoning ability in query optimisation tasks. The database management system technique will contribute to Expert Systems in giving them the ability to access large collections of facts and optimise access to knowledge base items

However Expert Systems will not replace the expert, but can assist those who are less knowledgeable in the subject domain in using the knowledge of more experienced experts (Kaetzel and Clifton, 1995). Knowledge Based Expert Systems are best used in situations where the knowledge needed to solve the problem is already understood and can be solved by an expert in a reasonable time. The common problem with Expert Systems was that of knowledge acquisition during the use of the Expert System. Expert Systems are not able to learn by themselves (Kaetzel and Clifton 1995, Moslehi et al, 1991). Research in automated knowledge abstraction from cases, and automated adaptation through machine learning and inductive systems, have not been successful yet. The major problem in these automated methods is in determining what to learn and when to learn (Melhem et al, 1996; Fenves, 1996).

It has been suggested that expert systems can be used successfully in geotechnical engineering, especially soil classification (McCracken and Cate, 1986). Some of these attempts are briefly reviewed below:

- An Expert System for soil classification was designed and used to identify the type of soil in accordance with the AASHTO recommendation from laboratory results of a soil sample. In the AASHTO soil classification system the soils are divided into groups and subgroups based on results from laboratory tests for sieve analysis, liquid limit and plasticity index (Malasri, 1988).
- An Expert System was developed that takes a soil description as input and attempts to match it at the appropriate level of detail within the knowledge base (Toll and Giolas, 1995). The match can be done both in terms of the ground type and on qualitative properties such as plasticity, particle shape, etc. A database was developed as part of the knowledge base and holds the data on which any interpretation is based (Toll and Oliver, 1995). The knowledge base holds ranges of typical values for the parameters for a wide variety of ground types. In this system, when a ground parameter is specified, the parameters needed for its evaluation and their permissible 'typical' values may be retrieved.
- GeoPredictor is a system that has been developed for the prediction of geotechnical parameters. For this system a case-based reasoning technique is used to consult a database

containing ground investigation data. The input is compared with the case base of solutions, and this then retrieves a matching or near matching case. The best match will be shown as the output. Some success was achieved in obtaining results using this system (Davey-Wilson and Mistry, 1995).

Some advantages of using expert systems in classifying soils are written below (McCracken and Cate, 1986):

- The application of judgement, experience, and intuition of soil scientists through knowledge engineering.
- Arranging this knowledge with the use of database techniques.
- The ability of computer to evaluate and establish soil relationships very quickly.

Problems that have been identified whilst using expert systems for soil classification or the prediction of soil parameters have been described as follows:

- If no values can be assigned to the soil-group the Expert Systems completes the analysis without an appropriate answer (Malasri, 1988). That shows that the expert system can only work within the available information, and can only solve limited problems.
- In the process of acquiring the knowledge base, expert systems use facts and rules, which are generally accepted. However, in some cases these may not be true, and therefore are often narrow in scope and address a specific set of problems (Kaetzel and Clifton, 1995).
- Uncertainty in data, which is the essence of something that is only believed to be true instead of known to be true, is another problem associated with Expert Systems. Although assigning a certainty factor to the facts in the knowledge base could help, it is generally not clear how such factors should be combined to provide consistent and reasonable estimates of how sure the system should be of the solution to each problem.

To overcome the limitations mentioned above a different type of artificial intelligence called Neural Networks can be used. One advantage of Neural Networks is that unlike Expert Systems they have the ability to learn from experience and can adapt to data which were not seen before, or which are incomplete. This eliminates problems associated with prior knowledge acquisition. In this study Neural Networks have been used to predict various soil parameters and also to classify glacial soils of Northern England. The following section describes Neural Networks briefly and reviews some of their applications in the field of geotechnical engineering.

2.8.2 Neural Networks

Research in Neural Networks stems from the idea that simulating, on a computer, the way that the brain processes information may prove useful in understanding thought processes. Since the paramount goal of Artificial Intelligence is to make machines or computers perform tasks like humans (such as learning, speech and image recognition) it is believed that Neural Networks have the greatest potential to achieve this goal. The brain is a highly complex, non-linear and parallel information-processing system. It has the ability to build up its own rules through what is referred to as "experience". The brain has the ability to organise its structural constituents known as neurons to perform certain tasks.

It is believed that biological neurons are the structural constituents of the brain (Jain et al, 1996). A neuron permits the developing nervous system to adapt to its surrounding environment. Each neuron is a specialised cell, which can propagate an electrochemical signal. The neuron has a branching input structure (the dendrites), a cell body, and a branching output structure (the axon). The axons of one cell connect to the dendrites of another via a synapse. When a neuron is activated, it fires an electrochemical signal along the axon. This signal crosses the synapses to other neurons, which may in turn fire. A neuron fires only if the total signal received at the cell body from the dendrites exceeds a certain level called the firing threshold. The strength of the signal received by a neuron, and therefore its chances of firing, critically depends on the efficacy of the synapses. Each synapse actually contains a gap, with neurotransmitter chemicals poised to transmit a signal across the gap.

Thus, from a very large number of extremely simple processing units the brain manages to perform extremely complex tasks. Of course, there is a great deal of complexity in the brain which has not been discussed here, but it is interesting that artificial neural networks can achieve some remarkable results using a model not much more complex than this. It is postulated that learning consisted principally in altering the "strength" of synaptic connections. Fig 2.10 displays the basic features of a biological neuron.

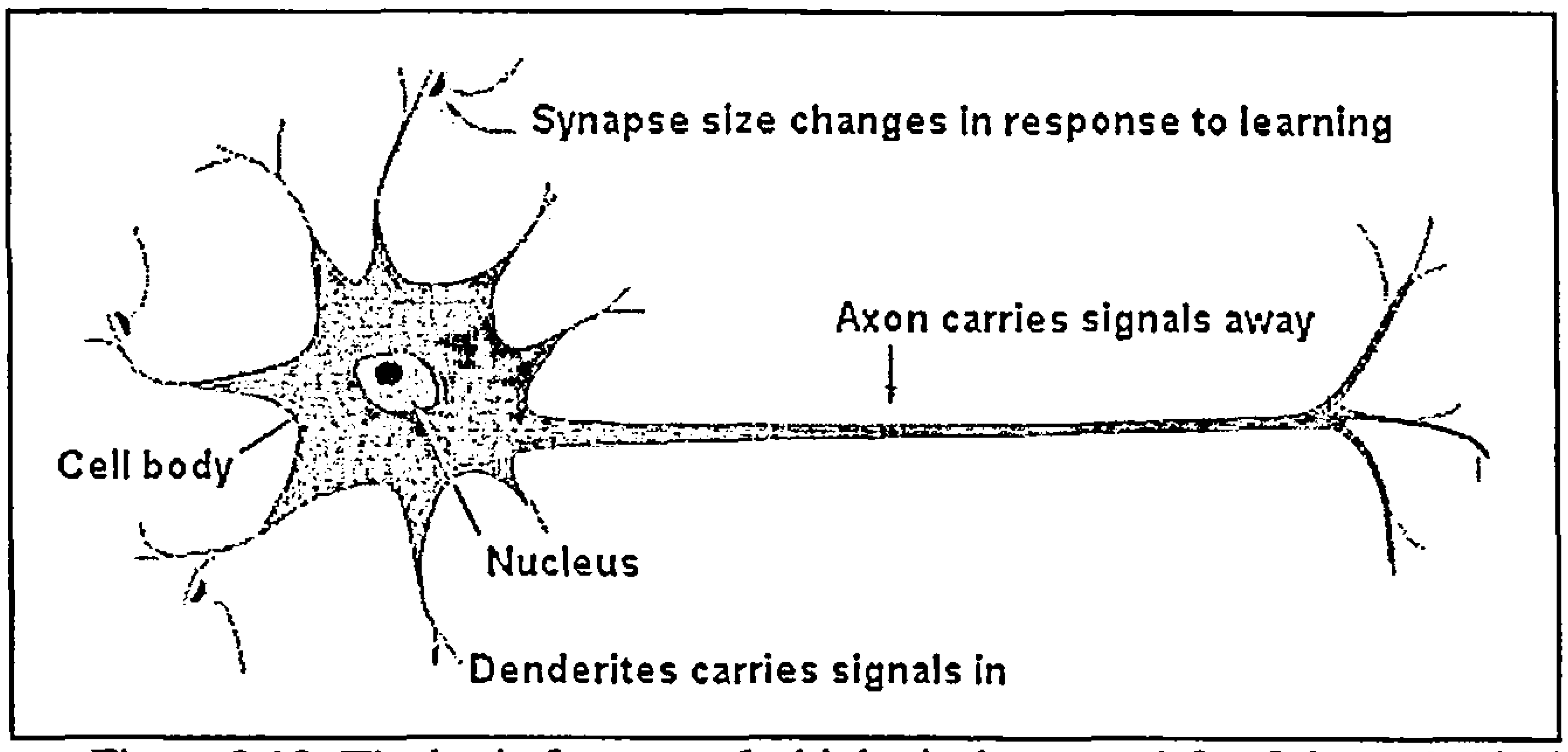


Figure 2.10: The basic features of a biological neuron (after Jain et al, 1996).

An Artificial Neural Network (ANN) is either a software or a hardware inspired by human information processing systems that can simulate biological Neural Networks. It is a computational model that is a directed graph composed of non-linear computational elements operating parallel to each other, and arranged in patterns similar to biological neural nets. The nodes are called the neurons. Connecting neurons together produces networks that can do something. With each connection in the network, a number is also associated which is called its weight. These are based on the firing rate of a biological neuron and the strength of a synapse (which is the connection between two neurons) in the brain. Weights are typically adapted during use to improve performance. The basic function of a biological neuron is to add up its inputs. The inputs go through the dendrites that are connected to the output of other neurons by junctions called synapses. The junctions change the effectiveness with which the signal is transmitted. The individual neuron sums weighted inputs and passes the result. The result is then computed according to non-linear computational elements, called activation functions or transfer functions, assigned in the neuron. The computed output is then passed to the other neurons in the next layer through the connections that the neurons have with them. This process, which is shown in figure 2.11, goes on until the last layer, and the output of the last layer is the output of the network.

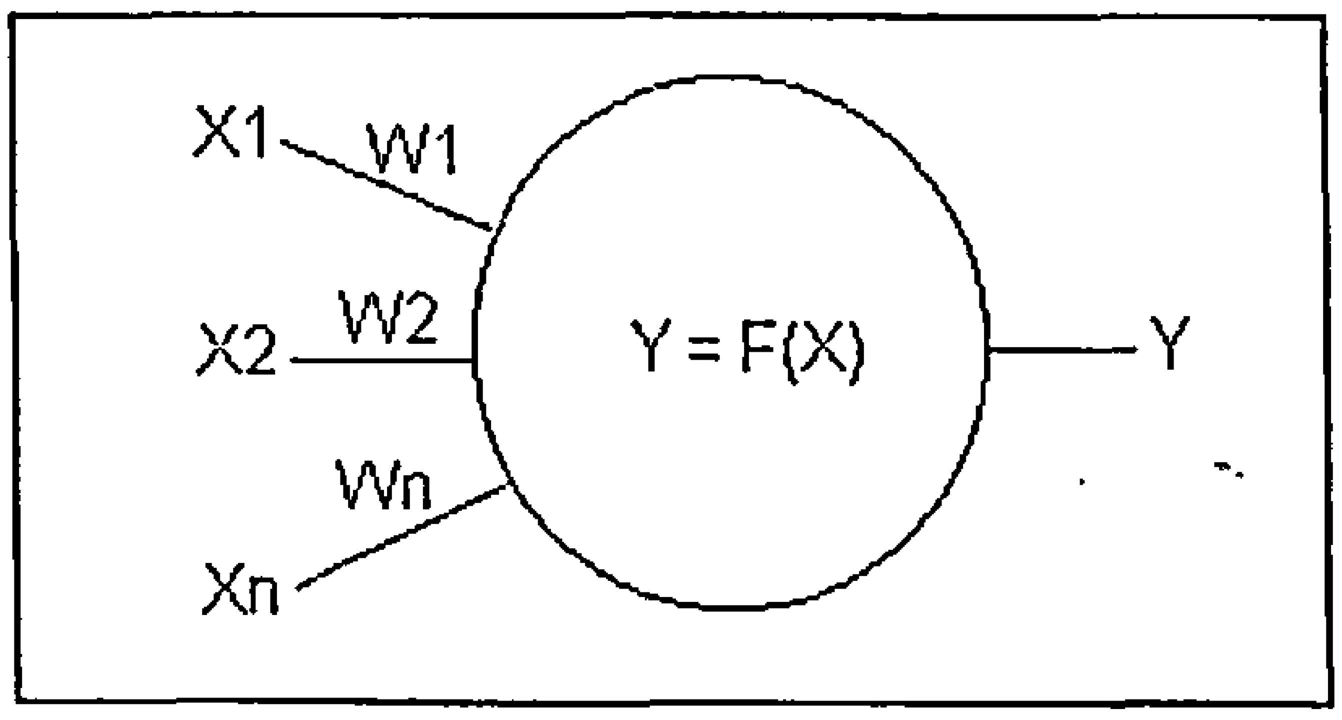


Figure 2.11: A schematic diagram of a neuron

A special characteristic of Neural Networks is that they can learn from experience and adapt the weights to simulate more accurate outputs using mathematical rules called learning algorithms or training rules.

The basic neuron was developed more than half a century ago but is still commonly in use (McCulloch and Pitts, 1943). In this model, the inputs are passed through the model neuron to produce the output and is therefore called a forward system. The model neurons that are connected very simply together are called perceptrons and it was proved that a perceptron could learn anything it could represent (Rosenblatt, 1961). The basic single-layer perceptron has shown great success for such a simple model but has limitations. A single-layer perceptron cannot solve any problem that is linearly inseparable because its outputs are a linear combination of their input (Beale and Jackson, 1992). To overcome this problem, multi-layer perceptrons have been used. This means that more than one perceptron is used. In the new model of Neural Networks, the adapted perceptron units are arranged in layers and is therefore called multi layer perceptron (Rumelhart et al, 1986). These new models have three layers: an input layer, an output layer, and a so-called hidden layer (Figure 2.12).

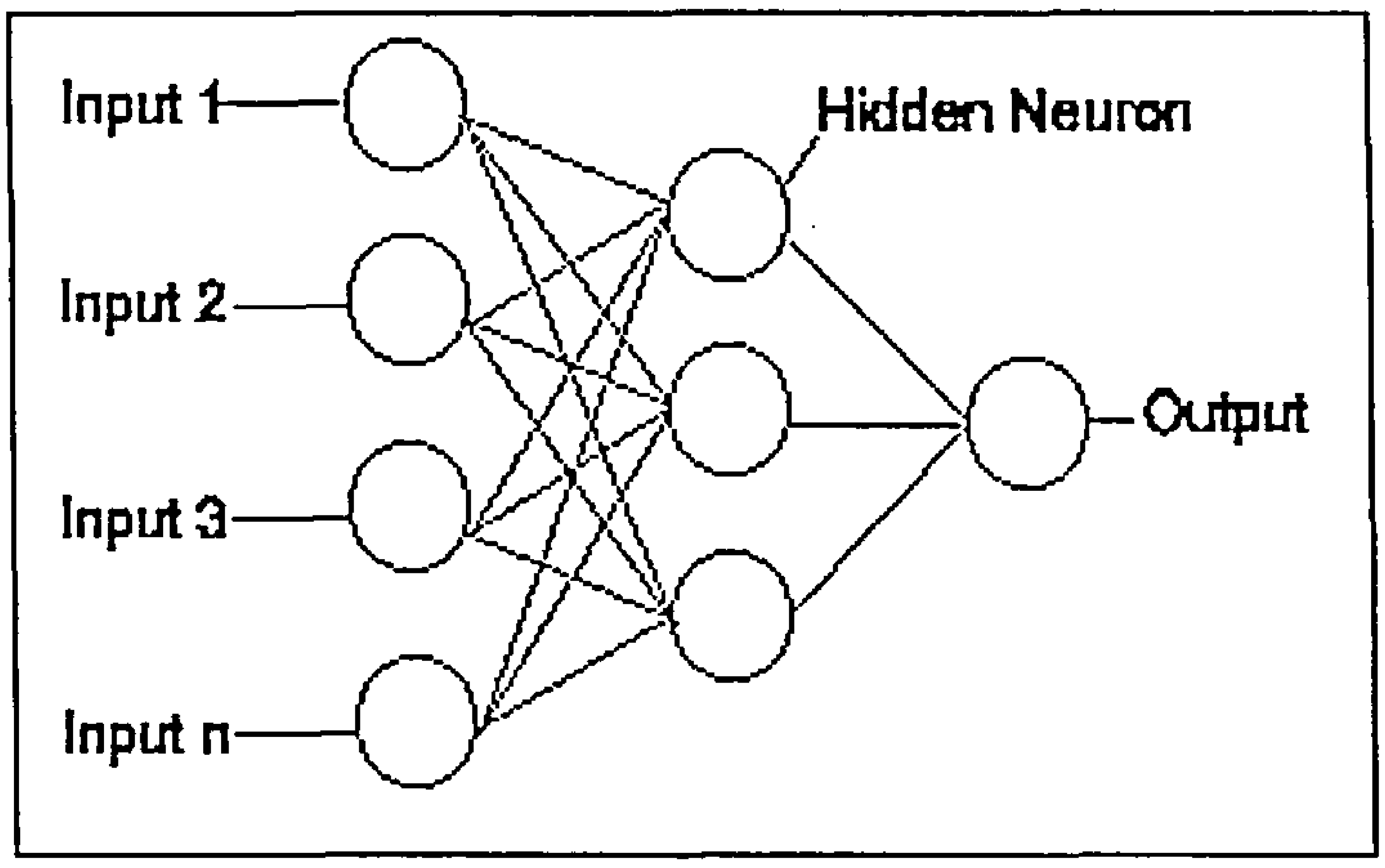


Figure 2.12: The multi-layer perceptron (after Haykin, 1999)

Most of the work in Neural Networks involves learning. Learning in a Neural Network occurs by adjustment of the weights. The guiding principle is to allow the neuron to learn from its mistakes. At the beginning of learning the weights are all wrong and the network performs badly at one of the tasks mentioned above, but by the end when the weights are adjusted, it is hoped that it will perform well. The activation of each neuron is based on the activations of the nodes that have connections directed at it, and the weights on those connections. Typically the activations would be updated simultaneously. Thus a Neural Network is a parallel model.

Neural Networks are finding applications in almost all branches of science and engineering. Applications in civil engineering only go back to the late 1980s. Several factors have stimulated this interest, the most notable being the recognition of the promise of certain information-processing characteristics apparent in the brain that have eluded capture within the conventional electronic digital-computing environment. These include the ability to learn and generalise from data which contain errors or are incomplete, to adapt solutions to problems even when the input data contains errors or are incomplete, to adapt solutions over time to compensate for changing circumstances, to process information rapidly, and to transfer readily between computing systems. Neural networks have been used in different aspects of soil engineering to solve various problems. Some of these applications are briefly reviewed below:

- A backpropagation Neural Network Model was designed and used for the classification of different kinds of soil (Cal, 1995). The plasticity index, water content and the clay content of the soil were used as input parameters, and the network was trained to classify between the following six types of clay: Heavy Clay, Light Clay, Heavy Sub-clay, Medium Sub-clay, Light Sub-clay and Sub sandy clay. The Network consisted of one hidden layer with eight neurons. The standard values for the input parameters of the six types of soil had been used to train the network. The results of this research showed that the Neural Network was able to learn from the training data and to classify other samples it had not seen before.
- In a different attempt, Neural Networks have been used for the classification of different types of sands, and also for the prediction of some quantitative measurements of the soil properties (Houlsby and Ruck, 1998). Results of conventional Cone Penetrometer (CPT) and an Acoustic Cone Penetrometer (ACPT) testing were modelled using the network with the vertical stress, the tip resistance, the friction ratio and acoustic data as input. The network was first used to identify and classify successfully between three different types of sand. The same inputs were then used to predict quantitative measurements of the soil properties such as the relative density and the in-situ horizontal stress. Poor results indicated that the identification of quantitative measurements can only be effective for

cases where the network is presented with material similar to those used for training the network.

- An attempt was made to investigate the use of Neural Networks for modelling the stress-strain relationship between sands with varying grain size distributions and stress history (Ellis et al, 1995). The network designed for this research used the following seven inputs: the initial stress, initial strain, initial pore water pressure, the confining pressure, the relative density of the sample, the Over Consolidation Ratio (OCR) that reflected the previous stress history and the coefficient of uniformity that characterised the grain size distribution of sand. The stress and the pore water pressure at failure were the expected outputs of the network. Undrained triaxial test results for 8 different sands with varying size distributions for both normally consolidated and overconsolidated states were used for the training and testing of the network. The Neural Network simulated the training data well and also effectively predicted the testing data, which had not been seen previously by the network.
- In another research exercise, the strain rate dependant behaviour of soils under pressuremeter stress was modelled using Neural Networks (Penumadu et al, 1994). A series of tests using pressuremeter stress paths were performed and the experimental results were used to train the Neural Network. The inputs for the network were the stress level and the strain rate obtained from the test data for a kaolin-silica mix for varying strain rates, and the output was the observed strain in percent. The feedforward network that had been used consisted of one hidden layer with 17 hidden neurons. The Neural Network predictions were consistent with the observed rate dependant behaviour of the soil, even though the normalised error allowed for this research was about 15%, which is fairly high, but still relatively good predictions were made by the Neural Network.
- Artificial Neural Networks have been used for the analysis and interpretation of site investigation data (Zhou and Wu, 1994). A multi-layer feedforward neural network was designed and presented with the X and Y co-ordinates and surface elevation as input. It was then asked to estimate the rockhead elevation for that location as output. Two hidden layers with 22 neurons in each layer were included in this network. A statistical analysis, performed on the field data in rockhead elevation and the neural network predictions, showed that a strong correlation between the network predictions and the expected values existed.

- In a different attempt, Neural Networks were used to predict the hydraulic conductivity (cm/s) of compacted soil liners (Goh, 1995a). Data from compacted soil liners constructed with natural clays from several landfill sites were used to train the network. The input of the network consisted of the Plasticity Index, Liquid Limit, percentage of gravel, percentage of clay, the soil's initial saturation at compaction and the compactor's weight (kN). The network showed that it was capable of making reasonable predictions.
- Neural Networks were used to predict oedometer loading curves (Logar and Turk, 1997). The results of 40 oedometer curves were used for training the network using the depth from which the samples were taken, the natural water content, the liquid and plastic limits of the soil and the vertical effective stress during testing as input. The expected output of the network was the corresponding void ratio, which is related to volumetric strain. The network was tested on 6 oedometer curves. Because of the lack of an adequate number of oedometer test results the average error of the Neural Network was around 8.9%. However the network gave relatively accurate results compared to experimental measurements.

2.9 Conclusion

Deposits from the Quaternary glaciation cover most of Northern England. Three distinct landsystems that can be found in glacigenic environments are subglacial, supraglacial and glaciated valleys. Each of these landsystems has its characteristic deposits and landforms. Tills are soils of glacioterrestrial origin and are a mixture of clay, silt, sand and granular material which have been deposited from ice sheets with little or no sorting by water. Different types of tills are known such as lodgement, melt-out and flow tills which have been reviewed earlier in this chapter. Till types reflect the nature of rocks traversed by the glacier or ice sheet. A genetic classification of the tills helps to understand depositional processes, which have a major effect on the engineering properties of tills (McGown and Derbyshire, 1977). A useful way of studying and analysing the engineering properties of tills is to gather data derived from site investigations from various locations. The most effective way of storing large amounts of data from such site investigations is the use of databases.

Databases have become an important tool in areas where large amounts of data need to be stored for further use. Over the years techniques for storing data have improved and specialised systems have been designed for the storage of geotechnical data. Some of these databases have been introduced in this chapter, and examples of the use of database technology in the field of geotechnical engineering and engineering geology have been reviewed. For this study, a database has been designed for the storage of geotechnical parameters related to glacial tills from Northern England. The structure of this database and its features will be discussed in detail in the following chapter.

Databases are used to gain quick access to data and retrieve data for further analysis or modelling. However, in some cases, data could be available but the fundamental understanding of the behaviour of soils may fall short of being able to predict the behaviour of the ground. In the last decade the use of Artificial Intelligence for analysing and modelling various parameters in geotechnical engineering has grown. Expert Systems and Neural Networks are two types of Artificial Intelligence that are becoming more frequently used. The structure of both these systems and some of their applications in the field of soil mechanics use were reviewed in this chapter. As mentioned in earlier sections, one of the main disadvantages of Expert Systems is the lack of ability to learn. Neural Networks however have the ability to learn and have therefore been chosen for this study. They have been used for the classification of till layers based on their degree of weathering. Their potential for the prediction of geotechnical design parameters is also investigated and will be discussed in detail in later chapters.

Chapter 3

'NETDATA' a relational database on geotechnical properties of Northern England glacial Till

3.1 Introduction

Databases and database technology have been a part of computing for many years and can provide a tool to extract information from datasets. A database is a collection of related data and is concerned with storing and processing data on computers. In the following sections various database management systems will be reviewed and the system and structure that has been used to develop a database on Northern England Till geotechnical properties will be discussed in detail.

3.2 Database Management System

DataBase Management Systems (DBMS) organise and structure data so that they can be retrieved and manipulated by users and application programs. Since the creation of DBMS the technique has improved significantly in terms of both quality (such as in performance, ease of use, data handling capability) and quantity (the number of available products). DBMS is a program or software that allows the user to create and maintain a database. The appearance of the Relational DataBase Management System (RDBMS) in the early 1980's has had a major impact on the use of computers. This system became very popular because of its simplicity and power, and was used for the production of a large number of relational databases (Kroenke and Dolan, 1988). An RDBMS must have properties such as storing data as relations such that each data column is independently identified by its name. The operations available to the user and those used by the system should be relational operations. The system must also support at least one variant of join operation.

A (R)DBMS architecture is needed to make the database useable. The following is a list of some of the existing architectures:

- Central Architecture, which was mainly used on mainframe computers. In this architecture the DBMS and the application program are both located on the mainframe and the user accesses the application and the DBMS directly. The mainframe searches through the data files and returns the output to the screen.
- File Server Architecture, is mostly used in Local Area Networks (LANs). In this architecture the DBMS and the application program are run on a PC while the data resides on the File Server on the network. The DBMS sends requests for each query to the file server for blocks of data, which are then constructed to the required form by the DBMS running on the PC.

- Client / Server Architecture is also common in a Local Area Network of PCs and a database server. The DBMS is split into two parts, the front-end and the back-end. The front-end which resides on the PC comprises the application programs, query tools, report writers and the user interface. The back-end, which resides on the database server, comprises a database engine that stores and manages the database itself. The communication between these two parts is implemented through a query language.
- PC based DBMS is used more and more with the increasing power of PCs. In this system both the front-end and the back-end are within the same application

The database architectures reviewed above show the interaction of the hardware with the software. The data stored in a database need to be organised to make them useable and therefore databases are constructed from data models. Data modelling aims to build a model of the information represented in a database. The model provides the database user and the data management system with a way to access and structure the data. The development of a data model is a crucial stage in building a database. The data model determines the types of information that will be stored in the database and ensures that the database is consistent. Therefore choosing the right data model is the first and most important step in creating a database. Various data management systems have been developed and used over the years (Hoeksema and Hart, 1990; Groff and Weinberg, 1990; Bamford and Curran, 1991; Elmasri and Navathe, 2000). These data models are briefly reviewed below:

- File Management Systems. In these systems the files are organised directly on a storage disk. This is done by keeping track of names and locations of files on the disk. The File Management System has no data model and therefore cannot distinguish between different types of files. Thus the knowledge about the contents of the file has to be embedded in the application programs that manipulate the data. The main disadvantage of this type of data management is that each time the data in the file changes, the changes have to be effected manually in the application programs.

- Hierarchical Data Model. In this model the data are presented as records which are linked together like a family tree (Figure 3.1). The records are organised in child/parent relationships, which means that each part is linked to its subpart. The hierarchical model uses the structure of a hierarchy, where a data type can have several "children" data types, but each child can have only one "parent" data type. The retrieval of the data involves navigation through the hierarchical structure from the "parent" to the "child" in a pre-order traversal. This model is not suitable for data with complex structures, as its structure is not flexible to changing data and access requirements.

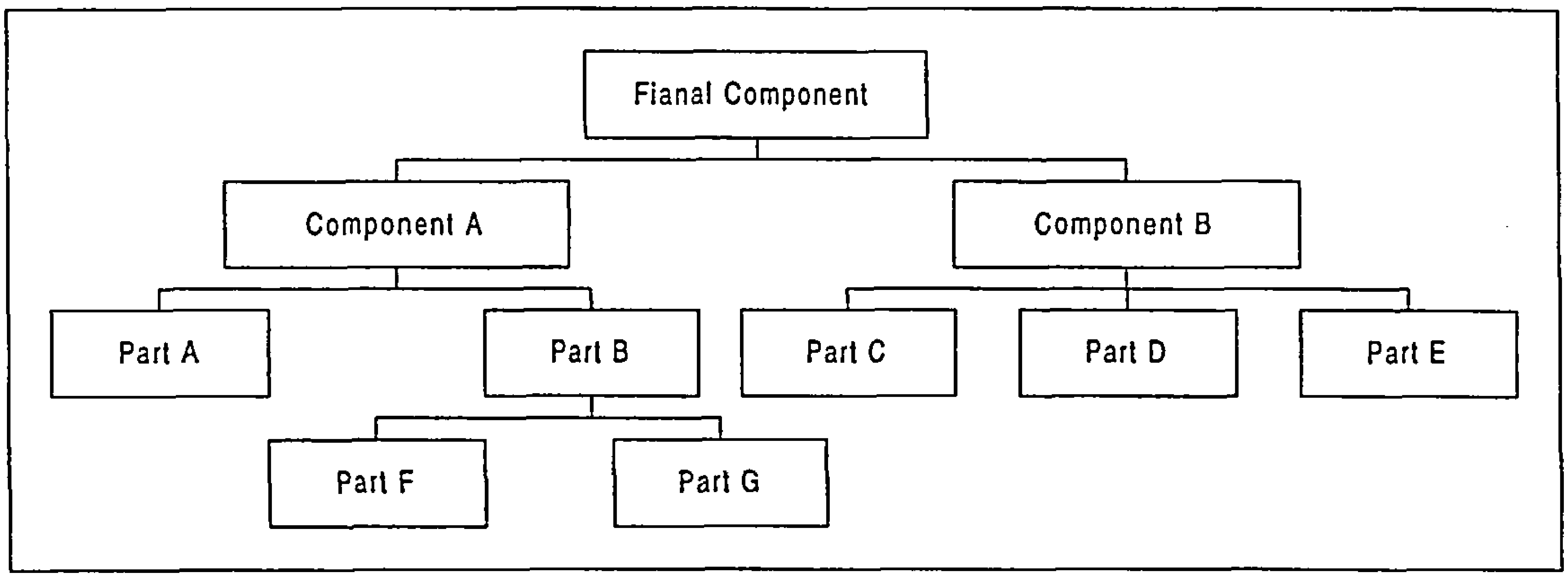


Figure 3.1: Example of a Hierarchical data model

- Network Data Model. This model is an extension of the Hierarchical Data Model. The Network Data Model allows data records to participate in multiple child and parent relationships known as sets (Figure 3.2). Explicit links or storage addresses, called pointers, contain the location of a related record and must be maintained at all times. To use the Network Model, the user is required to be familiar with the structure of the database and to know where the data are stored. The multiple parent/child relationships allow a network database to represent data with complex structures. The disadvantage of this model is that the relationships and the structure of the records are pre-set and therefore not very flexible. The user is also limited to see all the data from a given point in the network.

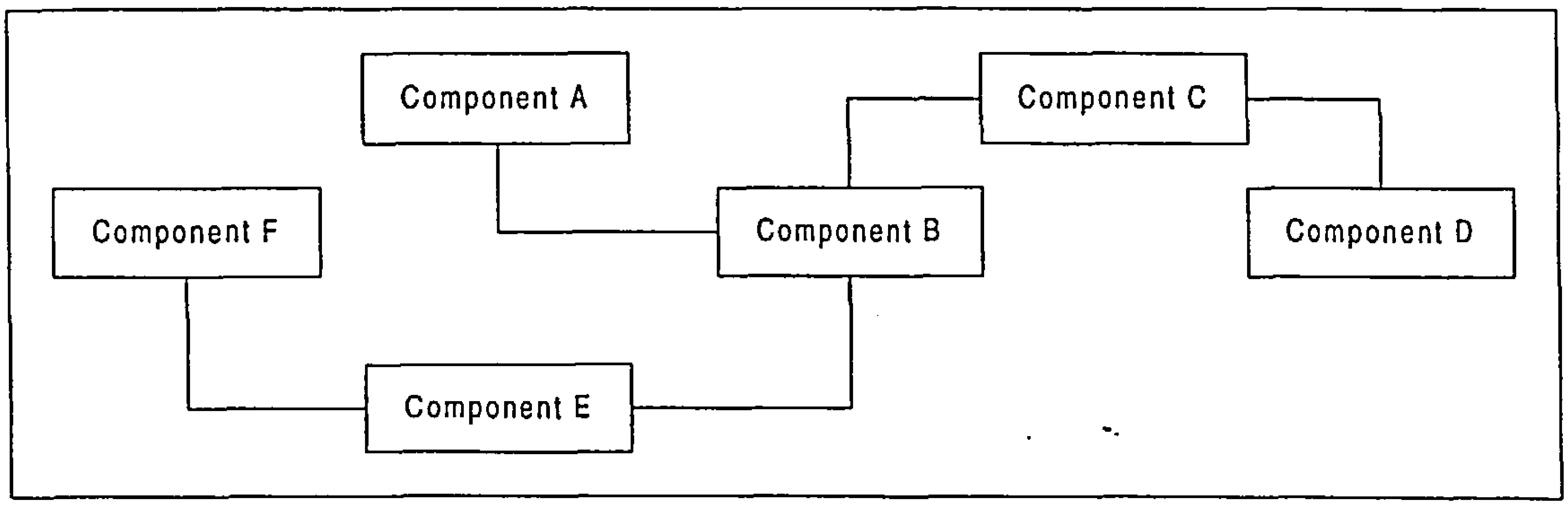


Figure 3.2: Example of a Network data model

- Relational Data Model. A relational database model is a collection of related data and is based on the concept that data are stored in two-dimensional tables, called relations. Each row in the table represents a record and each column represents a field. The entire table is roughly equivalent to a file. Common data columns known as primary key fields relate the tables to each other. A primary key field is a field that uniquely identifies each record. It can be said that a relational database is a database where all data are strictly organised as tables of data values, and where all database operations work on these tables. A relational database does not need structures like hierarchical or network databases, but can represent parent/child relationships, which are represented by the data values within the database tables.

Table 1	*Component ID*	*Component Name*
	C1	Comp A
	C2	Comp B
	C3	Comp C

Table 2	*Part ID*	*Part Name*	*Component ID*
	P1	Part A	C1
	P2	Part B	C1
	P3	Part C	C2

Figure 3.3: Example of a relational data model

Several types of relational data models can be used for creating an RDBMS. The relational model depends on the type and the condition of the data. The three main relational types are explained below (Microsoft Corporation, 1994):

- One-to-one relationship is used when a record of one table is related to no more than one record of another table.
- One-to-many relationship is used when a record of one table is related to many records of another table.

- Many-to-many relationship is used when a record of one table is related to many records of the second table, and many records of the second table are related to many records of the first table.

A brief description of the architecture of different database management systems and data models was given above. In the following section the design of NETDATA will be described.

3.3 The design of "NETDATA"

As mentioned in the previous chapters a geotechnical database was needed to give a better understanding of the engineering behaviour of glacial tills. NETDATA (Northern England Till DATA) is a database that has been designed and developed in order to fulfil this need. It stores and centralises available data of the tills from Northern England in an easy to use format and can be used to analyse the geotechnical parameters of Northern England's glacial tills.

In the previous section different database management systems and data models were reviewed in the previous section. As mentioned earlier the relational data model does not have the limitations of file management systems, hierarchical or network data models in order to access the stored data. The relational model is also more flexible if there is a need for modification in the structure of the data and therefore this model was chosen for the design of NETDATA. In the following section the software used for the design of NETDATA will be reviewed

3.3.1 The software

Broad ranges of commercial database programs and packages have been developed to meet the different needs of geotechnical engineers. Some of these software have been reviewed in the previous chapter. Various other software are also available in the market for the purpose of database design. Two well known and widely used software are Oracle and Microsoft Access. They are relational database management systems and are based on Structured Query Language known as SQL. These software differ in the way that the database is designed and run. Oracle for instance is a powerful system but a knowledge of the SQL language is needed for its maintenance and for alterations in the database structure (Koch and Loney, 1997).

Since SQL is a vast and difficult language for someone who is not professionally trained, a separate interface needs to be designed in order to interact with the user. Although a basic interface comes with the package it is not considered to be very user-friendly. In order to fulfil all the requirements for users to interact with the database easily a user-friendly interface needs to be designed. This however, requires the knowledge of another programming language such as Visual Basic or Java or the installation of additional software applications (Muller, 1997). This will limit the flexibility of the system to modifications for someone who has not a full knowledge of such programming languages (Abdellatif et al, 1990; Elmasri and Navathe, 2000).

Microsoft Access on the other hand has already a built in interface. This software which is a relational database management system is more widely used and is included in the Microsoft Office package. The user of this software does not need to have programming experience in order to design or make major modifications on the structure of the database. More advanced users can still use the SQL language for the design of Queries or for setting certain parameters or expressions in the database. Another advantage that Microsoft Access has is that it supports Visual Basic for Applications. Visual Basic can be used to write and run codes within the database for more advanced designs or to modify the interface into required forms. The software makes also the most use of the Windows operating system for communicating with other programs or software.

For this study it was decided to design a database that would include features of specialised databases. As mentioned in the previous chapter various commercial database systems have already been designed for managing site investigation and geotechnical data but the availability of such software was one of the factors considered when it was decided to design a database for this study. An advantage in using a software for designing a database was that it would be possible to modify the features if required, even after the design of the database was completed. This would not be possible with commercial software. Since Microsoft Access is included in the Microsoft Office package, which is used widely, users of the system are more familiar with the features of the software. Because of the flexibility and availability of this software it was decided to use it for developing NETDATA. The version used for this purpose is Microsoft Access version 97. This software is designed to give unparalleled access to data and is considered as part of an integrated set of tools for creating and managing databases on the PC Windows platform. Access is an RDBMS that has several components. One component is the underlying database engine called the Microsoft Jet Engine, which is responsible for managing the data and stores all the application data such as tables, indexes, forms, reports, macros, and modules. Another component is the user interface that calls the engine to provide data services, such as storage and retrieval of data. A complete set of user guides is available for learning and working with Microsoft Access. The software also has a powerful on-line help facility that provides step-by-step instructions to help and guide the user through the design of a relational database.

To make the most use of the tools within the software it was important to use an efficient model for the data. Data modelling is used to produce an accurate representation of the information needs of the system. It allows the designer to describe the data in a system and explain it to others. This is explained further in the following section.

3.3.2 The data model

To maintain efficiency and reliability it is important that the data follow a certain standard and format. A database should incorporate two key ideas (Rasmussen, 1995):

1. It should represent information by modelling reality. That means that a database should be a picture of a part of reality, which could be updated as new facts are discovered.
2. The management system of a database should have a flexible query system to allow people to view the database and retrieve information in various ways as required.

It is fundamental to ensure that the data in a database are held in a coherent way to allow all the potential links and queries to be made correctly and efficiently. The best way to achieve this is to build a data model (also called a logical model). This is effectively a map of the data, their elements and relationships. From this logical model a physical model is developed, for implementation within the chosen software.

There are two basic types of model. First, a logical model that views a system independently of specific hardware or software; this permits objective decisions to be made. Second, a physical model, which represents the logical model adapted to the constraints of specific hardware and software. The data model records the two main characteristics of the data within the system, which are the fields used in the tables and the relationship between the tables.

Fields within tables identify items stored in the database. They can be thought of as something real within the system, such as a borehole or a sample taken from that borehole. The purpose of identifying the fields is to define the types of objects the system must deal with, and what individual items of data are associated with each type of object. The fields are put into tables, which will relate to each other in various ways. The relationships shown in a data model record how data are interconnected.

One format that has been successfully introduced and adopted in most specifications for ground investigations is the AGS (Association of Geotechnical and Geoenvironmental Specialists) Format. This format was used as the main data model in the design of NETDATA. The AGS Format is introduced and explained in detail in the following section.

3.3.2.1 The AGS Format

In this format the files that are used should contain basic data, such as exploratory hole records, and the test data required to be reported by the relevant British Standards and other recognised documents, and which would normally be contained in a Factual Report. The file format is intended to provide a wide level of acceptance and, in view of this, it is considered that the data should be transmissible using American Standard Code for Information Interchange (ASCII) files.

To allow the file formats to be more easily recognised by the non-specialist, a Data Dictionary has been prepared that defines the Groups, Fields and Units used in this format. A dictionary can be a powerful tool for assisting database validation. They can help to eliminate erroneous values being entered in the database or unauthorised and undocumented codes created by users. The user of a database should be confident that data held are reliable. Dictionaries ensure that only valid values are used within the database. A dictionary also helps the user to understand clearly what is meant by a given term or set of terms used within the database (Giles et al, 1997).

Data Groups have been chosen to relate to specific elements of data, which are obtained, such as project information and exploratory hole details. Fields within each Data Group identify items such as test details or test results. Two types of Data Fields defined by the AGS format are the KEY Fields and the COMMON Fields. The KEY Fields must be included in every Data Group within a file. They are important for maintaining data integrity. Data entered into KEY Fields must be unique in each GROUP and the corresponding entries must be made in the PARENT GROUP. All other fields within a Group are called COMMON Fields.

The AGS Format Data Groups are organised in a hierarchy with an inverted tree like structure. This structure is represented in figure 3.4. At the top of the tree is the HOLE Group, and all other Groups lie below this. One of the Groups immediately below HOLE is SAMP, all the laboratory testing Groups lie below SAMP. The HOLE Group is termed the "parent" Group of SAMP. The PROJ Group sits above the tree, and has a general purpose. It must always be included in an AGS Format submission as it defines the project. This structure will be presented graphically and discussed further in the following section.

Each Group has only one parent, but there can be many Groups below each parent. KEY Fields link each Group to its parent (the Group above it in the hierarchy). They also link one Group to the Group(s) below it. For this structure to work, and the link to be made correctly between related Groups, the data in the KEY Fields must be consistent and unique.

Some rules are introduced to enable the use of the format by the simplest existing programs, in particular spreadsheets (AGS, 1999). A copy of the AGS File Format Rules can be found in Appendix A. These rules were taken into consideration in the design of NETDATA. The following section will explain and discuss the structure of the database in detail and will also point out some differences between the methods used in the design of the database and the rules introduced in the AGS Format.

3.3.3 The structure of NETDATA

As mentioned before the design of a database is very dependent upon the computer environment and the database management system used to implement the database. The features of the DBMS should be used to ensure adequate performance, which in some cases makes it necessary to alter the data model, although such changes are best avoided. However, if changes have to be carried out, the skill lies in minimising the impact of such alterations on the performance of the database (Rasmussen, 1995).

In the design of NETDATA the structure introduced in the AGS Format was kept in mind. The tables have been designed to be similar to the groups mentioned in the AGS Format and each table has a specific name related to the data stored in them. The fields in each table are logically related and physically close together. A unique field in each table is chosen as the Primary Key of the table. Microsoft Access allows interactive definition of relationships between tables that can specify referential integrity constraints via the relationship window. To relate the tables to each other the structure mentioned in AGS has been followed and the relationship between the tables represent a parent to child relationship. This can be described as follows:

The TBL-PROJ that contains the fields that define the project is the first table. Each project can have many boreholes; therefore a one-to-many relationship is created between TBL-PROJ and TBL-HOLE. Several Samples can be taken from each borehole therefore the tables TBL-HOLE and TBL-SAMP are connected to each other with a one-to-many relationship. Each sample may be used for different laboratory tests (more than one test) and therefore a one-to-many relationship has been created between TBL-SAMP and the test result tables. The structure of NETDATA and the connections between the tables in the relationship window is shown in Figure 3.4.

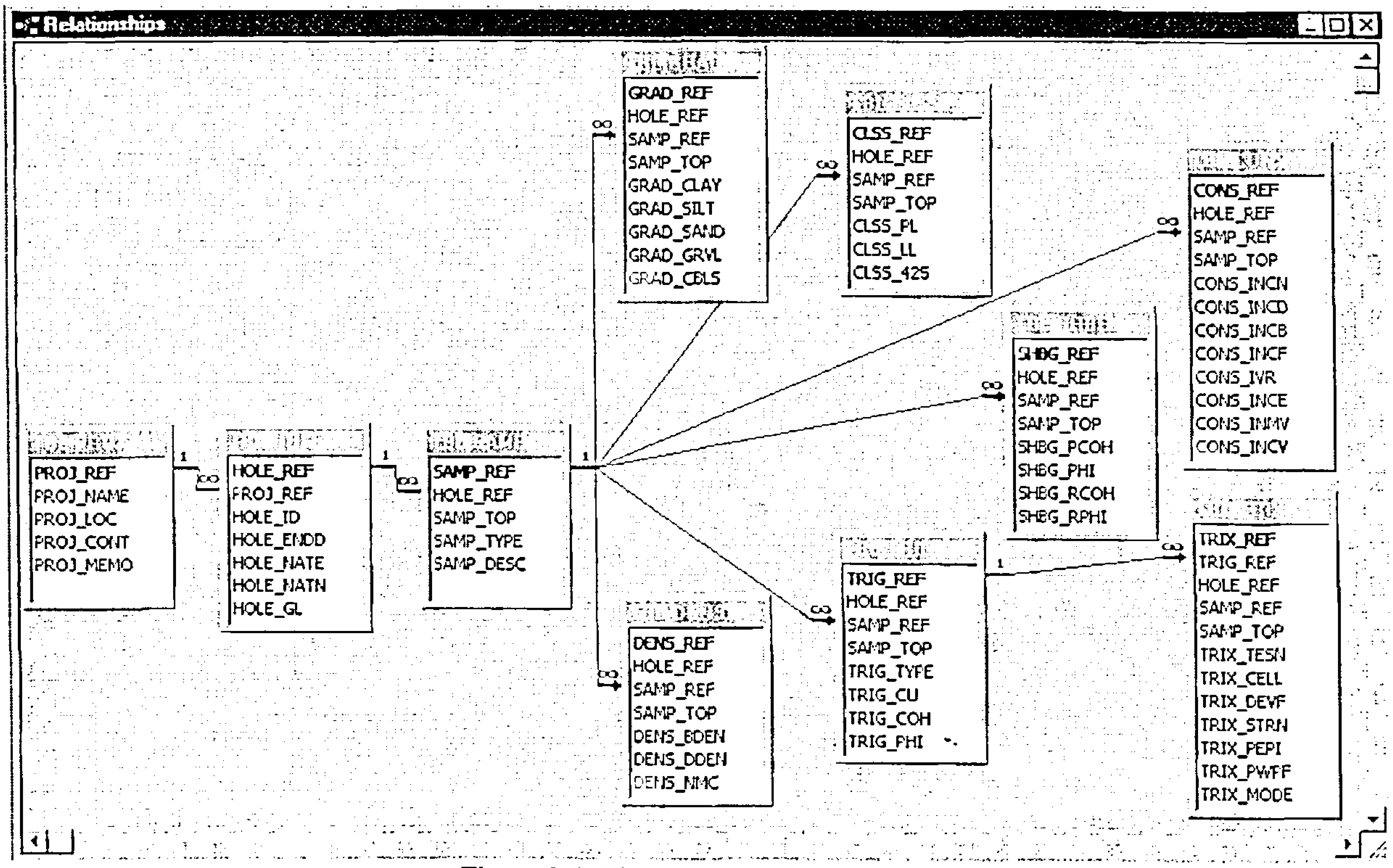


Figure 3.4: The structure of NETDATA

The above model was also incorporated into the database. Before the objects within the database are explained further it is important to point out some differences between the AGS rules and the design of NETDATA.

3.3.4 Notes on the use of AGS rules in NETDATA

In the design of NETDATA the AGS rules were followed as far as possible. Because the data were presented in different formats in different site investigation reports, adjustments had to be made to the structure of the tables and fields. It should be noted that the word "file" mentioned in the AGS rules is the database file itself and "Groups" are the tables within the database. Some of the alterations to the rules are explained below:

Alternative Headings and Group names were used rather than those introduced in the AGS rules. For instance rules number 8, 10, 11, 22 and 23 explain the use of characters such as asterisks (*), quotes (") or question marks (?) in the name of standard and non-standard Groups and Headings. These characters were not used in the names of the tables and fields within NETDATA to avoid confusion or mistakes, because of the use of these characters in modules (Visual Basic code), SQL (Structured Query Language) codes and Wildcards in the database. Wildcards are used for setting search criteria in a query. For instance (*) is used to find any string of characters, (?) is used to find any single character stored in the database and quotes ("") are used to search for phrases. Details of the use of wild cards for queries can be found in the NETDATA guide in Appendix B.

The table names within NETDATA have been adopted to be compatible with the AGS headings, but instead of using the asterisk (*) in the table name they are identified by the characters TBL, which is added at the beginning of the heading. Other objects within the database are similarly identified, for instance FRM is used in naming forms, QRY is used for queries, and RPT for naming reports.

It is mentioned in rule 7 of the AGS format that numbers should be in numerals but presented as a text field, and rule 15 states that Null values should be put in quotes (""). In the design of tables in Microsoft Access, the type of records must be set as the property of the field which expresses information about the type of data that will be stored in that field. Saving numbers as text fields prevents the queries from searching the database correctly when looking for numeric data, and limits the possible search combinations considerably. For instance if numeric data are saved as text it will not be possible to run a query and search for numbers between two values. It is possible to use special functions to convert text data to numeric data, but for ease of use and to make full use of query functions, numeric data are saved as numerals and their properties are also set as numeric fields. Null values are also shown as a number (0) in the data fields. They may be used to show that a soil contains zero percent gravel and this value is also used for the required calculations for producing grading classification charts. All numbers including zero may be used for some calculations for data analysis or plotting graphs. Where data are missing, fields should be left empty which would mean data not available or not measured.

Rule 18 of the AGS Format mentions that a UNITS line must be included in every GROUP even where the default units are used. The preferred units defined in the AGS format are used and included within all tables of NETDATA. They are either the appropriate SI units or the unit defined by the particular British Standard relating to that specific item of data. The units and the description of all fields within the database can be found displayed at the bottom left of the screen when the cursor is located in any of the field boxes in the tables or forms. They can also be viewed or altered from the table design view of the database. The units are also defined in the NETDATA Guide (Appendix B).

The objects used in the design of NETDATA are reviewed in the following section.

3.4 Database Objects

Various objects such as tables, forms and reports are used in the design of the database. These can be accessed from the database main switchboard or from the specially prepared database menu (Figure 3.5). The main objects of the database are reviewed in the following sections.

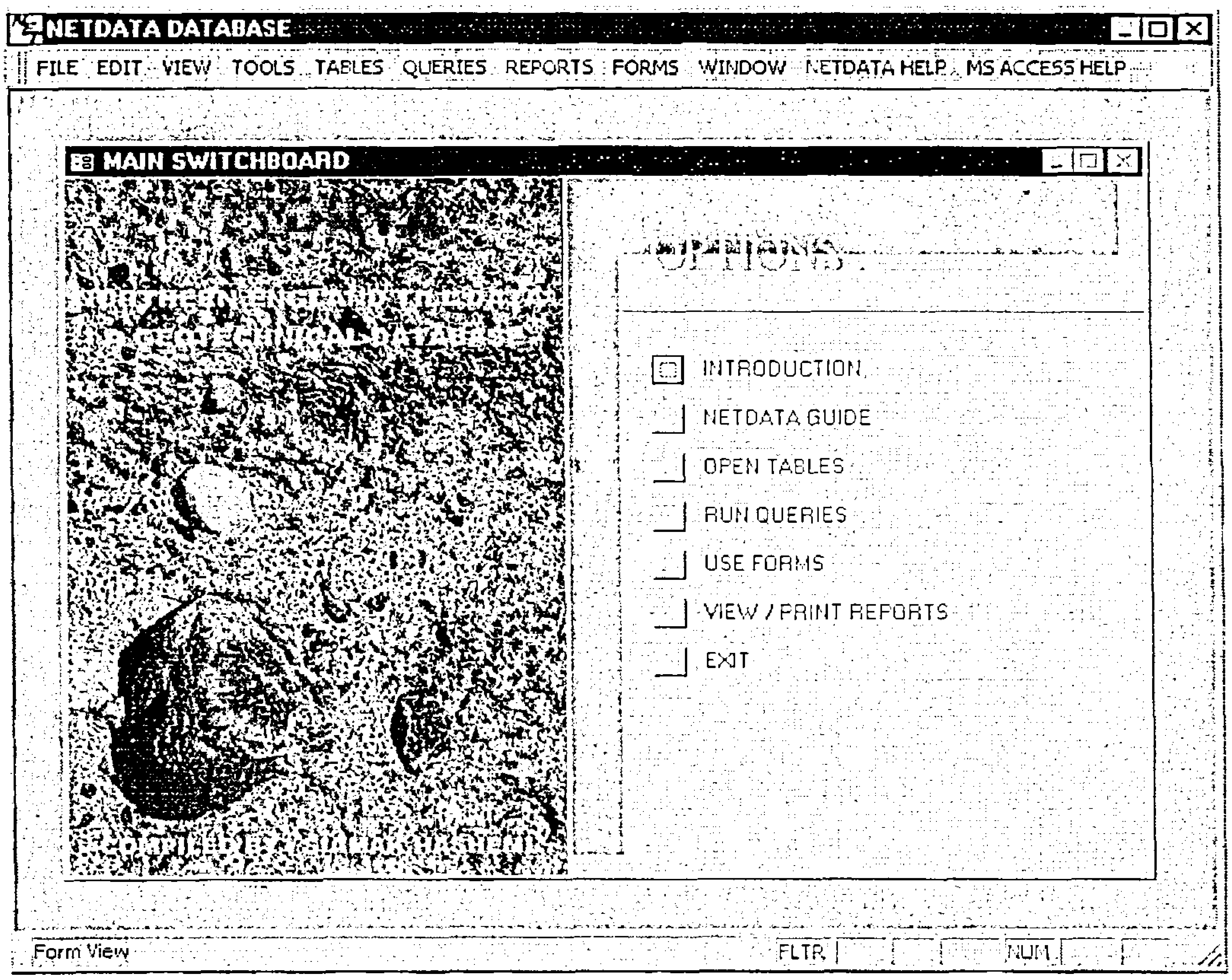


Figure 3.5: Screen shot of the switchboard and database menu

3.4.1 Tables

This section gives details about the structure of the tables within the database. The fields included in each table are those presented in site investigation reports.

The AGS format includes certain information and fields in the tables in such way that each table is not only part of the whole structure related to other tables but also is a complete set of records and information within its data group. For instance, including the borehole name and sample depth in addition to the sample reference number is just for the completion of a data group. The sample reference is unique to each sample and including only this field in the tables and using it for setting up relationships would be enough for the database to run correctly. The Groups introduced in the AGS Format may include other fields in addition to those used in NETDATA. Fields used within the database tables are described below. It should be noted that fields shown with bold letters are used as the primary keys within the tables.

3.4.1.1 TBL-PROJ

This table consists of the site name and the site identity number. The sites included in this table are those where the boreholes were drilled and samples were obtained. This table is placed at the top of the hierarchical structure of the database and is connected with the TBL-HOLE table through the PROJ_REF field.

Table 3.1: The fields of TBL-PROJ

Field name	*Data type*	*Description*
PROJ_REF	Auto-number	Number of project within NETDATA
PROJ_NAME	Text	Title of project
PROJ_LOC	Text	Location of site
PROJ_CONT	Text	Name of contractor
PROJ_MEMO	Text	General project remarks or comments

3.4.1.2 TBL-HOLE

The data within this table give information about the exact location of the borehole, the ground level and the dates the work was carried out. This table is connected with two tables within the database: the TBL-PROJ table and the TBL-SAMP table.

Table 3.2: The fields of the TBL-HOLE

Field name	*Data type*	*Description*
HOLE_REF	Auto-number	Number of borehole within NETDATA
PROJ_REF	Number	Number of project within NETDATA
HOLE_ID	Text	Exploratory hole name / number
HOLE_ENDD	Date / time	Hole end date
HOLE_NATE	Number	National grid easting of hole
HOLE_NATN	Number	National grid northing of hole
HOLE_GL	Number	Ground level relative to ordnance datum (m)

3.4.1.3 TBL-SAMP

This table, which is connected to TBL-HOLE and the test result tables, includes information about the samples such as the type of sample, depth of sample and the description of the sample.

Table 3.3: The fields of the TBL-SAMP

Field name	*Data type*	*Description*
HOLE_REF	Number	Number of borehole within NETDATA
SAMP_REF	Auto number	Number of sample within NETDATA
SAMP_TOP	Number	Depth to top of sample (m BGL)
SAMP_TYPE	Text	Sample type
SAMP_DESC	Text	Sample description

The AGS Format uses standard Abbreviation Codes to specify the type of samples that are included in the SAMP_TYPE field. A list of the codes used in the database can be found in Table 3.12.

3.4.1.4 TBL-CLSS

This table which is connected to the TBL-SAMP table, contains the results of the Atterberg limits tests. Parameters such as the Plasticity Index and the Liquidity Index can be calculated from the Plastic Limit and Liquid Limit values and are therefore not included in the table. However, these parameters are calculated in a specially designed form. This form may be used to automatically produce a plasticity chart for classification purposes. The calculated parameters are also presented in some of the relevant reports within the database.

Table 3.4: The fields of TBL-CLSS

Field name	*Data type*	*Description*
CLSS_REF	Auto number	Number of index text results within NETDATA
HOLE_REF	Number	Number of borehole within NETDATA
SAMP_REF	Number	Number of sample within NETDATA
SAMP_TOP	Number	Depth to top of sample (m BGL)
CLSS_PL	Number	Plastic limit (%)
CLSS_LL	Number	Liquid limit (%)
CLSS_425	Number	Percentage passing 425 (micro m) sieve (%)

3.4.1.5 TBL-GRAD

This table contains data about the particle sizes of the soils. The AGS Format uses a field that contains the sieve or particle size and a field that stores the percentage passing the sieve. These data were not present in many of the site investigation reports or data files. Instead, the percentage of clay, silt, sand, gravel and cobbles were given in the laboratory test result sheets. Therefore the following names were chosen for the grading details based on the AGS Format rules for non-standard fields.

Table 3.5: The fields of TBL-GRAD

Field name	*Data type*	*Description*
GRAD_REF	Auto number	Number of grading test results within NETDATA
HOLE_REF	Number	Number of borehole within NETDATA
SAMP_REF	Number	Number of sample within NETDATA
SAMP_TOP	Number	Depth to top of sample (m BGL)
GRAD_CLAY	Number	Clay fraction (<0.002 mm) - (%)
GRAD_SILT	Number	Silt fraction (>0.002 , <0.06 mm) - (%)
GRAD_SAND	Number	Sand fraction (>0.06 , <2 mm) - (%)
GRAD_GRVL	Number	Gravel fraction (>2 , <60 mm) - (%)
GRAD_CBLS	Number	Cobbles and boulders fraction (>60 mm) - (%)

3.4.1.6 TBL-DENS

This table contains data about the density and the water content of the samples. These values can be measured from samples used in various tests. The AGS format places the values for the density and the water content of the samples into the data-groups that represent individual test types. In some of the data sources used for NETDATA, the test used to obtain density and water content were not given, and in some other sources several values derived from different tests were given. These values were put in one table within the database, although this differs from the AGS format. The AGS Rules permit the creation of non-standard Groups and Headings (See rules 21 to23 in Appendix A for details). The headings in this table follow the above mentioned rules. The following fields are included in the table:

Table 3.6: The fields of the TBL-DENS Table

Field name	*Data type*	*Description*
DENS_REF	Auto number	Number of density test results within NETDATA
HOLE_REF	Number	Number of borehole within NETDATA
SAMP_REF	Number	Number of sample within NETDATA
SAMP_TOP	Number	Depth to top of sample (m BGL)
DENS_BDEN	Number	Bulk density (Mg/m^3)
DENS_DDEN	Number	Dry density (Mg/m^3)
DENS_NMC	Number	Natural moisture content (%)

3.4.1.7 TBL-TRIG

The following fields are used to build up the TBL-TRIG. As mentioned earlier in this chapter, only the test results are included in this table. Different types of triaxial test have been carried out and the AGS Format uses special Abbreviation Codes to describe the various test types. These codes have been used in the database to specify the type of test that has been carried out. The list of the codes used in the database can be found in Table 3.12.

Table 3.7: The fields of TBL-TRIG

Field name	*Data type*	*Description*
TRIG_REF	Autonumber	Number of triaxial test results within NETDATA
HOLE_REF	Number	Number of borehole within NETDATA
SAMP_REF	Number	Number of sample within NETDATA
SAMP_TOP	Number	Depth to top of sample (m BGL)
TRIG_TYPE	Text	Triaxial test type
TRIG_CU	Number	Value of undrained shear strength (kN/m^2)
TRIG_COH	Number	Cohesion intercept associated with TRIG_PHI (kN/m^2)
TRIG_PHI	Number	Angle of friction for effective shear strength triaxial test (deg)

3.4.1.8 TBL-TRIX

This table contains the details of the triaxial test.

Table 3.8: The fields of TBL-TRIX

Field name	*Data type*	*Description*
TRIX_REF	Autonumber	Number of triaxial test detail within NETDATA
TRIG_REF	Number	Number of triaxial test result within NETDATA
HOLE_REF	Number	Number of borehole within NETDATA
SAMP_REF	Number	Number of sample within NETDATA
SAMP_TOP	Number	Depth to top of sample (Unit: m)
TRIX_TESN	Number	Triaxial test / stage number
TRIX_CELL	Number	Total cell pressure (Unit : kN/m^2)
TRIX_DEVF	Number	Deviator stress at failure (kN/m^2)
TRIX_STRN	Number	Strain at failure (%)
TRIX_PEPI	Number	Porewater pressure at start of shear stage (kN/m^2)
TRIX_PWPF	Number	Porewater pressure at failure (kN/m^2)
TRIX_MODE	Text	Mode of failure

3.4.1.9 TBL-SHBG

This table contains the results of shear box tests that have been carried out on different samples.

Table 3.9: The fields of TBL-SHBG table

Field name	*Data type*	*Description*
SHBG_REF	Autonumber	Number of shear box test results within NETDATA
HOLE_REF	Number	Number of borehole within NETDATA
SAMP_REF	Number	Number of sample within NETDATA
SAMP_TOP	Number	Depth to top of sample (m BGL)
SHBG_PCOH	Number	Peak cohesion intercept (kN/m^2)
SHBG_PHI	Number	Peak angle of friction (deg)
SHBG_RCOH	Number	Residual cohesion intercept (kN/m^2)
SHBG_RPHI	Number	Residual angle of friction (deg)

3.4.1.10 TBL-CONS

Results of oedometer tests are included in this table. The fields within the table are shown below:

Table 3.10: The fields of TBL-CONS table

Field name	*Data type*	*Description*
CONS_REF	Autonumber	Number of consolidation test results within NETDATA
HOLE_REF	Number	Number of borehole within NETDATA
SAMP_REF	Number	Number of sample within NETDATA
SAMP_TOP	Number	Depth to top of sample (m BGL)
CONS_INCN	Number	Oedometer stress increment number
CONS_INCD	Text	Defined stress range (kN/m^2)
CONS_INCF	Number	Stress at end of stress increment / decrement (kN/m^2)
CONS_IVR	Number	Initial voids ratio
CONS_INCE	Number	Voids ratio at end of stress increment
CONS_INMV	Number	Coefficient of volume compressibility over stress increment (m^2/MN)
CONS_INCV	Number	Coefficient of consolidation over stress increment (m^2/yr)

3.4.2 Queries

The main use of a database is to gain access to data stored in the database and find required information. Queries make it possible to ask questions about the data stored in the tables of the database. They are the most important facility within the software and make it possible to ask for specific information about the required data. Queries can be used to retrieve data from the tables within the database for analysis and printing. The ability to query the data in a variety of sophisticated ways is one of the extremely powerful features of RDBMS. The data held within the RDBMS can be interrogated by using the industry standard Structured Query Language (SQL). This is an industry standard, non-procedural language used to manipulate and control databases. The language uses a series of SQL statements to perform a variety of tasks such as querying data and controlling access to data. This option is more suitable for more advanced users. The code can be used to design complex queries by joining tables (using the JOIN command), select data fields from tables that hold the required data (using the SELECT and FROM commands), define conditions for the data search (using the WHERE command), or impose a preferred order on the data according to specific criteria (using the ORDER BY command). A sample code is shown in Figure 3.6.

```
Query1 : Select Query
SELECT [TBL-PROJ].PROJ_LOC, [TBL-HOLE].HOLE_ID, [TBL-SAMP].SAMP_TOP, [TBL-TRIG].TRIG_CU
FROM ([TBL-PROJ] INNER JOIN ([TBL-HOLE] INNER JOIN [TBL-SAMP] ON [TBL-HOLE].HOLE_REF =
[TBL-SAMP].HOLE_REF) ON [TBL-PROJ].PROJ_REF = [TBL-HOLE].PROJ_REF) LEFT JOIN [TBL-TRIG]
ON [TBL-SAMP].SAMP_REF = [TBL-TRIG].SAMP_REF
WHERE ((([TBL-PROJ].PROJ_LOC)="Acklington") AND (([TBL-HOLE].HOLE_ID)="BH-9700") AND (([TBL-
SAMP].SAMP_TOP)>5))
ORDER BY [TBL-SAMP].SAMP_TOP;
```

Figure 3.6: Screen shot showing a query in SQL view

The above code searches for samples below "5 meters" taken from borehole number "BH-9700" from a location in "Acklington" and will display the undrained shear strength of the samples. The results of the query are then displayed in ascending order according to the depth of the sample.

A less daunting way of interrogating the database is the use of the graphical interface of the Microsoft Access software which makes it possible to ask questions about the data stored in the tables of the database without the need for writing SQL codes. This interface allows users to view and choose from the list of tables and fields, and to set criteria and expressions to make the search more specific and accurate. Figure 3.7 shows the graphical version of the SQL code shown in Figure 3.6.

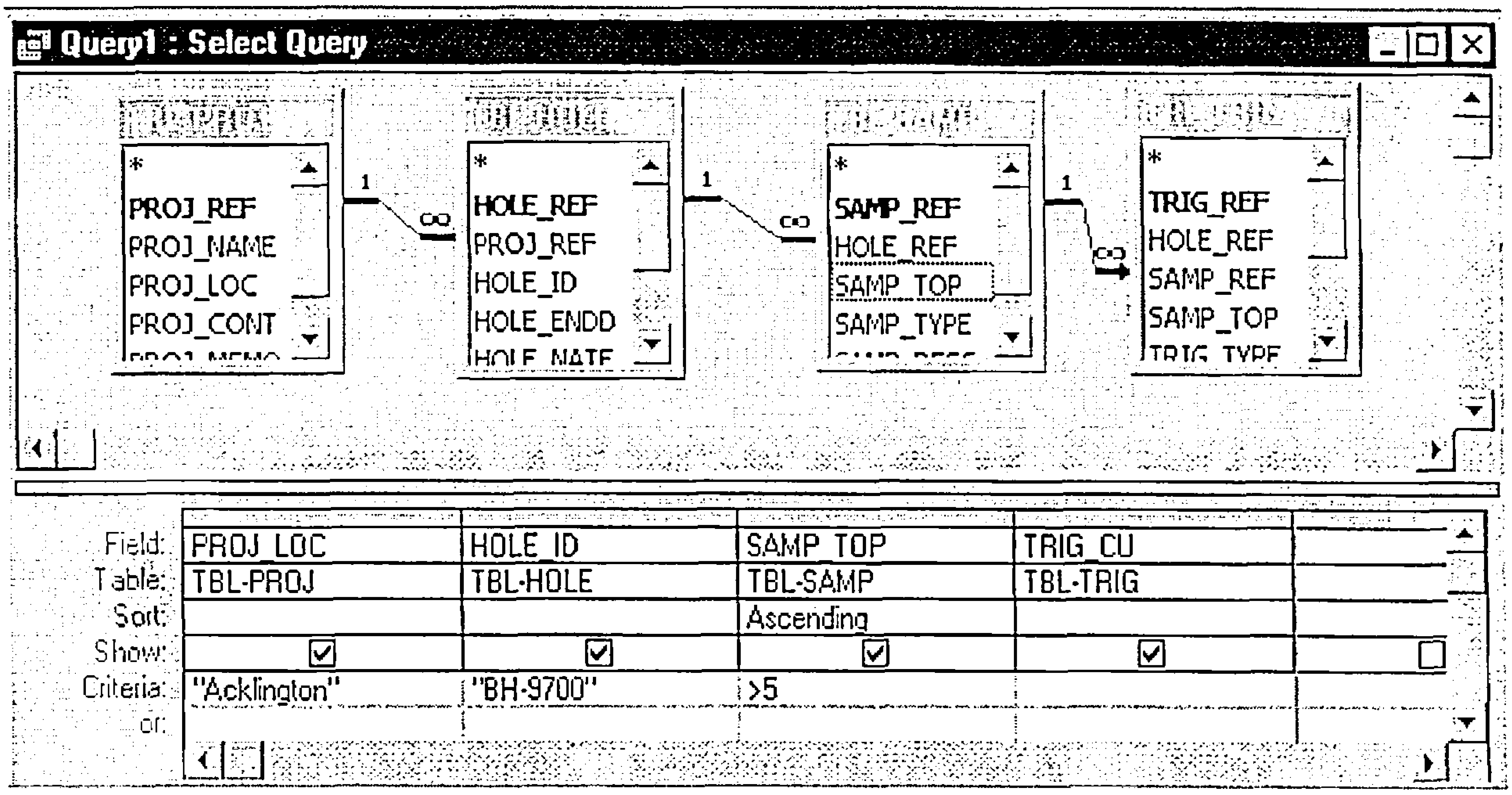


Figure 3.7: Screen shot showing a query in design view.

Several queries have been designed and prepared to retrieve data from the tables within NETDATA for analysis or printing. Further details about these queries and using search criteria can be found in Appendix B.

To make matters even easier a special form called "Query by Form" has been designed for filtering data, where the user of the database can set the criteria for various parameters without using queries. This specially designed form combines Visual Basic and SQL commands together, and creates a powerful and easy to use tool for searching and querying of data (Figures 3.8 and 3.9).

```
Private Function BuildSQLString(strFieldName As String, varFieldValue As
Variant, intFieldType As Integer)
   Dim strTemp As String

   strTemp = "[" & strFieldName & "]"
   If isOperator(varFieldValue) Then
     strTemp = strTemp & " " & varFieldValue
   Else
     Select Case intFieldType
         Case dbBoolean
           strTemp = strTemp & " = " & CInt(varFieldValue)
         Case dbText, dbMemo
           strTemp = strTemp & " LIKE " & QUOTE & varFieldValue & "*" &
QUOTE
         Case dbByte, dbInteger, dbLong, dbCurrency, dbSingle, dbDouble
           strTemp = strTemp & " = " & varFieldValue
         Case dbDate
           strTemp = strTemp & " = " & "#" & varFieldValue & "#"
         Case Else
           strTemp = ""
     End Select
   End If
   BuildSQLString = strTemp
End Function
```

Figure 3.8: Sample code combining Visual Basic and SQL commands (adapted from Getz et al, 1994)

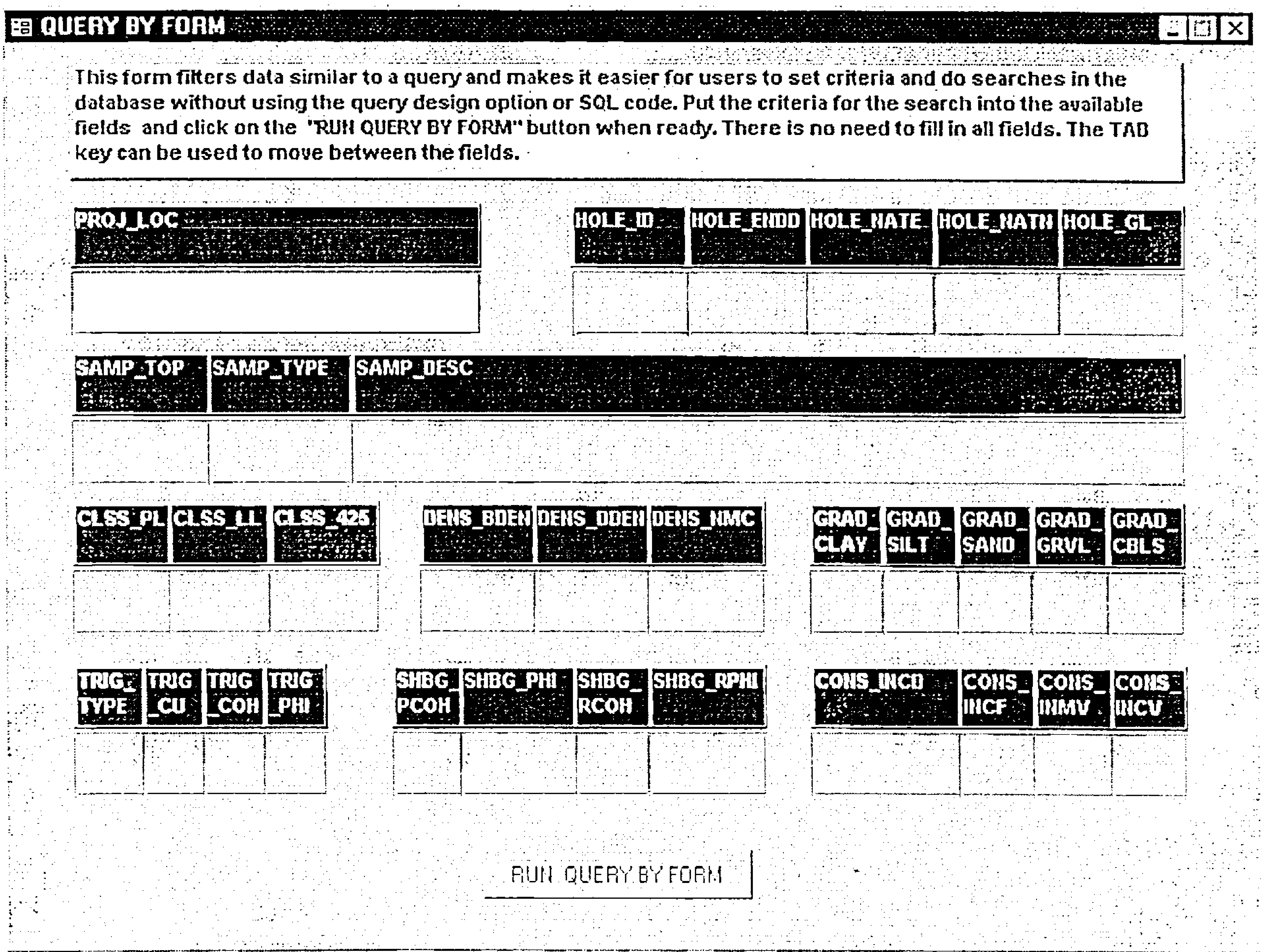


Figure 3.9: Screen shot showing the "Query by Form" designed for filtering data

Retrievals from the database can be displayed in forms, delivered as new database tables, printed as reports, or saved in other formats such as ASCII files or HTML files. Data can also be exported into other packages such as Microsoft Word and Microsoft Excel.

3.4.3 Forms

Forms are Microsoft Access database objects on which it is possible to place controls for taking actions or for entering, displaying and editing data in fields. This facility can be used for designing screens and presenting information with a more user-friendly format. Several forms have been prepared for the NETDATA database for viewing, editing or adding data to fields from test result tables (Figure 3.10).

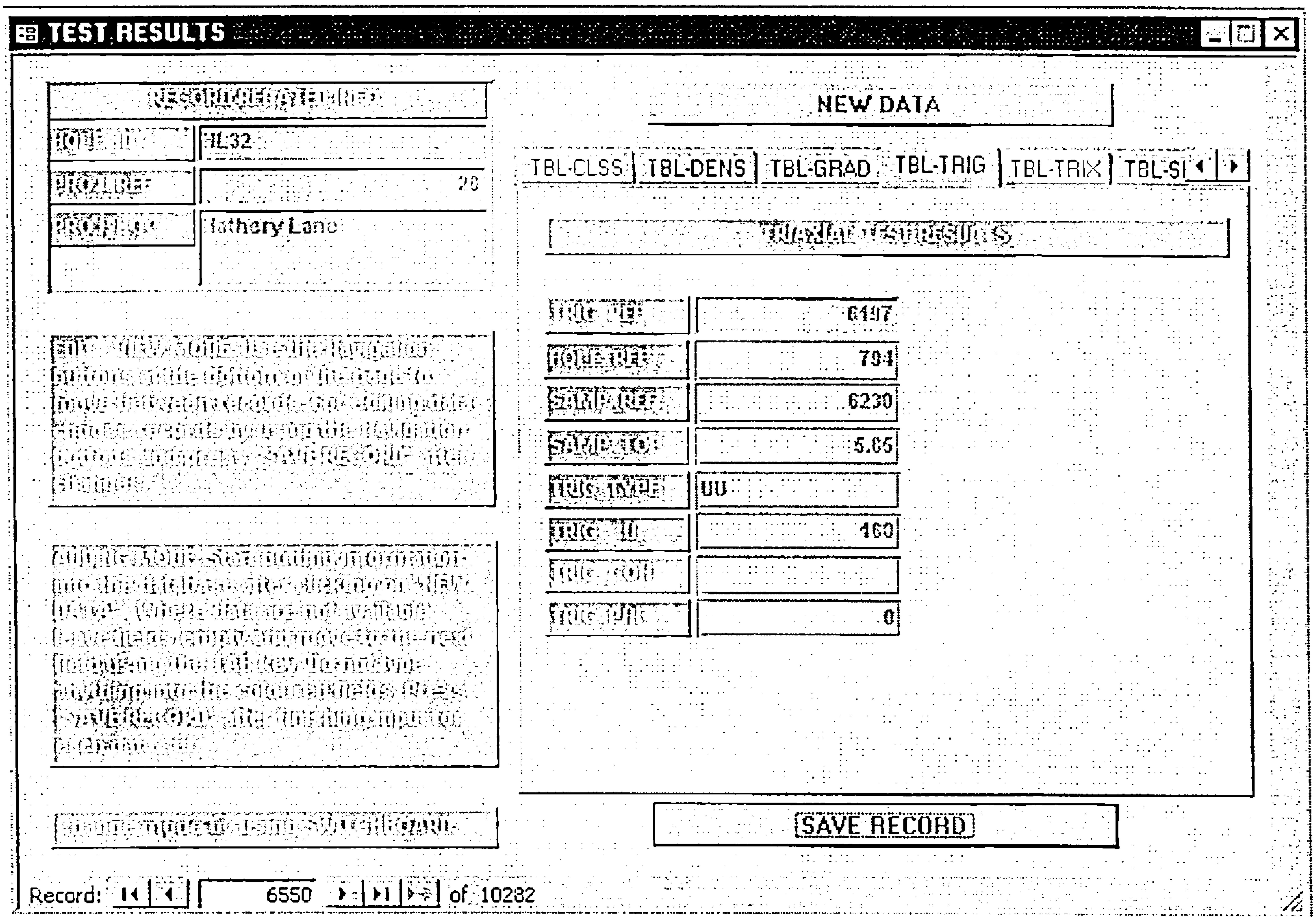
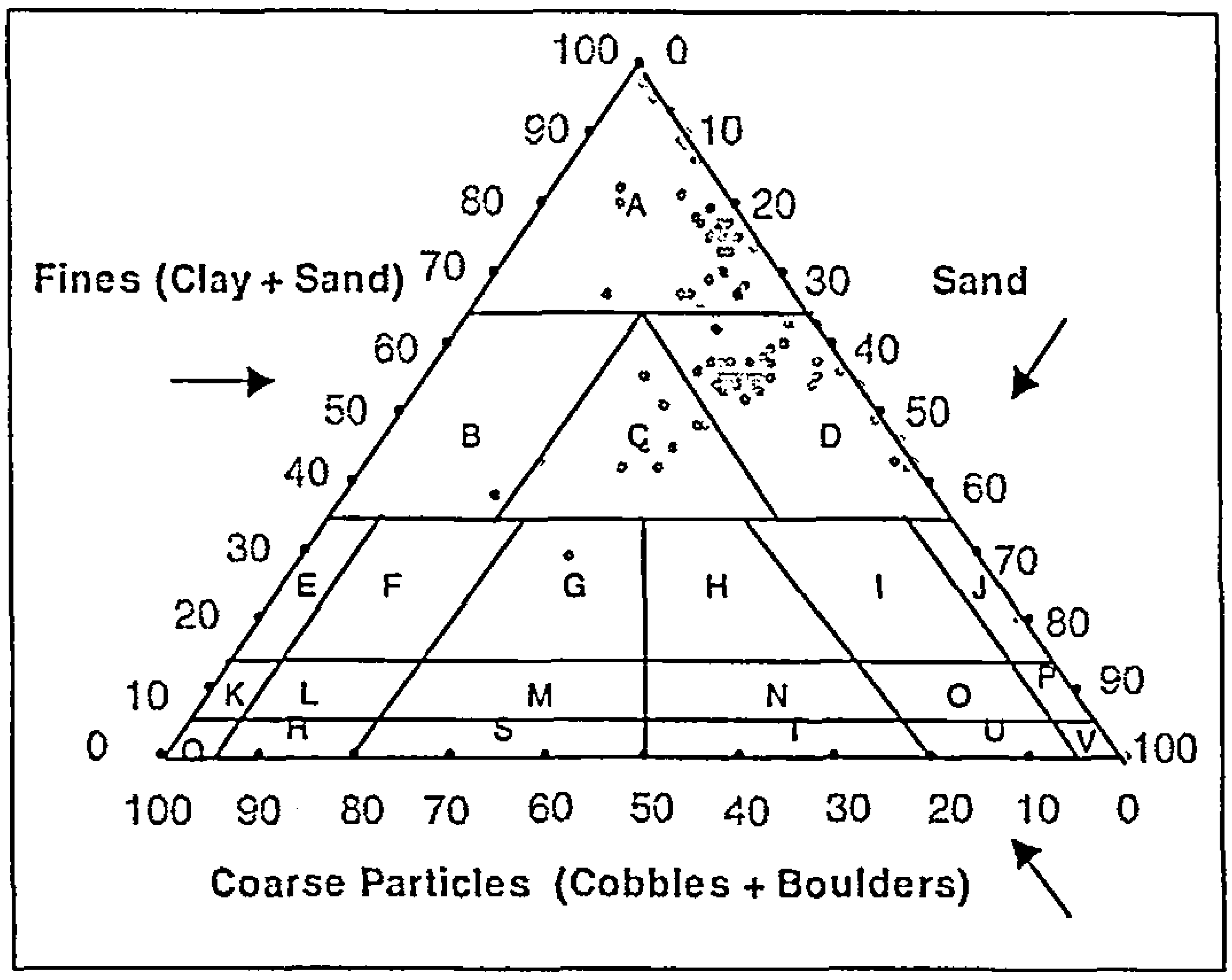
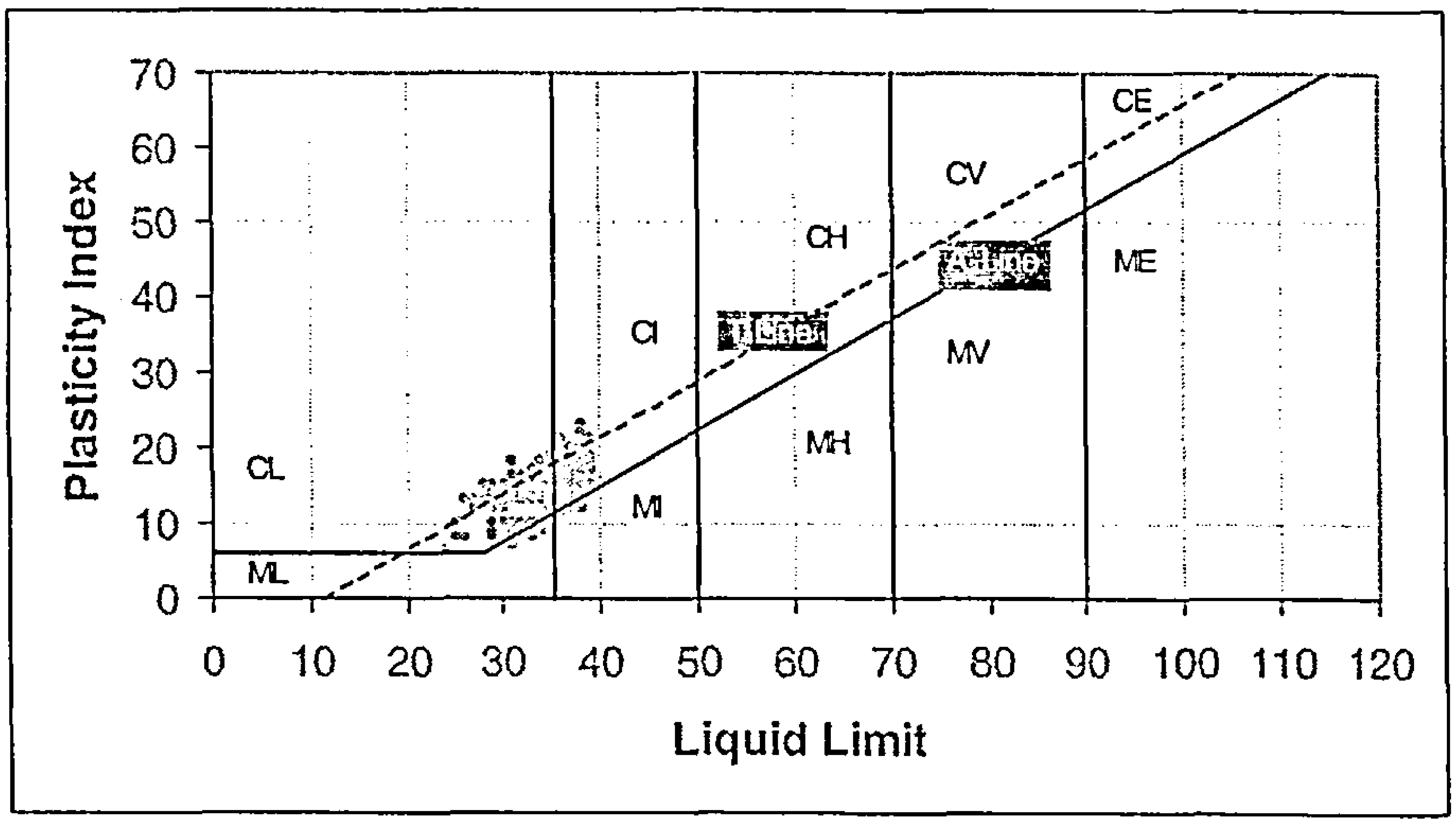


Figure 3.10: Forms prepared for viewing, editing and adding data

Some of the forms are designed to produce plots such as index and grading classification charts, which can be used for analysing the data. These forms make use of especially designed macros which transfer the results of index queries into a Microsoft Excel Sheet. The spread sheet will then automatically perform the required calculations on the data and display the results in the form of classification charts. Examples of these charts that are produced based on the results of a query are presented in Figure 3.11.



a) PSD classification chart



b) Plasticity chart

Figure 3.11: Example of classification charts produced based on query results

More details about the forms, designed for the database, can be found in Appendix B.

3.4.4 Reports

Reports are used to summarise and present data from tables and queries. They may be printed on paper or displayed on the computer screen. The report facility in the software can be used to organise and present data in groups, carry out calculations, produce graphs and put the data in required formats. Several reports have been prepared within NETDATA to present information about the projects and laboratory test results. A sample report is shown in Figure 3.11.

SAMP_REF	HOLE_ID	SAMP_TOP	SAMP_TYPE	SAMP_DESC	CLSS_PL	CLSS_LL	CLSS_PI	CLSS_425	DENS_NMC	DENS_BDEN	DENS_DDEN
4796	BH-9700	1.50		Firm reddish brown mottled light grey weathered occasionally laminated fine sandy very silty CLAY with occasional fine gravel and fine organic fibers (rootlets).	28	58	30	100	22.1	1.94	1.59
4797	BH-9700	2.50		Stiff becoming very stiff with depth, dark reddish brown slightly laminated slightly sandy CLAY with some sandstone, limestone and occasional mudstone fragments	20	37	17	88	16.8	2.13	1.83
4798	BH-9700	3.51		Stiff becoming very stiff with depth, dark reddish brown slightly laminated slightly sandy CLAY with some sandstone, limestone and occasional mudstone fragments	18	36	18	78	18.4	2.11	1.78
4799	BH-9700	4.60		Stiff becoming very stiff with depth, dark reddish brown slightly laminated slightly sandy CLAY with some sandstone, limestone and occasional mudstone fragments	19	37	18	81	16.9	2.13	1.82

Figure 3.12: Screen shot showing part of a sample report produced in NETDATA

The information displayed in a form are data retrieved from the database using the available queries. The first page of the reports contains the list and description of the fields used within the reports and the relevant units, which is followed by the results of the query. More details about reports can be found in Appendix B.

3.4.5 External files

Extensive use was made of the capabilities of Microsoft Access in communicating with other software. The database contains automatic links to Microsoft Excel spreadsheets, which can automatically produce Grading and Plasticity classification charts using query results from inside the database. There is also a link from one form in the database, which puts the results of a query automatically into an Excel file that can be used for producing various plots or analysis of data. A Microsoft PowerPoint presentation is also prepared and can be run from inside the database, which includes background information about the geology of Northern England and pictures of various opencast sites focusing on weathered and unweathered till layers on face exposures.

3.4.6 Help File

An essential part of the design procedure is to provide help for carrying out various tasks within the database. Using Microsoft Help Workshop Version 4 an online help facility was designed to eliminate the need for a physical manual (Figure 3.12). This hypertext help system along with the more technical help options provided by the Microsoft Access software related to database design, provides a useful facility for users who are not familiar with NETDATA.

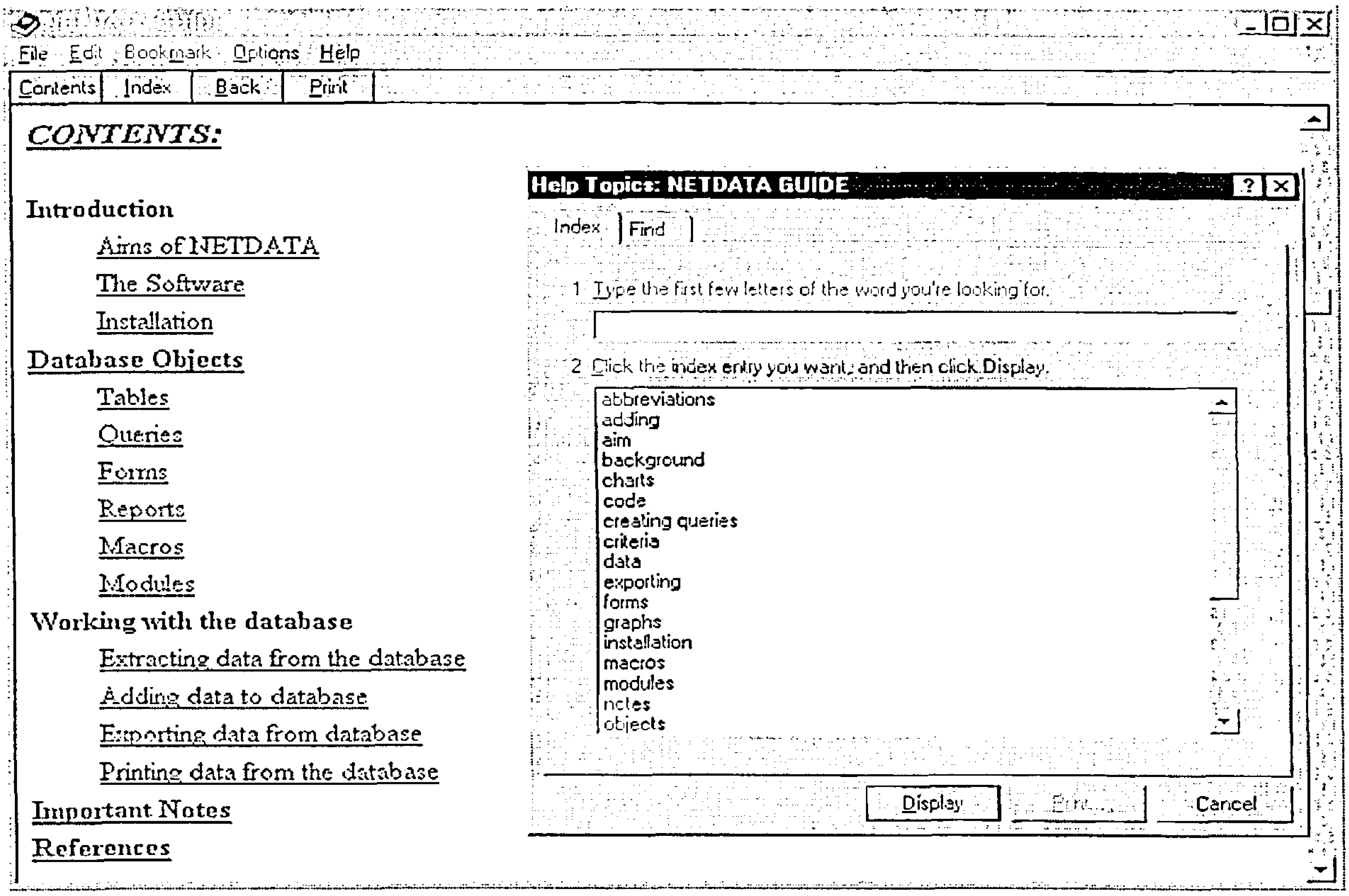


Figure 3.13: Help file prepared for NETDATA

This help facility contains information about all objects used in the database and provides help options to carry out tasks such as running available queries, adding or editing data in different ways, methods of using the specially designed forms, exporting data, producing reports etc. Included in the help file is the list of Units and Abbreviations used in NETDATA. These units are taken from the AGS dictionary and are as shown in Table 3.11.

Table 3.11: List of Units used in NETDATA

Measured Quantity	Symbol of Unit	Description of Unit
Length	m	metre
Length	mm	millimetre
Time	dd/mm/yy	Day month year
Concentration	%	percentage
Density	Mg/m3	megagrams per cubic metre
Pressure	kN/m2	kiloNewtons per square metre
Miscellaneous	m2/MN	square metre per megaNewton
Miscellaneous	m2/yr	square meters per year
Miscellaneous	deg	degree (angle)

Codes of abbreviations are used in a number of AGS Format Groups in order to insure consistency in terminology and for brevity. Some of these codes are used in the database and are as shown in Table 3.12.

Table 3.12: List of abbreviations used in NETDATA

Field Name	Abbreviation Code	Description
SAMP_TYPE	U	Undisturbed sample
SAMP_TYPE	D	Small disturbed sample
SAMP_TYPE	B	Bulk disturbed sample
TRIG_TYPE	CD	Consolidated drained (single stage)
TRIG_TYPE	CDM	Consolidated drained (multi-stage)
TRIG_TYPE	CU	Consolidated undrained (single stage)
TRIG_TYPE	CUM	Consolidated undrained (multi-stage)
TRIG_TYPE	UU	Unconsolidated quick undrained (single stage)
TRIG_TYPE	UUM	Unconsolidated quick undrained (multi-stage)

A copy of this guide can be found in Appendix B.

3.5 Summary

A good database management system should not only be able to store any amount of data but also should provide entry screens to get data in, search screens to find data, and output screens to present the data found. It should also be able to process data to enhance the system (Mallender, 1995). Bearing these points in mind NETDATA a relational database was developed to help engineers as a source of information about tills in Northern England.

Microsoft Access version 97 was found to be a suitable RDBMS with an appropriate interface and software tools for the design of NETDATA. The AGS Format was followed as a data model in order to put the available data into a standard format and ensure consistency and coherency between the data. This format has been successfully adopted in most specifications for ground investigations.

The main use of a database is to gain access to data stored in the database and find required information. Queries are prepared and can easily be designed and added to the database to carry out searches to find certain data. A special form has also been designed as an alternative method to queries for filtering data.

Although it is possible to enter or edit data directly in relevant tables of the database, several forms have also been designed to make the process of data entry and editing easy for the user. Other forms are also available to process the data within the database. For instance, it is possible to plot Index or grading classification charts or to calculate further geotechnical parameters such as Liquidity Index, Plasticity Index, Permeability or Compression Index by using the data already stored in the database.

Reports have been designed and are available to view the results of a query on screen or to print them on paper.

Data can be imported or exported from and to other software such as spreadsheets for further analysis. The database stores and centralises available data in a standard format, which can easily be updated. This makes data from various locations available for comparison. The data can be used for analysing the geotechnical parameters of tills in the region. It is also possible to use the data to re-analyse some earthwork failures, such as excavated slopes and spoil mounds, where records are available.

Data of several sites of the Northern England region were obtained and have been put into the database throughout this project. Details of the site investigations and the geology of these sites are reviewed in the following chapter.

Chapter 4

Geology of Northern England

4.1 Introduction

In the previous chapter the structure of NETDATA was explained in detail. The data that have been put into the database for this study were mainly found in hardcopies of site investigation reports from various projects carried out on sites in Northern England. Northern England has a long history of coal mining with reserves having been exploited by both underground and opencast mining methods. Opencast coal mining involves the excavation and movement of substantial quantities of material in order to extract the coal. The overburden material generally includes agricultural soil, superficial (glacial) deposits and waste rock. When mining is complete, the sites are required to be restored such that the ground can be used for other purposes such as agriculture and industry. The main overburden material include topsoil, subsoil and rocks and are stored in mounds so that the land can be restored to its original state as near as possible. Many site investigations were carried out in order to determine the properties and extent of the superficial deposits prior to the excavation of the sites. They provided additional information for other related constructions such as the construction of temporary disposal points or access roads. The British Coal Opencast (BCO) possessed one of the largest collections of geotechnical data on glacial soils for the Northern England region. These records have been obtained under a legal agreement between the British Coal Opencast and the University of Newcastle upon Tyne.

Results of 33 site investigation projects and the related laboratory tests from various locations of Northern England were put into NETDATA. Although some of the site investigations date back to the last two decades, their value should not be underestimated. It is difficult to assess the useful life of geological and geotechnical data. Data apparently superseded by more recent information or re-interpretations may still have potential value. The availability of original data allows recalculation without costly re-analysis. The potential lifetime of such data whether archived or active is unlimited (Lowe, 1995).

This project aimed to study the geotechnical properties of the tills in their natural condition, and therefore samples taken from the topsoil or Made Ground were not included in the database. The topsoil layer is usually an organic layer including turf, subsoil, organic filling weathered material with roots etc.; and the term Made Ground is used to describe any artificially deposited superficial materials. Therefore the description of the sites and also the analysis on the data in later chapters concentrates on the description and test results of natural till material.

In this chapter methods used for site investigation are reviewed and the general condition of the sites based on the data stored in the database are described.

4.2 Site Investigation Methods

The main objectives of site investigations are (Craig, 1997):

- to explore the surface and subsurface features and to determine the sequence, thickness and lateral extent of the soil strata and where appropriate the level of bedrock;
- To obtain representative samples of soils and rocks for identification and classification and for use in laboratory tests to determine relevant soil parameters;
- To identify the groundwater conditions.

The wide variation in ground conditions associated with glacial terrains frequently introduces problems for site investigations. The identification of the strata succession at a site is a major concern in any ground investigation. Methods of strata definition vary depending upon the landsystem. For subglacial till often found in English lowlands, methods such as cable percussion boring and rotary drilling may be satisfactory, but these techniques could prove difficult when penetration and representative sampling is required in coarse deposits typical of glaciated valley terrains (Trenter, 1999). Problems with glacial tills include:

- Penetration of a mixed sequence which may comprise clays, cobbles and boulders
- Possibility of misidentification of boulders as bedrock
- Identification of glaciofluvial layers or lenses and glacio-lacustrine laminated silty clays
- Obtaining representative samples suitable for identification and testing purposes

Trial pits and drilling of boreholes are two ways to identify the strata and take samples. Trial pits provide a good opportunity for visual inspection. They are a useful way of investigating tills, especially coarser clast materials, because they provide the opportunity for careful sampling, logging and taking photos.

Cable percussion boring in glacial tills produces satisfactory results over a wide range of depths although unlike trial pit investigations, the strata succession is usually inferred from samples taken at discrete depth intervals.
Rotary core drilling provides the opportunity for continuous recovery of soils and rocks but it is a less manoeuvrable form of investigation and more expensive than cable percussion techniques.

Different types of samples can be taken depending on the type of till. The two main types are disturbed and undisturbed samples. Disturbed sampling (such as bulk sampling) is carried out where there is no attempt to retain the physical integrity of the soil whereas undisturbed sampling (such as block sampling, rotary-core sampling or U100 drive sampling) are methods in which the soil sample is subjected to little disturbance to allow laboratory experiments to determine the approximated physical characteristics of the soil, such as strength, compressibility and permeability. These types are explained below (Clayton et.al, 1995; Trenter, 1999):

- U100 tube samples: This is a 450mm long, 100mm diameter undisturbed sample. The tube has a cutter at one end and the driving equipment at the other. Behind the cutter is a core catcher, incorporating 3 arms that go into the sample as it is withdrawn, to prevent the sample from falling out. Care should be taken to ensure that the cutting shoe is as clean and sharp as possible. The sample quality in this type decreases with the increase of coarse material in the tills. Driving the tube into the soil also causes strains in the material. Voids may be created when large clasts are pushed aside.

- Bulk Samples: Usually taken from trial pits or in soils where there is little or no cohesion. This type of sample is usually used for coarse granular soils where only disturbed material is necessary. Bulk sampling in fine grained granular soil is unsatisfactory because fines are often washed out.

- Block sampling is a method that may be adopted to retrieve samples of matrix and some clast-dominant tills which could otherwise be disturbed by tube sampling. The operation is normally performed in trial pits where the top and the sides are excavated and then trimmed such that a steel box can be lowered and retain the sample in position. The base is then excavated and the sample removed.

Samples taken from any of the above mentioned methods will be used to describe the stratum conditions. The description of soils and rocks is a progressive exercise which at each step involves further departure from strictly factual description and thus an increased interpretative element (Norbury et al, 1986). The following steps are involved:

- Description of individual samples from a borehole.
- Combining sample descriptions to form a stratum description on the borehole log. This should take field observations and results of field and laboratory tests into consideration, which may indicate conditions significantly different from the samples recovered.
- Drawing together and assimilation of stratum descriptions from a number of borehole logs to arrive at an interpretation of the mass properties of each stratum in the text of a report.

In some cases placing a soil into the correct category is a simple process based on direct observations, but generally it is more complex. To describe a soil simply as a clay or a sand and gravel is seldom adequate for engineering purposes and more detail is necessary to give a full account of its nature, state and properties. This involves qualitative and quantitative assessment and the classification of the soil by certain criteria. The soil and rock descriptions should be as defined in the standard code of practice. The following two standards were used in the available site investigations.

The description procedure and the terms used in both the CP2001:1957 and BS 5930:1981 depend on the principal soil type (Norbury et al, 1986). The code of practice on site investigation CP2001:1957 laid emphasis on the cohesive and non-cohesive natures of soils and hence the concept that soils should be described on the basis on how they would behave as engineering material. In section 8 of the revised code of practice on Site Investigation BS 5930:1981 soils are described primarily on the basis of their size distribution. Their engineering behaviour is only considered for differentiating between clay or silt. The following table compares the difference between the two standards (Norbury et al, 1986):

Table 4.1: A comparison between two code of practices for site investigations.

CP 2001:1957	BS 5930:1981
Soils possessing cohesion and plasticity are described as fine soils, although the majority of the soil by weight may be coarse or very coarse soil. It is not possible to give a percentage of clay and / or silt above which they become the principal component, since the mass behaviour depends on the mineralogy of the soil particles. The description is based on engineering judgement	Soils with more than 35% clay and / or silt are described as either clay or silt. Soils with less than 35% are described in terms of coarse or very coarse soils, irrespective of whether they have cohesion and plasticity. The description is therefore based on the particle size distribution, but the division between silt and clay is strictly on the Atterberg limits. These factors can be difficult to visually assess for some materials and laboratory tests are required to confirm descriptions.

The site investigation projects stored in NETDATA used one of the above mentioned standards depending on the time of the investigation. No data complying with the most recent Code of Practice BS 5930:1999 has yet become available for inputting, but as it is the intention that constant expansion and updating of NETDATA should take place, it is intended that data complying with this latest Code of Practice will be added in the future. The revised BS 5930:1999 has tried to describe soils based on a combination of their particle size distribution and plasticity. In general it can be said the descriptions of the sites are relatively consistent despite the differences in the specifications and the number of operators.

Table 4.2: Standards used for site investigations and laboratory testing for various sites

County	*Location*	*Contractor*	*Year of site investigation*	*SI-Standard*	*Testing Standard*
Cumbria	Oughterside	Norwest Holst Soil Engineering Ltd.	August to September 1980	CP 2001:1957	BS 1377:1975
Cumbria	Maryport	Norwest Holst Soil Engineering Ltd.	September 1983	BS 5930:1981	BS 1377:1975
Cumbria	Linefoot	Norwest Holst Soil Engineering Ltd.	February to May 1986	BS 5930:1981	BS 1377:1975
Cumbria	Foxhouse South	Norwest Holst Soil Engineering Ltd.	November 1985 to March	BS 5930:1981	BS 1377:1975
Cumbria	Broughton Lodge	Norwest Holst Soil Engineering Ltd.	March to April 1990	BS 5930:1981	BS 1377:1975
Cumbria	Potatopot	Norwest Holst Soil Engineering Ltd.	January to February 1985	BS 5930:1981	BS 1377:1975
Cumbria	Workington	Norwest Holst Soil Engineering Ltd.	May and June 1990	BS 5930:1981	BS 1377:1975
Cumbria	Lost Rigg	Norwest Holst Soil Engineering Ltd.	October and November	BS 5930:1981	BS 1377:1975
Cumbria	Keekle Extension	Norwest Holst Soil Engineering Ltd.	July and August 1985	BS 5930:1981	BS 1377:1975
Cumbria	River Keekle	Norwest Holst Soil Engineering Ltd.	June and August 1985	BS 5930:1981	BS 1377:1975
Cumbria	Moresby and Keekle	Soil Mechanics Limited	February to March 1980	CP 2001:1957	BS 1377:1975
Northumberlan	Chester House	Norwest Holst Soil Engineering Ltd.	September to October 1984	BS 5930:1981	BS 1377:1975
Northumberlan	Acklington	Allied Exploration & Geotechnics	September 1992 to April 1993	BS 5930:1981	BS 1377:1990
Northumberlan	Acklington Spoil	Norwest Holst Soil Engineering Ltd.	December 1981	BS 5930:1981	BS 1377:1975
Northumberlan	Chevington	Northumbrian Drilling Contractors	November 1979 to March	CP 2001:1957	BS 1377:1975
Northumberlan	East Chevington	Northumbrian Drilling Contractors	August 1979 to August 1980	CP 2001:1957	BS 1377:1975
Northumberlan	Colliersdean	Norwest Holst Soil Engineering Ltd.	September to October 1989	BS 5930:1981	BS 1377:1975
Northumberlan	Malden's Hall	Norwest Holst Soil Engineering Ltd.	November 1991 to February	BS 5930:1981	BS 1377:1990
Northumberlan	West Linton	Northumbrian Drilling Contractors	April 1980	CP 2001:1957	BS 1377:1975
Northumberlan	Linton Lane	B B Drilling Limited	May 1988	BS 5930:1981	BS 1377:1975
Northumberlan	Butterwell	Northumbrian Drilling Contractors	December 1974 to	CP 2001:1957	BS 1377:1975
Northumberlan	Stobswood	Norwest Holst Soil Engineering Ltd.	October to December 1988	BS 5930:1981	BS 1377:1975
Northumberlan	Widdrington	Allied Exploration & Geotechnics	November 1992 to March	BS 5930:1981	BS 1377:1990
Northumberlan	Steadsburn	Allied Exploration & Geotechnics	April to July 1993	BS 5930:1981	BS 1377:1990
Northumberlan	Bebside	Allied Exploration & Geotechnics	November to December	BS 5930:1981	BS 1377:1990
Northumberlan	Hathery Lane	Norwest Holst Soil Engineering Ltd.	February to September 1992	BS 5930:1981	BS 1377:1990
South of Tyne	Plenmeller	Norwest Holst Soil Engineering Ltd.	1982-83 and 1990	BS 5930:1981	BS 1377:1975
South of Tyne	Melkridge	Norwest Holst Soil Engineering Ltd.	February 1983	BS 5930:1981	BS 1377:1975
Tyne and Wear	Hunters Moor	Ian Farmer Associates	July 1993	BS 5930:1981	BS 1377:1990
Tyne and Wear	Herrington	Ian Farmer Associates	August to November 1991	BS 5930:1981	BS 1377:1990
Durham	Red Barns	Norwest Holst Soil Engineering Ltd.	May to June 1983	BS 5930:1981	BS 1377:1975
Durham	Hill Top	Norwest Holst Soil Engineering Ltd.	May to June 1986	BS 5930:1981	BS 1377:1975
Durham	Whitwell	James Associates	January 1995	BS 5930:1981	BS 1377:1990

Tills include material from more than one category and this makes it sometimes difficult to describe them as one or the other. As shown in table 4.2 most of the available site investigation reports follow the British Standard (BS:5930:1981) for the description of the soil. Such descriptions should contain the information described below:

- Mass characteristics
    - Bedding, laminations
    - Discontinuities such as fissure, joints, fractures, shear planes
    - State of weathering
    - Scale of strength and compactness (Table 4.3)
- Material characteristics
    - Colour which is an indicator of chemical and mineralogical content.
    - Particle shape and composition,
    - Soil name (CLAY, SILT, SAND, GRAVEL, etc.)
- Geological formation, age, type of deposit
- Classification such as plasticity and grading

Table 4.3: Relationship between stiffness and undrained shear strength, and density and the SPT 'N' Values

Term	Cu (kN/m^2)	Term	SPT 'N' Value
Very Soft	<20	Very Loose	<4
Soft	20-40	Loose	4-10
Firm	40-75	Medium dense	10-30
Stiff	75-150	Dense	30-50
Very stiff	>150	Very dense	>50

Included in the report should be a location of all the boreholes, trial pits, other excavations and their logs. These logs should give as much information as possible on the soil and rock structure and also the ground water conditions. A sample of borehole logs and test summary sheets and test result details can be found in Appendix C.

4.3 Tills in Northern England

It is generally agreed that most of the present-day till succession in Northern England was deposited during the late Devensian glaciation (Hughes et al, 1998). Exceptions include some basal sands and gravels in Cumbria and the Warren House Gill deposits on the Durham Coast. However, some of these tills may include materials that were re-worked deposits from earlier glacial phases. As mentioned earlier in this chapter details of 33 sites of Northern England were put into a database of which 11 are from the Cumbrian coastal area, 15 are from the North of Tyne coastal area, and 7 are from the South of Tyne area (Figure 4.1). The geology of the sites is reviewed in later sections of this chapter. The locations of some of these sites are shown in Figure 4.1.

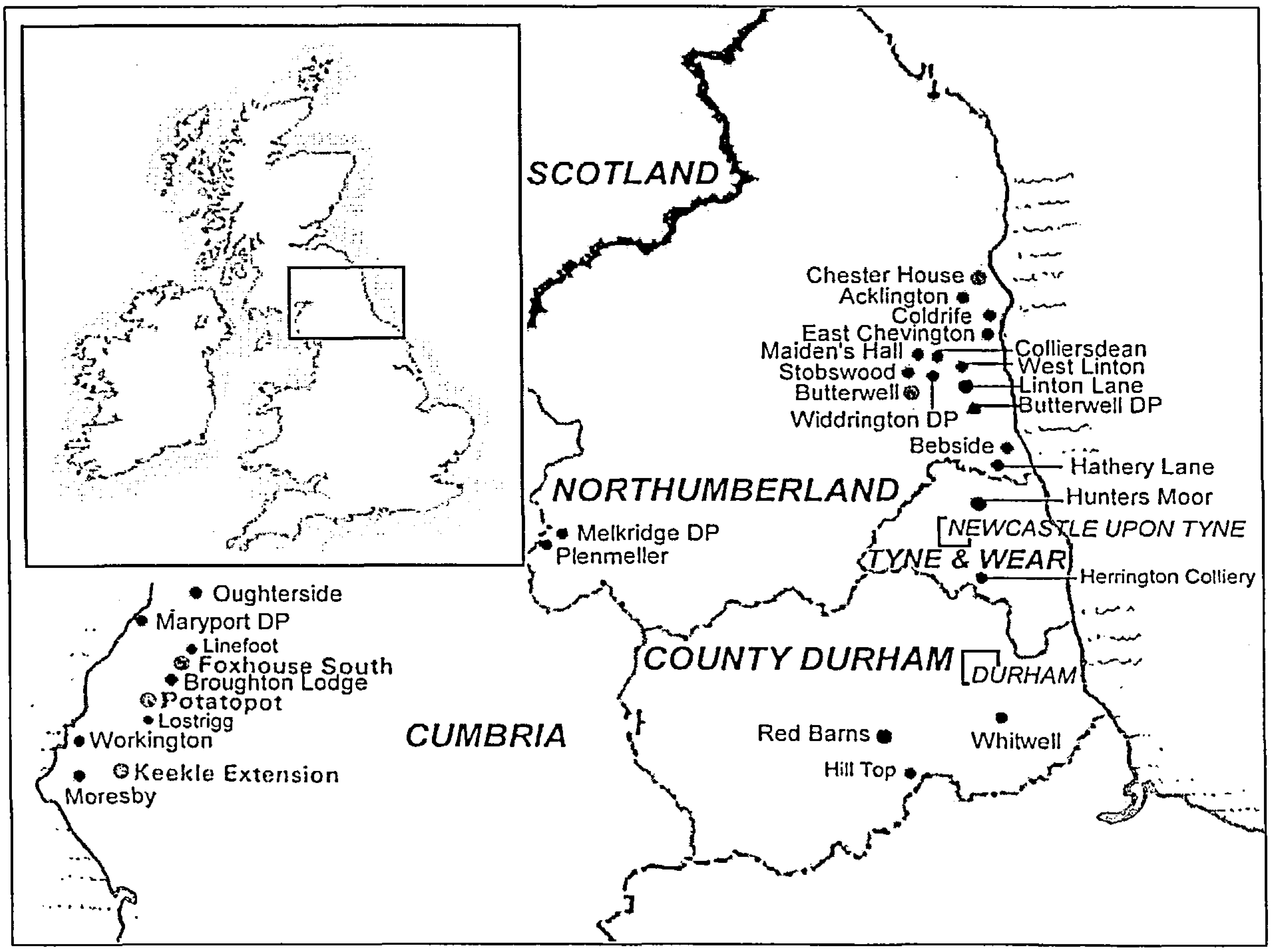


Figure 4.1: Location of few opencast mining related ground investigations stored in NETDATA

It should be noted that the geology of the sites is reviewed according to their geographical locations. For the analysis of the soil properties, in chapter 5, the direction of ice movement also needed to be considered as it would affect the source of material. Figure 4.2 and 4.3 show the direction of ice movement in Great Britain.

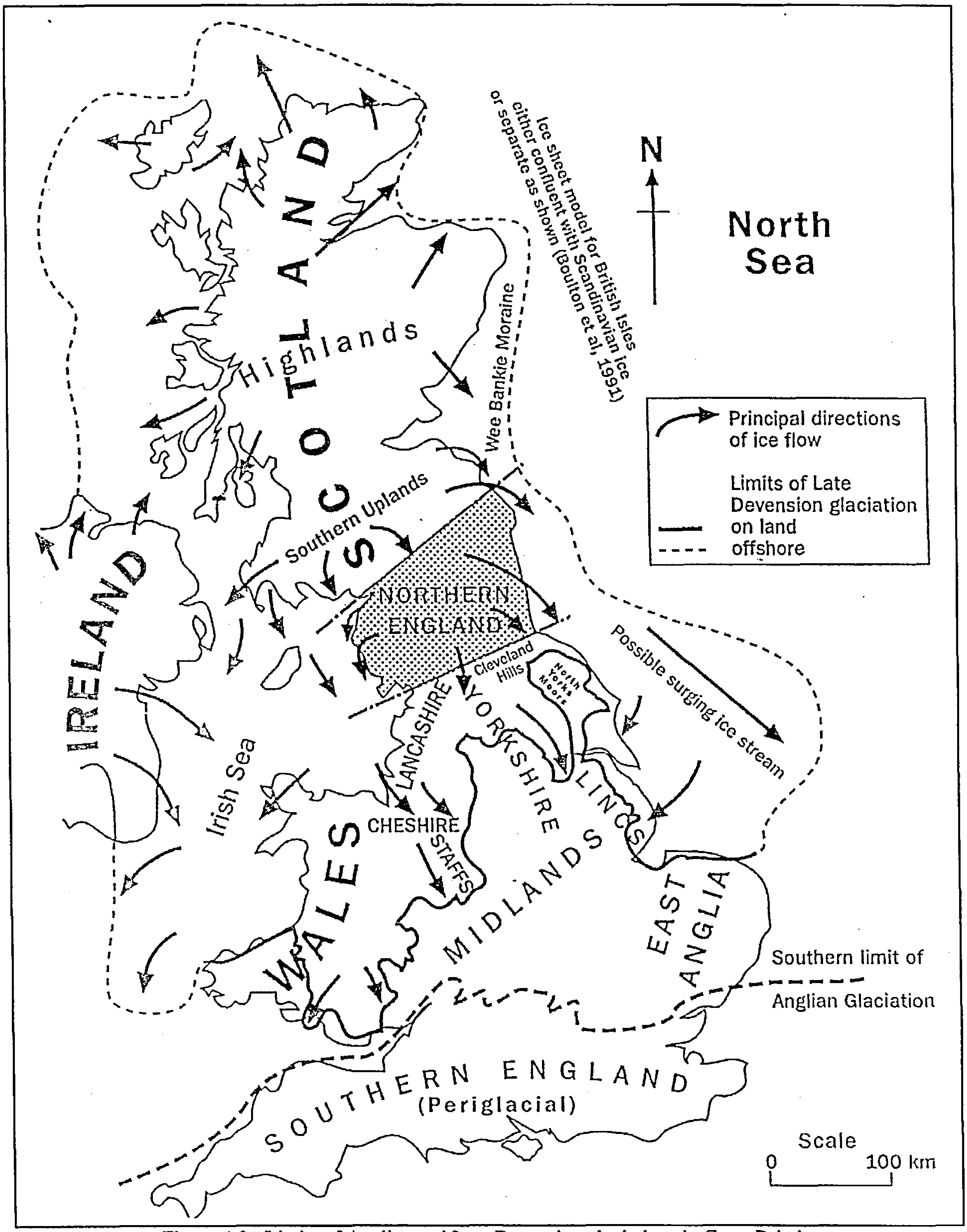


Figure 4.2 : Limits of Anglian and Late Devensian glaciations in Great Britain.

(after Hughes et al, 1998 and based on Eyles and Dearman, 1981; Eyles and McCabe, 1989; Boulton et al, 1991; Catt, 1991 a and b; and Stewart, 1991)

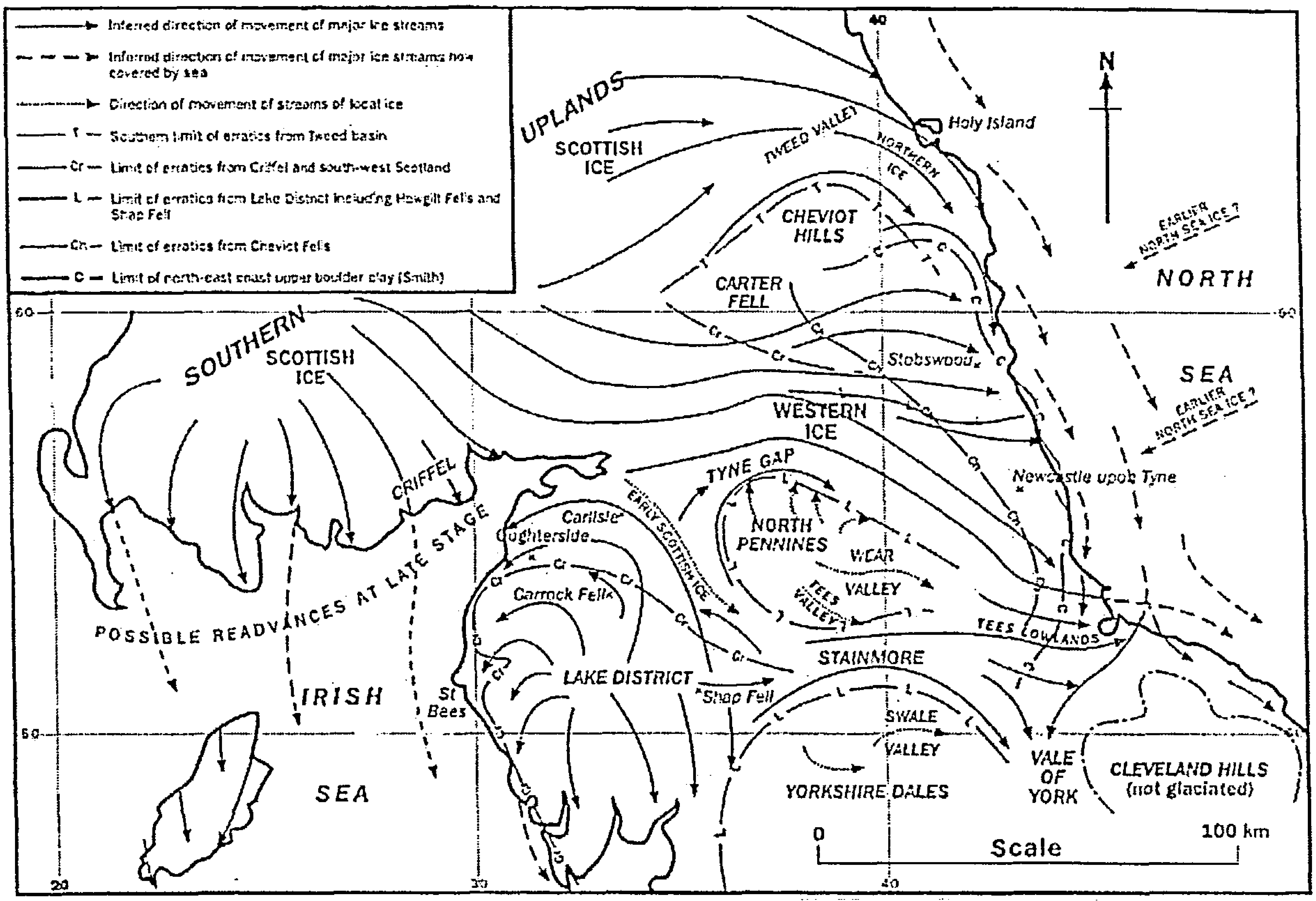


Figure 4.3: The pattern of Late Devensian ice movement in Northern England (after Hughes et al, 1998 and based on Taylor et al, 1971).

It can be seen from Figure 4.2 that ice sheet extended across the Scottish Highlands and the Southern Uplands. This ice flowed outwards in all directions. Figure 4.3 shows that during the Late Devensian glaciation ice initially moved southwards from Southern Scotland and covered the area. The red tills to the north and west of the area were deposited by this ice which mainly derived from the Permo-Triassic bedrock located farther north (Hughes et al, 1998). In the eastern part of the area the grey tills, which are derived from the local Coal Measures, appear to be dominant. The ice from the Lake District moved toward Eastern England via the Tyne Gap. This figure also shows that ice travelled from the Southern Uplands to Northumberland. These ice streams were joined further south in County Durham. It is suggested that the western ice stream was responsible for depositing lodgement till over the Northumberland coastal plain and much of County Durham (Taylor et al, 1971; Smith, 1981 and 1994). In the following sections the geology of the above mentioned three groups are reviewed separately. The description of individual sites may be found in Appendix D.

4.3.1 Glacial geology of Northumberland

The Northumbrian plain is the area that lies north of the River Tyne and is bound to the west by the rising ground of the northern Pennines and to the north by the Cheviot Hills and is a relatively low-lying coastal plain that is similar to adjacent areas to the north and south. The area between the Tyne and the Tees was one of intermingling ice sheets. A local ice cap was developed in the Northern Pennines and ice also streamed into the area from South-west Scotland, from the Lake District and southwards down the coast. Flow was strongly influenced by local topography. At the time of maximum glaciation the whole of the region was completely buried by ice with glaciers even overriding the higher parts of the North Pennines to the west.

All the BGS Memoirs for the Northeast of England and in particular north of the River Tyne refer to a tripartite succession in the glacial drift deposits which is explained below (Hughes et al, 1998):

- Lower grey till which is considered to be a lodgement till and generally occurs throughout the region. In some places it could be a deformation till. It can overlie basal sands and gravels, boulder beds or rockhead and its thickness can be up to 40 metres.
- Middle sand that separates the lower till from the upper till. This granular layer can occur in various thicknesses from a few millimetres to 40 metres. They also can vary from sand to gravel and include lenses of laminated clay in some places.
- Upper red / brown till has been described as lodgement till, ablation, melt-out or flow till. It may be a product of postglacial weathering, and may have been subjected locally to some preglacial modification.

A wide variety of glaciofluvial sediments and landforms exist in Northumbria. Three environmental situations can be distinguished (Douglas, 1991):

- Relatively isolated constructive landforms of sand and gravel are associated with the lowland area of lodgement till deposits. These are found near Bamburgh and are aligned with the direction of ice flow and represent subglacial channels draining the Devensian ice sheet.
- Certain areas comprise terrain which is almost entirely the product of ice sheet wastage and consists of extensive ice-contact forms. These are best developed on the margin of

Cheviot Hills near Wooler and to the south of Cornhill in the Tweed valley and consist mainly of sand and gravel and the product of the downwasting ice.

- Glaciofluvial deposits are found in Northumbria as outwash and sometimes ice-contact features aligned along the major river valleys such as Tyne and Wear Valleys.

There is debate about the status of the extensive formations of tills, silts, sand and gravel that cover much of the lowland in Northumbria. Several glacial episodes were identified for the glacial drifts in this area and a tripartite classification was introduced. This classification consisted of a Lower Till, Middle Sands and Upper Till. North of the river Tyne the relative persistence of the middle sand is not evident, although waterlain material is identified frequently within the till sequence. A different model was introduced which demonstrated that the complex stratigraphy consists of crosscutting lodgement till units (Eyles and Sladen, 1981). This model explained the colour difference of the upper and lower till units as the result of post-depositional weathering. This theory however attracted strong opposition by some other researchers who suggested that there have been two successive Late Devensian ice sheets which deposited the upper and lower till (Smith, 1994).

4.3.2 Geology of Tyne and Wear, South West Northumberland and County Durham

As shown in Figure 4.3 ice travelled to the Northumberland coast from the Southern Uplands, the Tweed valley, the Cheviot Hills and from the Lake District via the Tyne Gap. In County Durham these ice streams were joined by Pennine ice and more Lake District ice via the Stainmore Gap. The eastern Lake District ice stream moved towards the east and into Teesdale and forced another ice sheet, which probably originated on the Pennines, northwards into County Durham. The Lake District ice also crossed the Pennines further north through the Tyne Valley. Between the Tyne and Teesdale streams, central parts of County Durham were covered by the eastward flowing ice from the Pennine (Catt, 1991a). The western ice stream was responsible for depositing lower till over much of County Durham. The later Cheviot-Tweed ice deposited the upper till in the Tyne estuary and eastern County Durham. The lower till includes volcanic rocks and granites from the Lake District, Scottish greywackes and granites, and red sandstone of Devonian and Triassic age (Catt, 1991a). Similar to the Northumberland area, glaciofluvial sands and gravel are scattered in the area and in many places overlay the Lower Till. In parts of County Durham the lower till is overlain by interbedded sands, silts, laminated and gravelly clays which overlie the eroded surface of a greyish-brown lower till. These layers are further overlain by an upper till. The upper till contains Cheviot erratics and is lithologically similar to much of the upper till in Northumberland, and was probably deposited from the southwards flowing ice stream (Smith, 1981).

The laminated clays in the Sunderland and Newcastle area were probably accumulated in a single large lake. This lake, termed Lake Wear, was created when the eastward flowing meltwater from the retreating western ice was cut-off by advancing northern ice. The resulting Tyne and Wear Complex deposits are generally interbedded laminated silty clays and clayey silts, fine grained sands, lenses of stony clays and some gravel (Smith, 1981). These deposits occupy most of the buried valleys and generally overlie the lower till but in places directly overlie bedrock. The laminated clays are commonly dark brown with fine sandy and silty partings. Gravel, cobbles and boulders are few but when present tend to be concentrated at certain levels. The sands occurring in association with the laminated clays are generally pale brown and fine to medium grained. An upper layer, which contains Cheviot erratics, lies on top of the glaciofluvial layer. It is suggested that this upper layer is similar to the upper till in Northumberland (Catt, 1991a).

4.3.3 Glacial geology of Cumbria

It is generally agreed upon that most of the glacial material in the Cumbrian Coalfield was deposited in the Late Devensian. It is likely that most of the material from early glaciations has been incorporated into the Late Devensian deposits (Huddart, 1971; Dickins, 1995; Hughes et al, 1998). It is suggested that during the Late Devensian glaciation the first ice flowed westwards from the Lake District which crossed the Carlisle and West Cumberland plains (Eastwood et al, 1931). This ice was then opposed by ice flowing southwards from Scotland, which filled the area of the Irish Sea. The two ice-bodies united and there was intermingling of their burdens of rock debris due to their different strength relative to each other. The southward flowing ice from Scotland eventually became dominant and covered the Lake District (Boulton et al, 1977).

A tripartite succession consisting of a lower and an upper clay separated by a middle sand layer is reported for the glacial deposits in Northwest England (Eastwood et al, 1968; Huddart, 1977). This model which also showed the succession of glacial deposits in Cumbria involved deposition of the lower clay by glacier ice from Lake District followed by the deposition of the middle sand and the upper clay. The red tills to the north and west of the area were deposited from the southwards flowing ice. These derived from Permo-Triassic bedrock located farther north and also contained clasts of granite and metamorphic rocks from the Scottish Highlands. In eastern parts of the area the grey till appears to be dominant which derived from the local Coal Measures, and Carboniferous bedrock from Lake District. The clasts consist mainly of Sandstone, mudstone, limestone and coal. The latest glacial phase that has been recognised in the Cumbria lowlands is the readvance of southern Scottish ice onto the Cumbrian lowland after the main glaciation. The main effect of the Scottish readvance was thought to be the deposition of an upper till and research had been carried out in order to recognise the extent of the readvance (Huddart 1991).

4.4 Summary and Discussion

In this chapter the methods used for site investigation were reviewed and different standards were compared to each other. A list was produced for a comparison of the standards used in site investigations on sites in Northern England. The glacial geology of Northumberland, Tyne and Wear, County Durham and Cumbria were also reviewed followed by the description of the sites in these areas whose data are included in NETDATA.

According to the literature a tripartite division of glacial deposits was identified in many lowland areas of England that has been covered by Late Devensian ice sheet, but it was suggested that the mode of deposition may not have been the same in each area.

- It is argued that in Northumberland the lower grey till was produced from a western source that was later overridden by a northern ice flow from which the upper till was deposited (Carruthers, 1953, Smith, 1981 and 1994). It was also suggested that the tripartite succession was the product of the Late Devensian glacier only and it was proposed that grey lodgement till was formed beneath the ice sheet and the red / brown coloured upper till was the result of post-depositional weathering (Eyles and Sladen, 1981).
- A similar tripartite succession is also identified in Tyne and Wear, South West Northumberland and County Durham where the lower grey till occurs throughout the region. This layer is separated from the upper layer by granular layers, which can vary

Chapter 5

Geotechnical properties of glacial tills in Northern England

5.1 Introduction

The previous chapter reviewed the geology of the sites where ground investigations were carried out. The soil description of the different horizons found in the sites was also explained. Different theories are brought forward to explain the differences between the units. Some research puts the difference of the colour and the presence of finer particles in the upper till units to the process of physical and chemical disintegration of large clasts within the deposits (Eyles and Sladen, 1981). Other research explains that the differences between the upper till and the lower till are due to their different sources and depositional sequences (Carruthers, 1953; Catt, 1991 a and b; Smith, 1994). The latter research does not support the interpretation of the glacial deposits based on their colour but on their geotechnical properties. This approach was also taken in this study where the upper and lower tills were distinguished based on the properties of the soil, in addition to their physical descriptions.

Tables were produced containing a summary of test results that have been stored in NETDATA. Various parameters derived from laboratory tests included in these tables are Atterberg limits, grading, shear strength and compressibility parameters. These parameters will be reviewed and discussed in this chapter. These values were used to characterise and classify the different till units and glaciofluvial clays.

5.2 Summary of test results

Similar to chapter 4 the data were put into three major groups for analysis. As it was mentioned in the previous chapter, for the analysis of the soil properties the direction of ice movement needed to be considered in addition to the geographical location of the sites. This is particularly important as the ice moves over bedrock and is the main source of material. By taking the above mentioned factors into consideration the sites were divided into the following three groups:

- *Northumberland*: Chester House, Acklington, Acklington Spoil Heap, Coldrife Lake, Chevington Burn Diversion, East Chevington, Colliersdean (West Chevington), Maiden's Hall, Widdrington, Steadsburn, Stobswood, West Linton, Linton Lane, Butterwell Disposal Point, Hathery Lane.
- *Tyne and Wear, South of Tyne and County Durham*: which include data from Herrington, Hunters Moor, Plenmeller, Melkridge, Hill Top, Red Barns, Whitwell.

- *Cumbria*: Oughterside, Maryport, Linefoot, Broughton Lodge, Foxhouse South, Potatopot, Workington, Lost Rigg, Moresby and Keekle, Keekle extension, River Keekle Diversion.

A combined summary of the soil classification and engineering parameters for each glacial unit of all sites stored in the database is produced and presented in this chapter. The parameters for the individual sites are summarised in Appendix E. The tables contain results derived from standard statistical analysis (Caulcutt, 1991) such as the total number of samples for each glacial unit from one area, the minimum and maximum values, and the total average for each parameter which was calculated. The average values in these tables are based on the mean value of all available samples taken from a particular glacial unit in an area. The tables also contain the standard deviation calculated for the various parameters.

It should be noted that in order to identify the glacial units of individual samples several factors were considered. For this purpose the depth and position of the samples within the boreholes along with the properties of the samples such as the natural moisture content, bulk density, plastic limit and liquid limit were considered. The description of the samples was also considered however these were used with care since some samples have similar physical properties (such as their colour) but show significant difference in their index properties.

It should be noted that although some of the samples show extreme values and their properties are much higher or lower than expected for a certain glacial unit, in general samples from sites in one area generally fall within the same range and follow similar trends. The three areas, Northumberland, Durham, and Cumbria however are different compared to each other. This could confirm that the tills from one area could be deposited under one ice sheet, but the deposition was different for the three areas.

The summary tables presented in this chapter and the plots produced, show all samples within each of the above mentioned areas (eg. all sites within Northumberland). The following tables show the results of Unit 1, 2 and 3. Summary of test results related to Unit 4 are presented in later sections.

Table 5.1:Summary of test results for samples of Unit 1.

	Northumberland					Tyne and Wear and County Durham					Cumbria				
Unit1	Count	min	max	average	S.D.	Count	min	max	average	S.D.	Count	min	max	average	S.D.
Depth (m)		0.1	7.0				0.1	5.7				0.0	4.2		
ρ (Mg/m^3)	627	1.47	2.50	1.99	0.10	178	1.46	2.25	1.98	0.14	87	1.35	2.18	1.98	0.13
ρ_D (Mg/m^3)	490	1.09	2.01	1.63	0.12	178	1.11	1.98	1.63	0.18	84	0.96	1.95	1.64	0.18
e	627	0.27	1.47	0.63	0.14	178	0.35	1.40	0.66	0.21	87	0.37	1.79	0.65	0.20
NMC (%)	696	7.2	54.0	21.8	4.9	202	10.0	50.0	22.3	7.4	95	11.0	47.0	21.5	7.9
PL (%)	665	12.0	36.0	20.6	3.3	179	12.0	56.0	21.0	5.0	73	13.0	34.0	20.6	4.6
LL (%)	665	22.0	89.0	46.8	8.0	179	21.0	97.0	38.0	9.4	74	22.0	66.0	39.9	8.5
PI (%)	662	7.0	69.0	26.3	6.5	180	1.0	48.0	17.1	5.9	73	9.0	38.0	19.8	5.5
LI	643	-1.000	0.964	0.038	0.189	179	-1.333	4.000	0.108	0.552	73	-1.000	1.000	0.010	0.318
<425 fraction	587	44.0	100.0	92.7	8.2	183	22.0	100.0	84.3	11.5	72	34.0	100.0	83.5	12.5
Activity	582	0.08	0.73	0.28	0.07	167	0.01	0.73	0.21	0.09	68	0.10	0.60	0.24	0.09
CLAY (%)	26	8.0	47.0	30.2	10.8	29	3.0	30.0	18.0	6.8	6	6.0	19.0	12.4	4.1
SILT (%)	26	24.0	55.0	38.7	7.5	29	14.0	44.0	30.2	7.1	6	17.0	41.0	28.2	8.9
SAND (%)	26	8.0	55.0	24.8	10.7	29	18.0	56.0	35.5	9.0	6	16.0	48.0	31.0	10.8
GRVL (%)	26	1.0	22.0	5.8	4.6	29	0.0	43.0	15.6	9.5	6	16.0	48.0	28.4	12.0
CBLS (%)	26	0.0	2.0	0.1	0.4	29	0.0	0.0	0.0	0.0	6	0.0	0.0	0.0	0.0
c_u (kN/m^2)	547	7.0	368.0	104.4	54.9	104	7.0	197.0	68.8	47.1	47	8.0	202.0	72.6	45.2
c' (kN/m^2)	27	0.0	21.0	6.2	5.3	9	0.0	21.0	11.9	7.1	4	1.0	5.0	2.8	1.5
ϕ' (degrees)	27	3.0	34.0	23.3	9.2	9	3.5	33.7	27.0	8.7	4	24.0	35.0	29.5	4.6
c'_p (kN/m^2)	3	20.0	59.0	33.3	18.2						5	16.0	42.0	28.4	9.7
ϕ'_p (degrees)	3	20.0	31.0	25.7	4.5						5	17.0	35.0	27.4	6.3
c'_r (kN/m^2)	2	20.0	20.0	20.0	0.0						5	4.0	18.0	10.8	5.0
ϕ'_r (degrees)	2	13.0	13.0	13.0	0.0						5	8.0	27.0	21.4	6.8

Table 5.2: Summary of test results for samples of Unit 2.

	Northumberland					Tyne and Wear and County Durham					Cumbria				
Unit2	Count	min	max	average	S.D.	Count	min	max	average	S.D.	Count	min	max	average	S.D.
Depth (m)		0.4	35.5				0.3	42.8				0.4	17.5		
ρ (Mg/m^3)	1826	1.44	2.56	2.06	0.09	202	1.60	2.34	2.06	0.13	95	1.77	2.34	2.05	0.12
ρ_D (Mg/m^3)	1195	1.02	2.07	1.73	0.12	202	1.23	2.02	1.73	0.15	90	1.32	2.04	1.72	0.15
e	1826	0.25	1.26	0.54	0.10	202	0.33	1.05	0.55	0.13	95	0.31	1.04	0.57	0.15
NMC (%)	1953	7.6	42.0	18.6	3.7	227	11.0	33.0	19.1	4.7	113	10.0	38.0	19.7	6.4
PL (%)	1786	12.0	49.0	17.9	3.0	211	12.0	31.0	19.5	3.4	102	11.0	27.0	18.3	2.9
LL (%)	1785	22.0	71.0	39.4	6.3	211	23.0	62.0	37.3	6.7	102	21.0	54.0	35.8	5.1
PI (%)	1784	4.0	44.0	21.5	5.0	207	4.0	50.0	17.9	5.9	102	7.0	27.0	17.4	3.7
LI	1762	-4.750	1.083	0.019	0.211	207	-1.500	1.714	-0.012	0.334	101	-0.615	0.714	0.016	0.280
<425 fraction	1747	41.0	100.0	89.7	8.9	213	47.0	100.0	82.3	11.2	94	35.0	100.0	80.2	14.4
Activity	1743	0.04	0.59	0.24	0.06	202	0.06	0.78	0.22	0.08	94	0.07	0.51	0.23	0.07
CLAY (%)	27	12.0	66.0	27.0	11.8	18	5.0	32.0	20.1	7.9	6	13.0	26.0	20.0	5.0
SILT (%)	27	19.0	54.0	34.3	8.6	18	21.0	48.0	32.9	7.8	6	13.0	38.0	29.2	8.3
SAND (%)	27	7.0	57.0	32.1	13.6	18	14.0	61.0	34.8	10.6	6	14.0	30.0	24.8	5.4
GRVL (%)	27	0.0	27.0	5.6	6.6	18	0.0	44.0	10.9	11.1	6	10.0	34.0	21.8	7.7
CBLS (%)	27	0.0	4.0	0.2	0.8	18	0.0	0.0	0.0	0.0	5	0.0	25.0	5.0	10.0
c_u (kN/m^2)	1690	5.0	537.0	106.5	60.7	113	7.0	253.0	80.0	56.4	63	6.0	196.0	65.5	46.9
c' (kN/m^2)	48	0.0	43.0	6.8	8.6	13	0.0	64.0	13.7	19.7	5	4.0	16.0	9.0	4.6
ϕ' (degrees)	48	3.0	41.0	25.3	7.1	13	13.0	34.0	23.1	5.3	5	3.0	34.0	23.6	10.7
c'_p (kN/m^2)	13	0.0	88.0	34.8	26.0										
ϕ'_p (degrees)	13	13.0	34.0	22.2	6.0										
c'_r (kN/m^2)	15	0.0	49.0	11.3	14.5										
ϕ'_r (degrees)	15	8.0	28.0	16.4	6.1										

Table 5.3: Summary of test results for samples of Unit 3.

	Northumberland					Tyne and Wear and County Durham					Cumbria				
Unit3	Count	min	max	average	S.D.	Count	min	max	average	S.D.	Count	min	max	average	S.D.
Depth (m)		1.0	41.9				0.1	55.5				0.3	42.0		
ρ (Mg/m^3)	1231	1.61	2.76	2.17	0.08	539	1.79	2.54	2.22	0.09	528	1.84	2.48	2.21	0.09
ρ_D (Mg/m^3)	808	1.40	2.40	1.93	0.09	539	1.42	2.33	1.96	0.09	508	1.05	2.28	1.96	0.11
e	1231	0.10	0.84	0.39	0.06	539	0.15	0.66	0.36	0.06	528	0.17	0.71	0.36	0.07
NMC (%)	1403	4.5	27.6	12.6	1.9	617	5.0	23.0	12.9	2.3	637	7.0	20.0	12.1	2.1
PL (%)	1340	3.0	27.0	15.0	2.0	564	4.0	26.0	16.2	2.6	513	11.0	23.0	15.6	1.8
LL (%)	1341	18.0	49.0	31.3	3.5	564	20.0	44.0	31.5	3.2	514	18.0	49.0	30.8	4.4
PI (%)	1339	2.0	31.0	16.4	3.2	564	6.0	25.0	15.3	3.1	510	3.0	29.0	15.3	3.7
LI	1298	-5.500	0.667	-0.163	0.292	563	-2.167	0.625	-0.230	0.236	508	-3.333	2.000	-0.237	0.263
<425 fraction	1238	43.0	100.0	83.1	9.4	566	28.0	100.0	75.0	10.7	473	32.0	100.0	74.0	12.4
Activity	1236	0.02	0.43	0.20	0.04	543	0.07	0.54	0.21	0.05	417	0.04	0.46	0.21	0.06
CLAY (%)	22	8.0	29.0	20.9	4.8	26	5.0	25.0	15.5	6.2	31	7.0	31.0	16.5	7.5
SILT (%)	22	18.0	45.0	30.1	5.9	26	15.0	46.0	29.0	6.4	31	11.0	50.0	26.4	9.5
SAND (%)	22	16.0	36.0	30.0	5.4	26	14.0	50.0	32.8	8.1	31	21.0	54.0	35.7	8.3
GRVL (%)	22	8.0	43.0	18.1	8.6	26	8.0	50.0	21.7	11.0	31	0.0	50.0	26.4	9.5
CBLS (%)	22	0.0	20.0	1.5	4.6	26	0.0	9.0	0.3	1.7	31	0.0	21.0	1.6	4.8
c_u (kN/m^2)	1175	14.0	818.0	185.7	103.1	337	12.0	519.0	141.0	87.8	211	13.0	625.0	191.1	104.5
c' (kN/m^2)	39	0.0	30.0	8.6	6.8	41	0.0	55.0	14.0	12.3	50	0.0	25.0	7.1	7.7
ϕ' (degrees)	39	21.0	39.0	27.7	2.9	41	3.2	37.0	26.2	6.5	50	3.0	39.0	26.2	7.6
c'_p (kN/m^2)	3	15.0	140.0	56.7	58.9	1	137.8	137.8	137.8	0.0	1	17.0	17.0	17.0	0.0
ϕ'_p (degrees)	3	6.0	33.0	22.3	11.7	1	24.8	24.8	24.8	0.0	1	34.0	34.0	34.0	0.0
c'_r (kN/m^2)	3	0.0	140.0	46.7	66.0	1	65.0	65.0	65.0	0.0	1	10.0	10.0	10.0	0.0
ϕ'_r (degrees)	3	4.0	32.0	21.0	12.2	1	24.7	24.7	24.7	0.0	1	33.0	33.0	33.0	0.0

5.2.1 Atterberg Limits

The index properties of a soil form an essential background of any site investigation. Atterberg limit tests determine the Plastic Limits (PL) and the Liquid Limit (LL) of a soil. The Plastic Limit is the moisture content at which the soil passes from the plastic state to the solid state, and becomes too dry to be in a plastic condition, as determined by the Plastic Limit test. The Liquid Limit is the moisture content at which soil passes from the plastic to the liquid state, as determined by the Liquid Limit test. These limits and their difference, the Plasticity Index (PI), provide a measure of the range of the moisture contents over which a clay soil has a plastic consistency. These tests offer a useful mean of classifying fine-grained cohesive soils and frequently form the basis for assessing and correlating their main engineering properties. They are related to the combined effects of particle size and mineral composition and can provide additional information on the type and likely behaviour of the soil.

In this project the Atterberg limits along with some other soil properties, such as the natural moisture content and density, have been used to identify similar glacial materials that occur at different sites. The nature of the grain size distribution for a till gives the till distinct geotechnical properties which depend on the amount of clay size materials compared with the coarser silt, sand, gravel fraction. Glacial tills are poorly sorted compared to other sedimentary clays and contain a substantial proportion of granular material bigger than 425 μm. They therefore have a lower plasticity index and liquid limit. The type of rock forming the glacial bed determines the mineralogical content of the mode of the till and influences the particle size. That means the deposition and nature of the host terrain over which an ice sheet has traversed are important factors governing the plasticity of a till.

A plasticity chart shows a plot of Liquid Limit against Plasticity Index, together with the Casagrande A-line. The chart helps in classifying the material as well as characterising its properties. On a standard plasticity chart, the Casagrande A-line separates the behaviour of clays and silts. A straight line, called the T-line, has been produced above and parallel to the A-line and defines the position of glacial lodgement tills which lie within a narrow band around the T-line (Boulton, 1976). This line reflects the nature of the grain size distribution and although it is not unique to glacial tills but allows them to be distinguished from sedimentary clays due to their differences in grading. The A-line is expressed by Equation 5.1 and the T-line is expressed by Equation 5.2:

Equation 5.1 $$PI=0.73\,(LL-20)$$

Equation 5.2 $$PI=0.73\,(LL-11)$$

It has been stated that the type and amount of clay in till has a great influence on the position of till along the T-line (Boulton and Paul, 1976). If the clay concentration is high the till will lie on the upper part of the T-line and if the concentration is small the till lies on the lower part of the T-line. The data plotted on the plasticity charts shown in Figure 5.1 lie about the T-line. It can be seen that the data of Unit 1 and 2 tend to lie lower compared to data from Unit 3. It can also be seen that data from unit 3 tend to have a lower plasticity compared to tills from Unit 1 and 2.

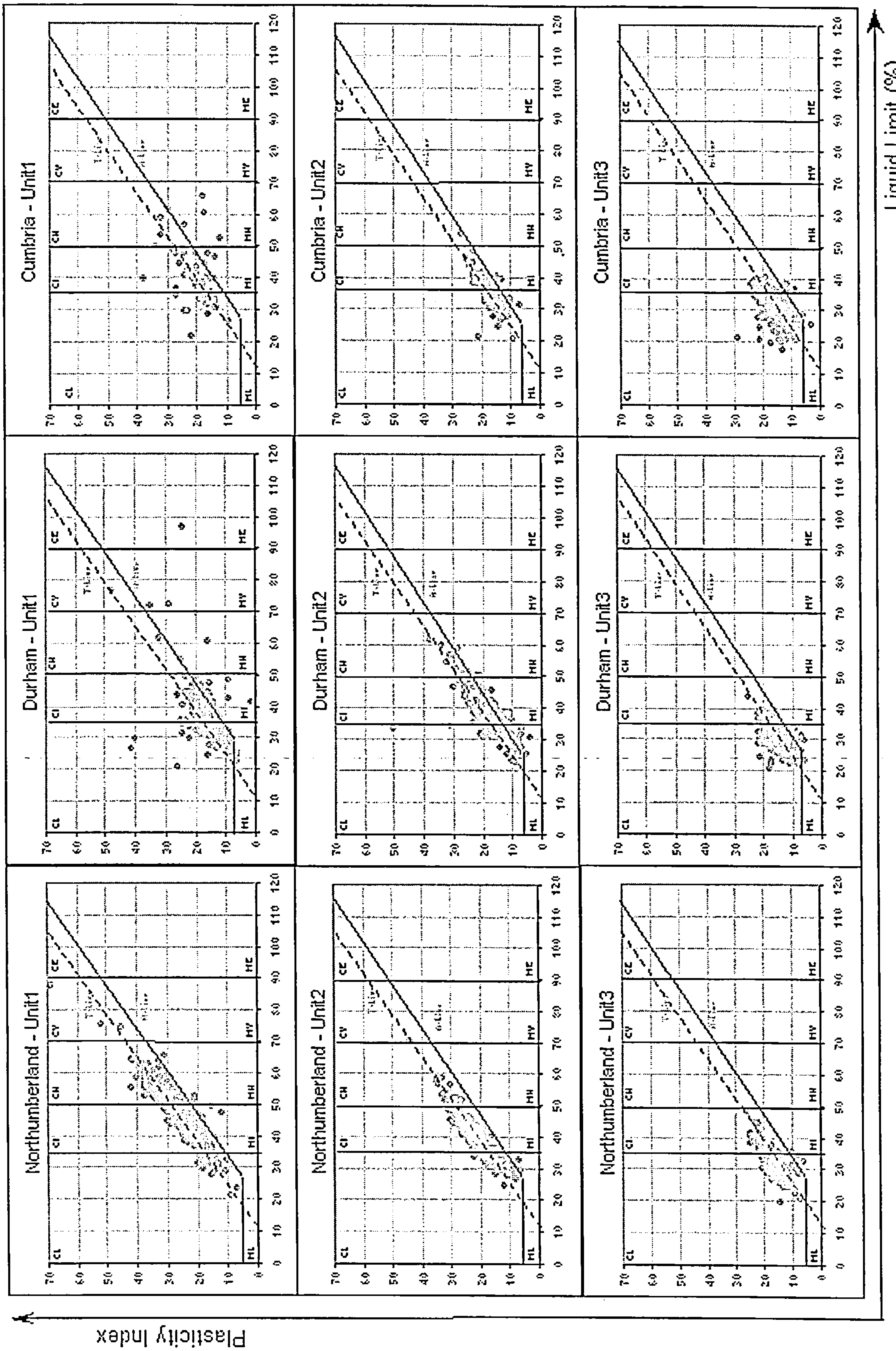


Figure 5.1: Plasticity chart for glacial Tills in Northern England

By comparing the plasticity plots for each unit in the three main areas as shown in Figure 5.1 it can be seen that all samples lie around the T-line. However samples in Northumberland and Durham lie slightly lower on this line compared to samples from Cumbria. Samples from Northumberland are further extended along the T-line compared to samples in Durham and Cumbria. This can especially be recognised in Unit 1. The reason for this could be the different mineralogy of the soils in these areas due to different sources of material and the amount of weathering in these soils. As it can be seen from Figure 5.1 samples from Unit 3 which are generally stiffer and more dense compared to the other units tend to lie lower along the T-line and Unit 1 and 2 lie further up along this line. This is an indication that the finer particles of the tills behave more like clay even though much of the fine particles are rock flour and contain very few clay particles. This then raises the question of whether the engineering behaviour of glacial tills can be predicted from Atterberg Limits when those classic predictions are based on results of true sedimentary clays. The frequency distribution curves shown in Figures 5.2 to 5.4 demonstrate in more details the distribution of values found for the different Units.

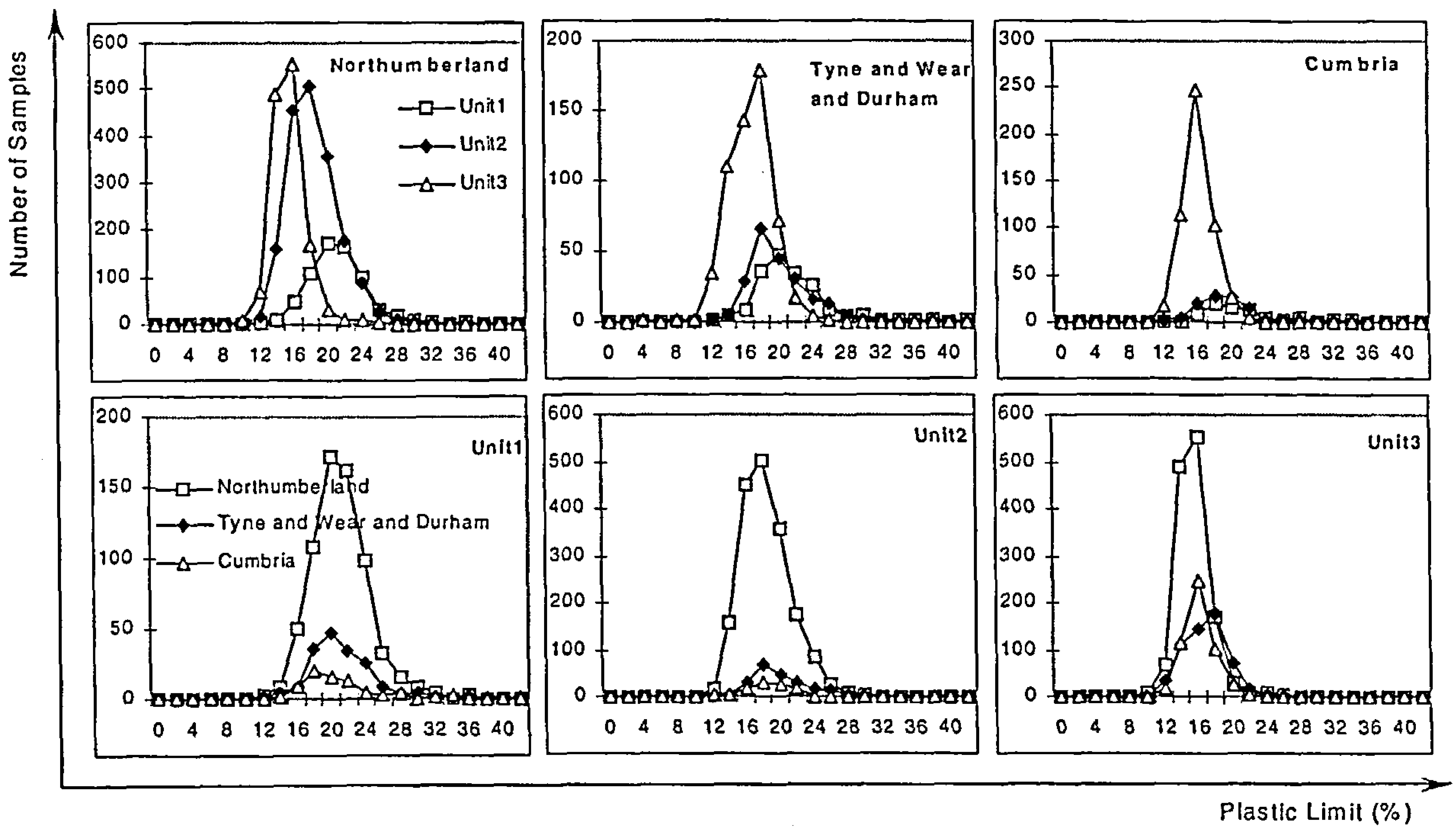


Figure 5.2: Frequency Distribution of Plastic Limit.

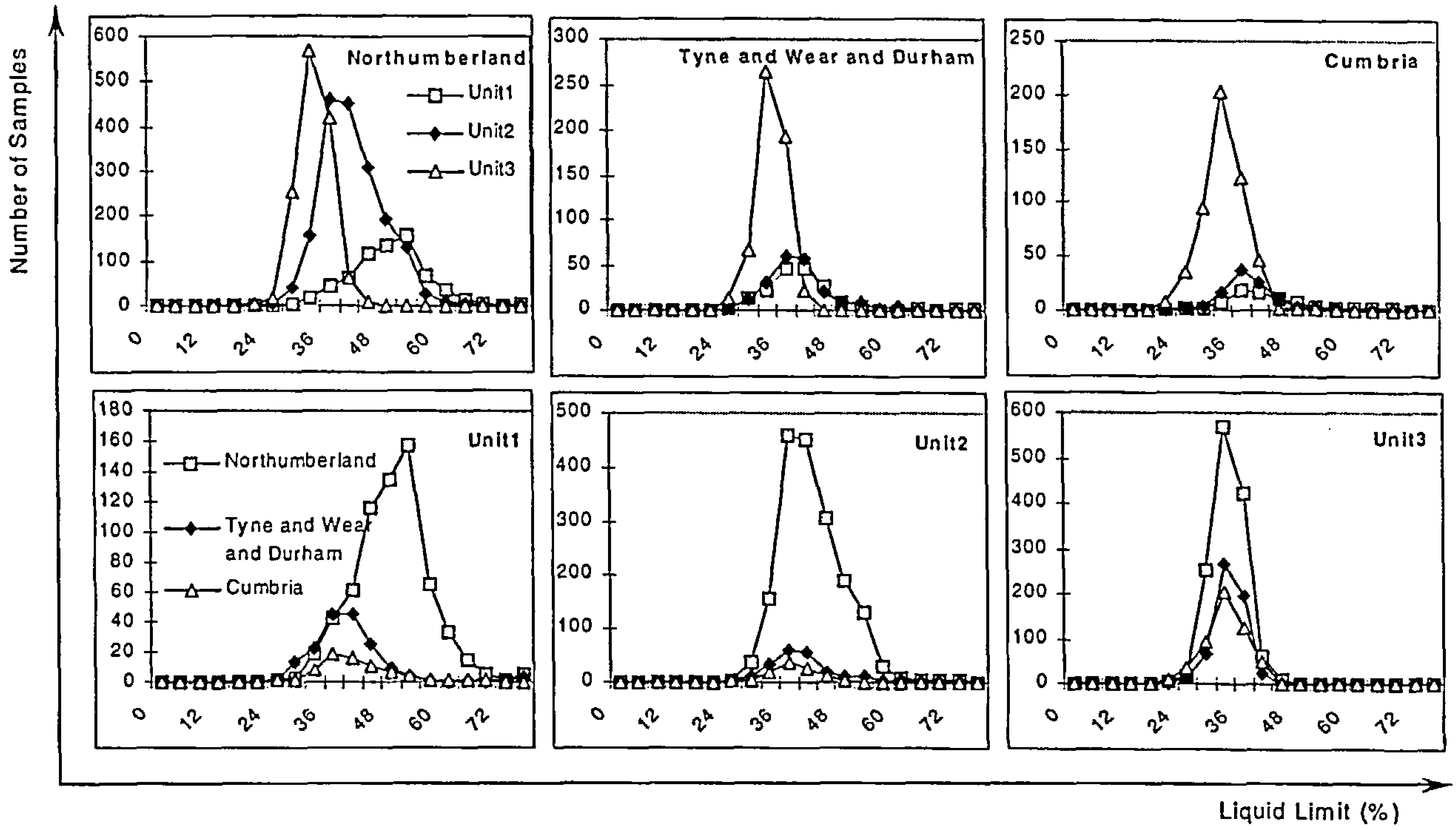


Figure 5.3: Frequency Distribution of Liquid Limit

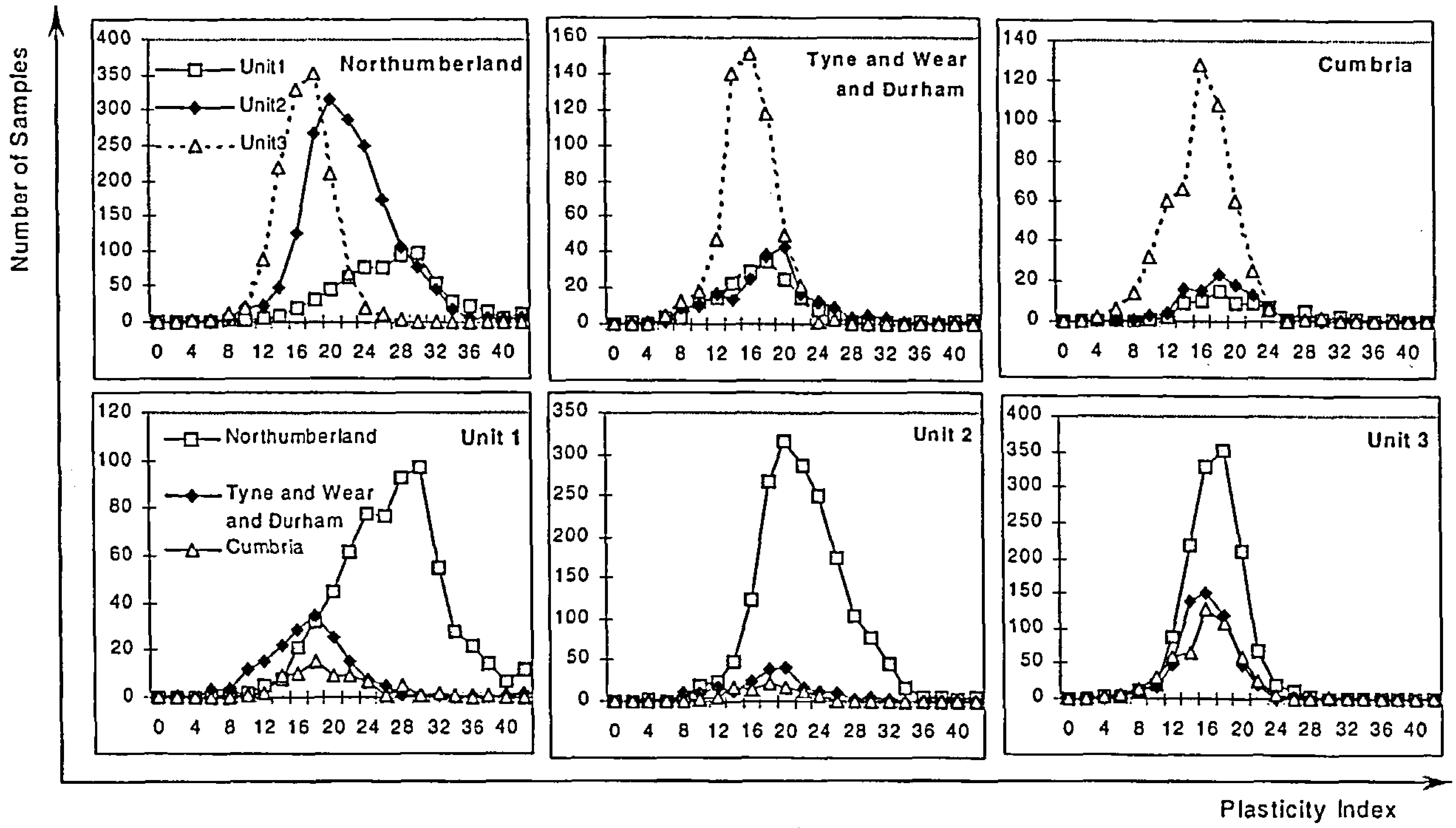


Figure 5.4: Frequency Distribution of Plasticity Index.

5.2.2 Natural Moisture Content

In this study the moisture content was one of the key parameters for distinguishing the glacial units. Plots of natural moisture content against depth can be found in Figure 5.5. It can be seen that there is a general trend of gradually decreasing moisture content with depth. In all locations the moisture content found in Unit 1 gradually reduces in Unit 2 and reaches its smallest values in Unit 3. The change in moisture content at the boundaries with the different units is usually very obvious, particularly at the interface between Unit 2 and Unit 3. Thus water content can be used as a simple means of identifying different till Units.

As the plots in Figure 5.5 shows, the water content generally reduces with depth. The test results, as presented in tables 5.1 to 5.3, show that the moisture contents of samples from Unit 3 are usually at or below the plastic limit whereas in Unit 1 and Unit 2 they are mostly above.

The plastic limit and the liquid limit provide an indication of the type of clay present in a cohesive soil, but the condition of the clay and hence those engineering properties which control the strength and compressibility of the soil depend on the moisture content of the clay in relation to those limits. This relation is usually expressed in terms of the liquidity index which is defined in Equation 5.3:

$$\text{Equation 5.3} \quad LI = (W - PL) / (LL - PL)$$

Values of the liquidity index throughout the moisture content range are summarised in Table 5.4 :

Table 5.4: Ranges of moisture content and liquidity index (Head, 1992)

Moisture content range	Liquidity Index
Below PL	Negative
At PL	0
Between PL and LL	0 to 1
At LL	1
Above LL	>1

Plots of the liquidity index against depth are shown in Figure 5.6.

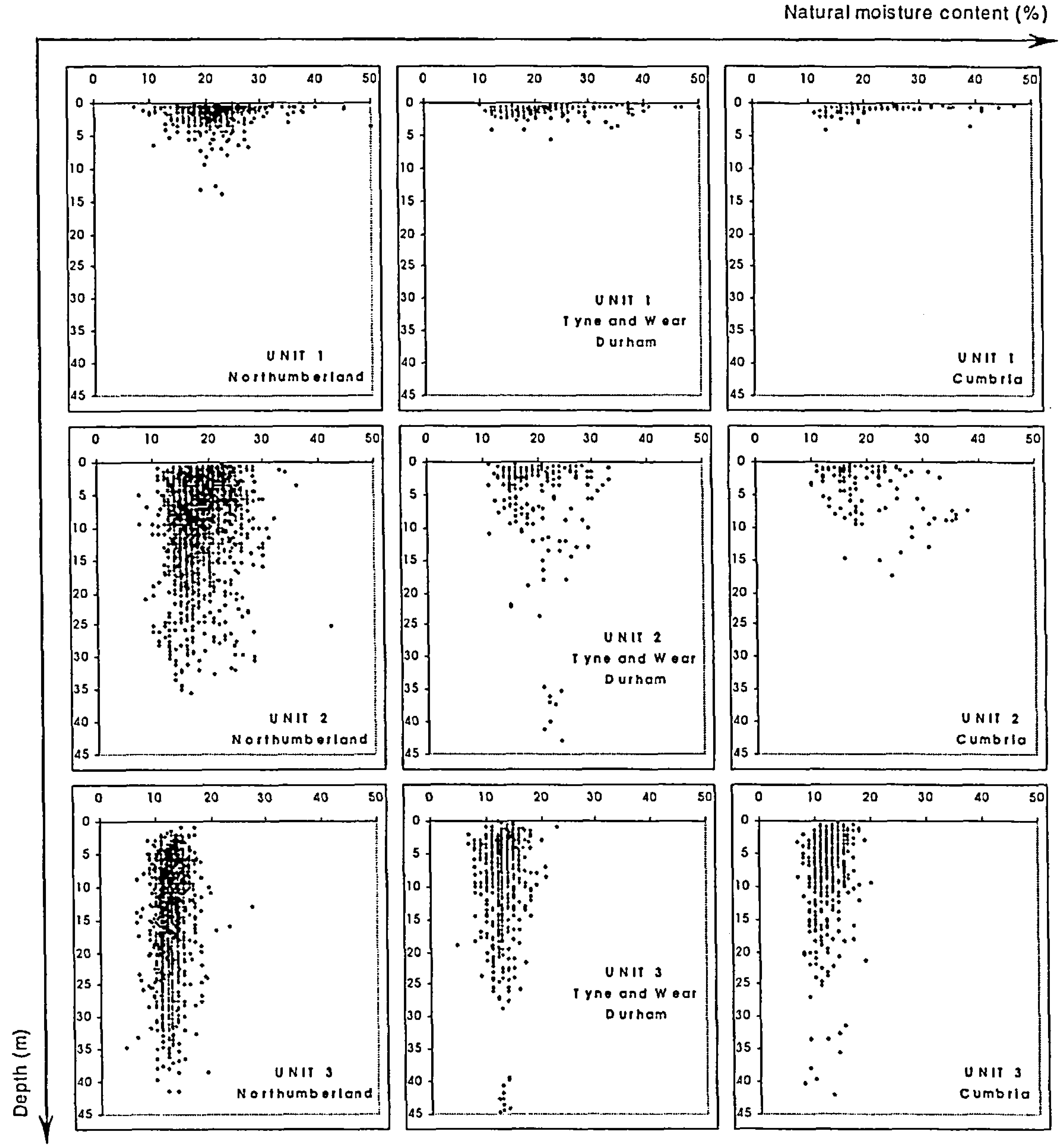


Figure 5.5: Plot of natural moisture content against depth for different till units.

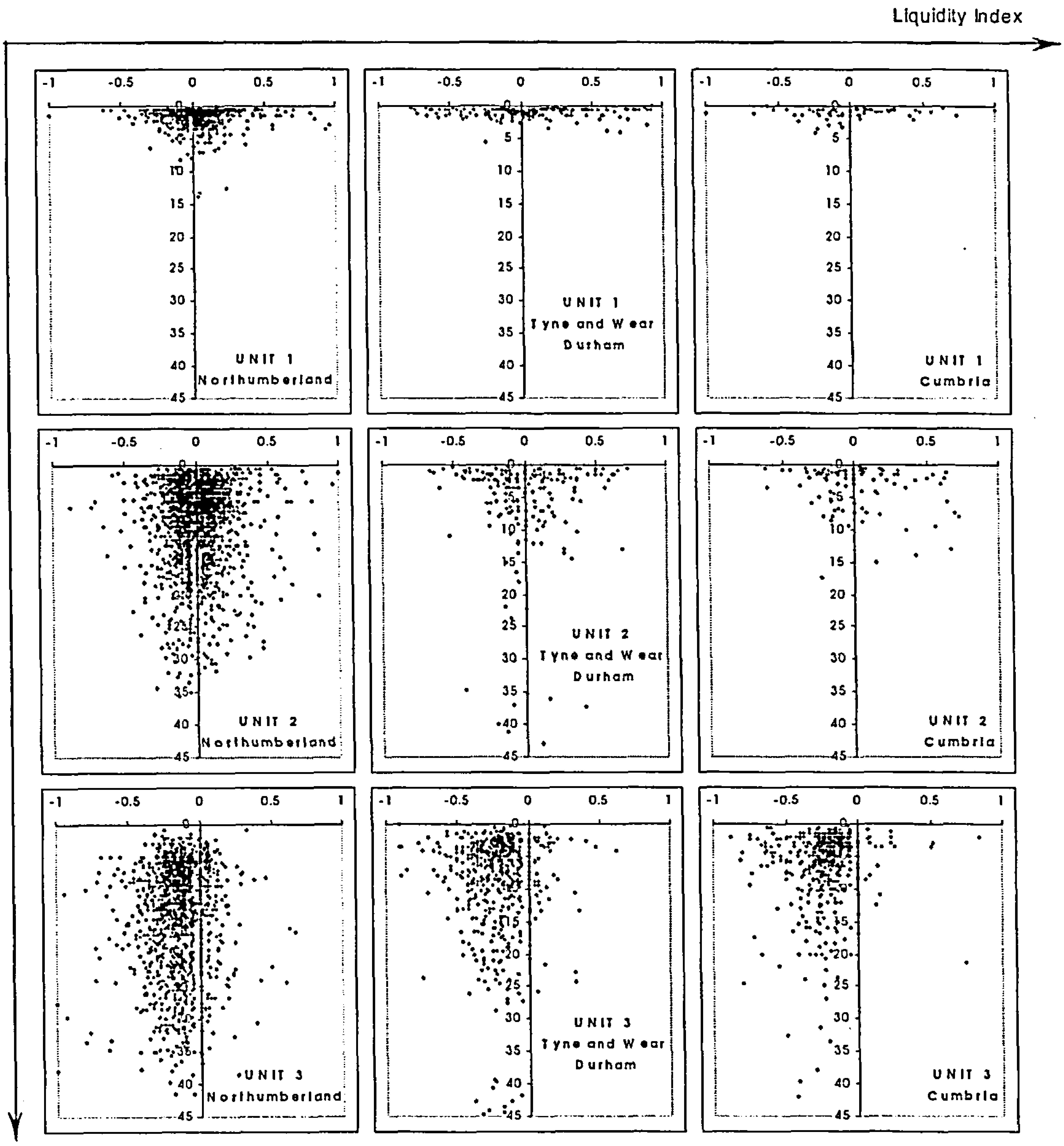


Figure 5.6: Plot of liquidity index against depth for different till units.

As the summary results presented in Table 5.1, 5.2 andTable 5.3 show the values of liquidity index in Unit 3 are generally lower compared to other units and are mostly negative. The average liquidity indices for the upper tills in Unit 1 and 2 are mostly positive with Unit 1 having a slightly higher average value. Although negative liquidity index values can also be found in some samples taken from these units but in general the values are higher compared to the values found in Unit 3. Post-depositional alterations also tend to increase the liquidity index as a result of increasing natural moisture content with the degree of weathering. This can be seen by comparing the results of Unit 1 and 2 where the measured moisture content and liquidity index values for Unit 1 are higher than in Unit 2.

5.2.3 Activity

The plasticity of a soil is caused by the adsorbed water that surrounds the clay particles. Therefore the Atterberg limits are related to the combined effects of particle size and mineral composition of the soil. It was shown that for a clay soil mixed with coarser material the plasticity depends on the clay fraction (Skempton, 1953). The relationship between the plasticity index and the clay fraction can be shown as follows:

Equation 5.4 $$\text{Activity} = \text{PI} / \text{Clay fraction}$$

To be consistent with the Atterberg limits, in this project the fine fraction (<425 μm) used for the calculation of PI / fine fraction. The grading depends largely on the lithology of the rock source. It has also been suggested that the higher percentage of fine particles in the Upper Till compared to the Lower Till could be due to the effect of post-depositional weathering (Eyles and Sladen, 1981). Clays can be classified according to their activity into the groups shown in Table 5.5 (Head, 1992):

Table 5.5: Classification of clays according to their activity

Description	Activity
Inactive clays	< 0.75
Normal clays	0.75 - 1.25
Active clays	1.25 - 2
Highly active clays	> 2

As it can be seen from the summary results presented in tables 5.1 to 5.3 that all the till units from all locations in this study fall into the inactive clay group (considering that the fine fraction was used). Comparing the values for different units it can be seen that Unit 1 has a slightly higher activity value compared to Unit 2, and Unit 3 has the lowest activity. Figure 5.7 shows the frequency distribution curves for the different areas and units.

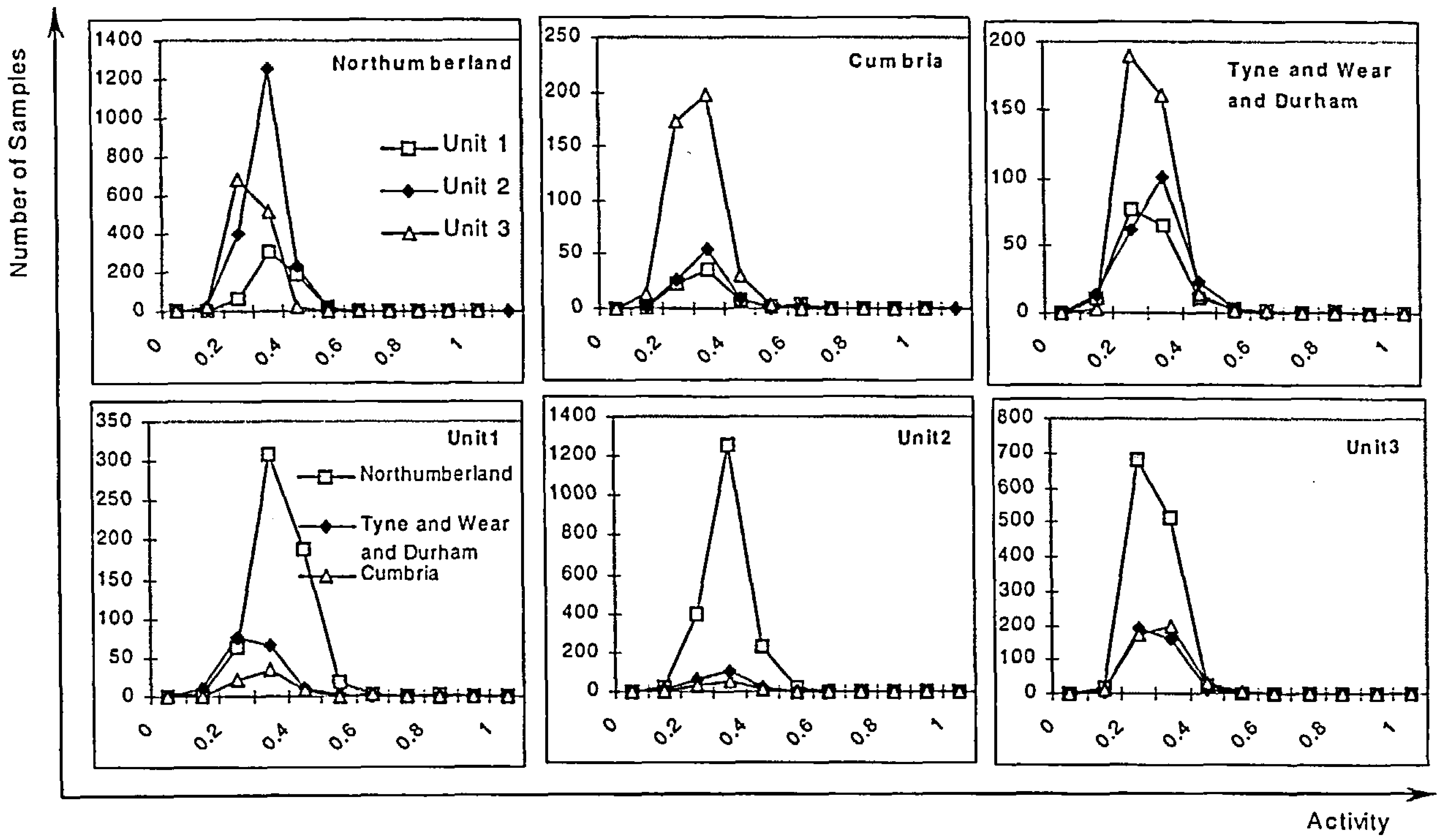


Figure 5.7: Frequency Distribution curves for PI/fine fraction for different till units.

It has been suggested that one factor for the low activity of the tills could be the mineralogical composition of either inactive clay fraction or clay size fraction composed of predominantly rock flour (Thabet, 1973; Aflaki, 1996).

5.2.4 Particle size distribution

Particle size distribution test is used to determine the relative proportions of the different grain sizes which make up a given soil mass. Particle size distribution of tills is one of the most informative features in term of their engineering behaviour. The distribution of particle sizes that make up a particular soil determine many of the soil characteristics, like void space, its degree of interconnection and hence permeability. Poorly graded soils that show a small range of particle sizes contain a higher proportion of voids than well-graded soils in which the finer particles fill the voids between coarse grains. In this way grading influences soil density. The degree of particle interlocking affects shear strength but no direct correlation exists because other factors such as particle shape, confining pressure, consolidation history and type of clay material are of overriding importance. A well sorted sand underlying till is much less compact than the till, because once the sand grains have been pressed into grain to grain contact, further compaction cannot occur without fracturing the grains.

Tills usually have a fairly well graded grain size distribution consistent with their high bulk density. The grading of a till however, depends on various factors such as the lithology of rocks from which the till has been derived, the distance from the bedrock source, incorporation and reworking of older sediments, post-depositional weathering (Trenter, 1999). A classification system was developed in this regard which is given in Table 5.6.

Table 5.6: Gradational series of till textures (after McGown and Derbyshire, 1977)

Dominant soil fraction	Nature of dominant fraction	Approximate percentages of fines	Textural description
Clasts	Granular	0 - 15	Granular (G)
No dominant fraction	-	15 - 45	Well graded (W)
Matrix	Granular	45 - 70	Granular Matrix (Mg)
Matrix	Cohesive	70 - 100	Cohesive Matrix (Mc)

Analysis of particle size distribution of glacial tills in the site investigation reports studied is generally confined to sieve analysis of cohesionless material. However on a limited number of cohesive samples particle size distribution have been carried out with results presented as grading curves or in summary sheets as percentage of the fine and coarse particles. Table 5.1 , 5.2, and 5.3 show the average percentage of finer particles passing through the 425 μm sieve for each glacial unit. It can be concluded that Unit 1 and Unit 2 are very similar in terms of the content of fine and coarse particles. Unit3 generally contains less fines compared to the other units. The similarity in grading between Unit 1 and Unit 2 is also reflected in the plastic properties of these tills as discussed earlier. Figure 5.8 shows the grading of samples from various locations in Northern England. It can be seen that Unit 1 and Unit 2 from sites in Northumberland have either a cohesive or granular matrix, whereas in Cumbria and Durham they fall into the granular matrix or well graded category. Samples from Unit 3 in all three areas have a granular matrix or are well graded. This confirms that the source of material found in Unit 1 and 2 of Northumberland could be different from that of Cumbria and Durham, whereas the sources of the material in Unit 3 could be similar in all areas.

Using the minimum, maximum and average values of Tables 5.1 to 5.3 standard PSD curves have been plotted for the different areas and units, as shown in Figures 5.9 to 5.11.

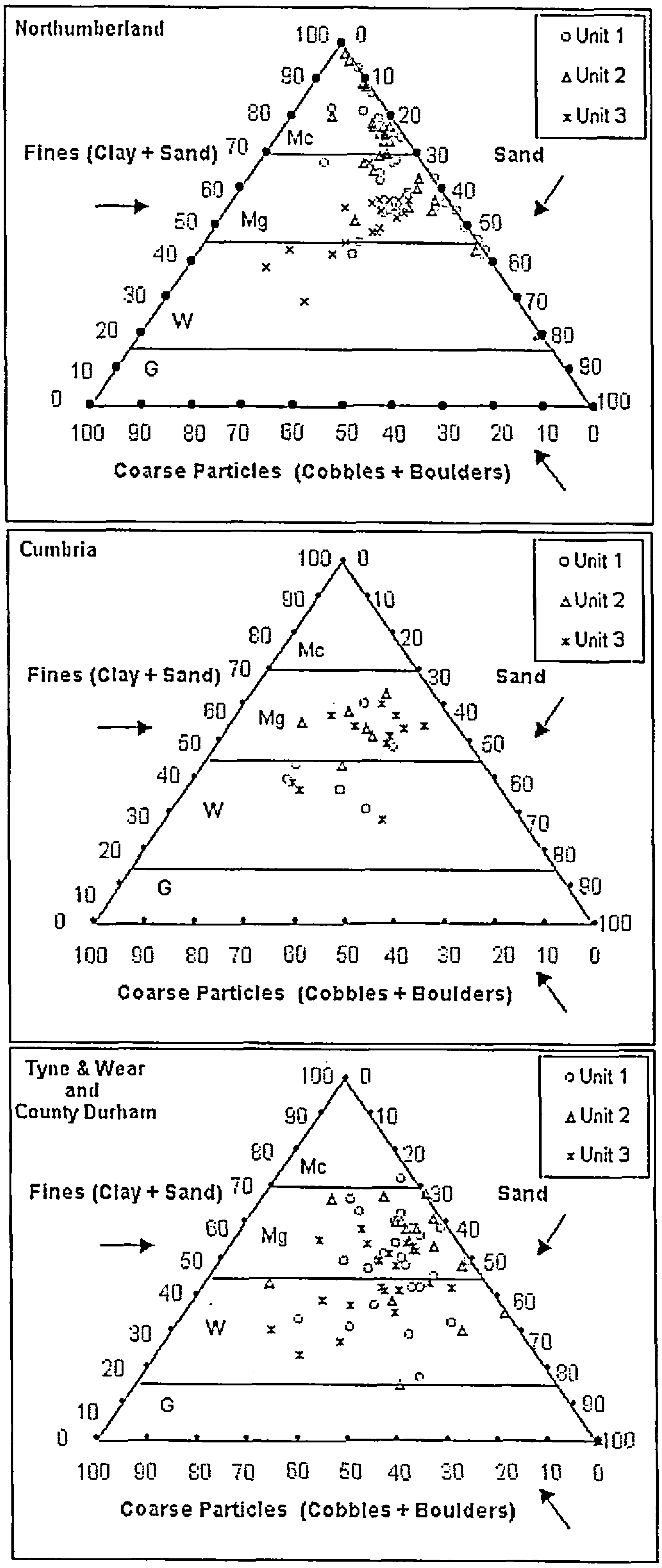


Figure 5.8: PSD test results for glacial tills from Northern England.

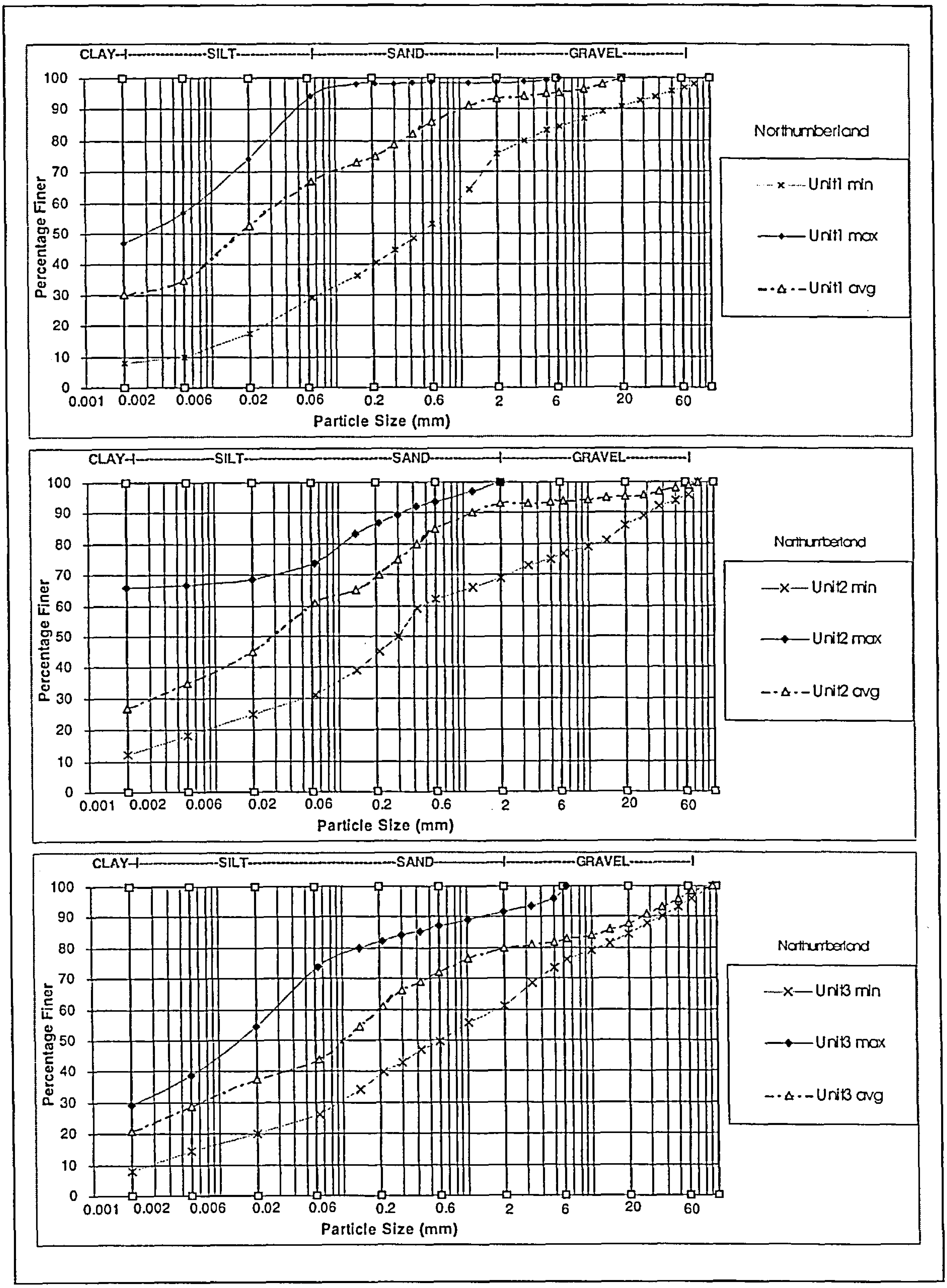


Figure 5.9: Particle Size Distribution chart for Northumberland.

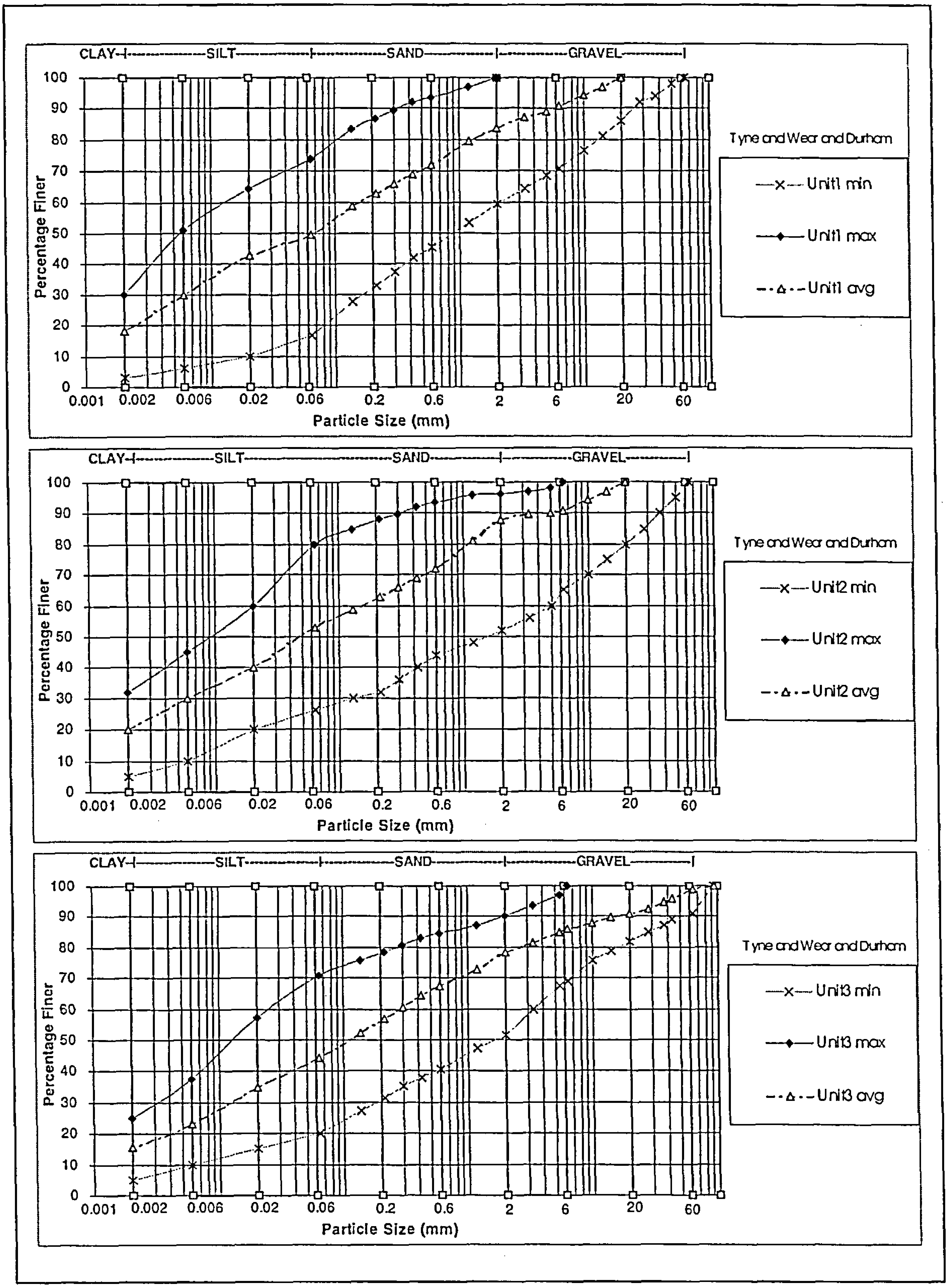


Figure 5.10: Particle Size Distribution chart for Tyne and Wear and Durham.

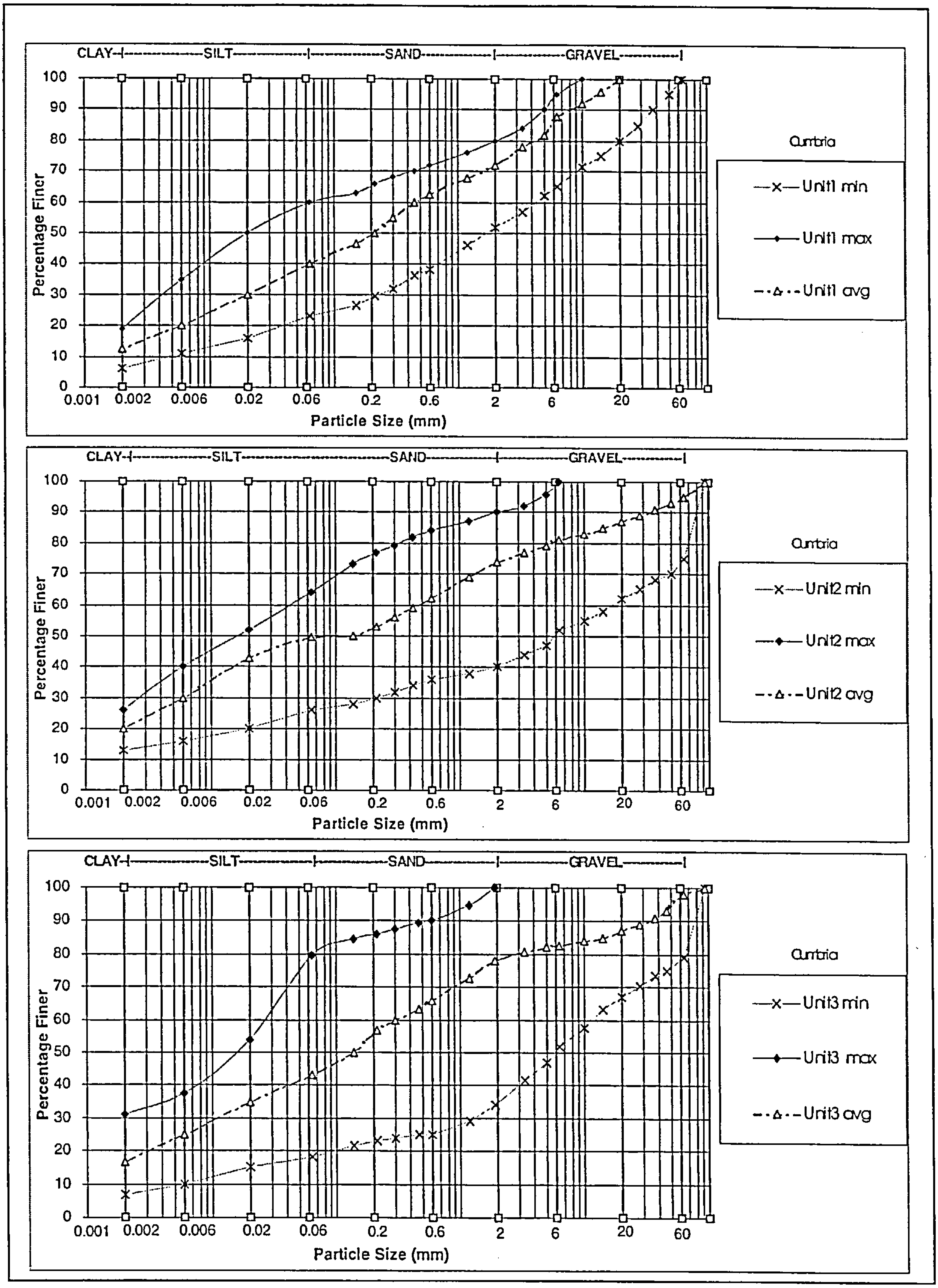


Figure 5.11: Particle Size Distribution chart for Cumbria.

5.2.5 Density

The density is another important property used in the identification of glacial units in this study. The bulk density of a sediment is defined as the weight of that sediment per unit volume (Head, 1992). The bulk density of a sediment in its natural state depends on the specific gravity of the individual grains, the grain size distribution, the texture of the sediment and the degree of saturation. The dry density can be calculated from Equation 5.5:

Equation 5.5 $$\text{Dry density} = \text{Bulk density} / (1 + \text{Moisture content})$$

The density of a soil is of importance where the body weight of the deposit is an important factor such as in slope stability analysis. This is because the weight of the soil provides the main force. For the calculation of forces the bulk density is normally considered since the combined mass of the soil and the water determine the pressure.

The plots of dry density and bulk density against depth (Figure 5.12 and 5.13) show a tendency of increasing with depth. This could be due to the increasing thickness of the overriding ice sheet or in other words with increasing overconsolidation pressure. Tills however are not only gravitationally deposited and were spread through the process of pressure and shear. Hence the density of this material could also be due to the amount of shearing to which the soil was subjected. Although the bulk density and the dry density generally increase with depth but there is often a remarkable change between the glacial units which indicates differences in the character of the tills or the depositional process.

Distinct differences are found in the average bulk densities of the different glacial units. The range of values measured for the densities of the different units can be seen from the summaries shown in tables 5.1 to 5.3. The wide range of values for the units also reflects the variation of fine and coarse material within the tills. Unit 3 is clearly the most dense of the three till units. It is likely that the small values of void ratio in Unit 3 appear because of the sandy and gravely nature of this till and could also be due to the weight of the readvancing ice sheet which deposited the Upper Till. The dry densities of Unit 1 and Unit 2 are similar but differ significantly from the relatively high dry density of Unit 3.

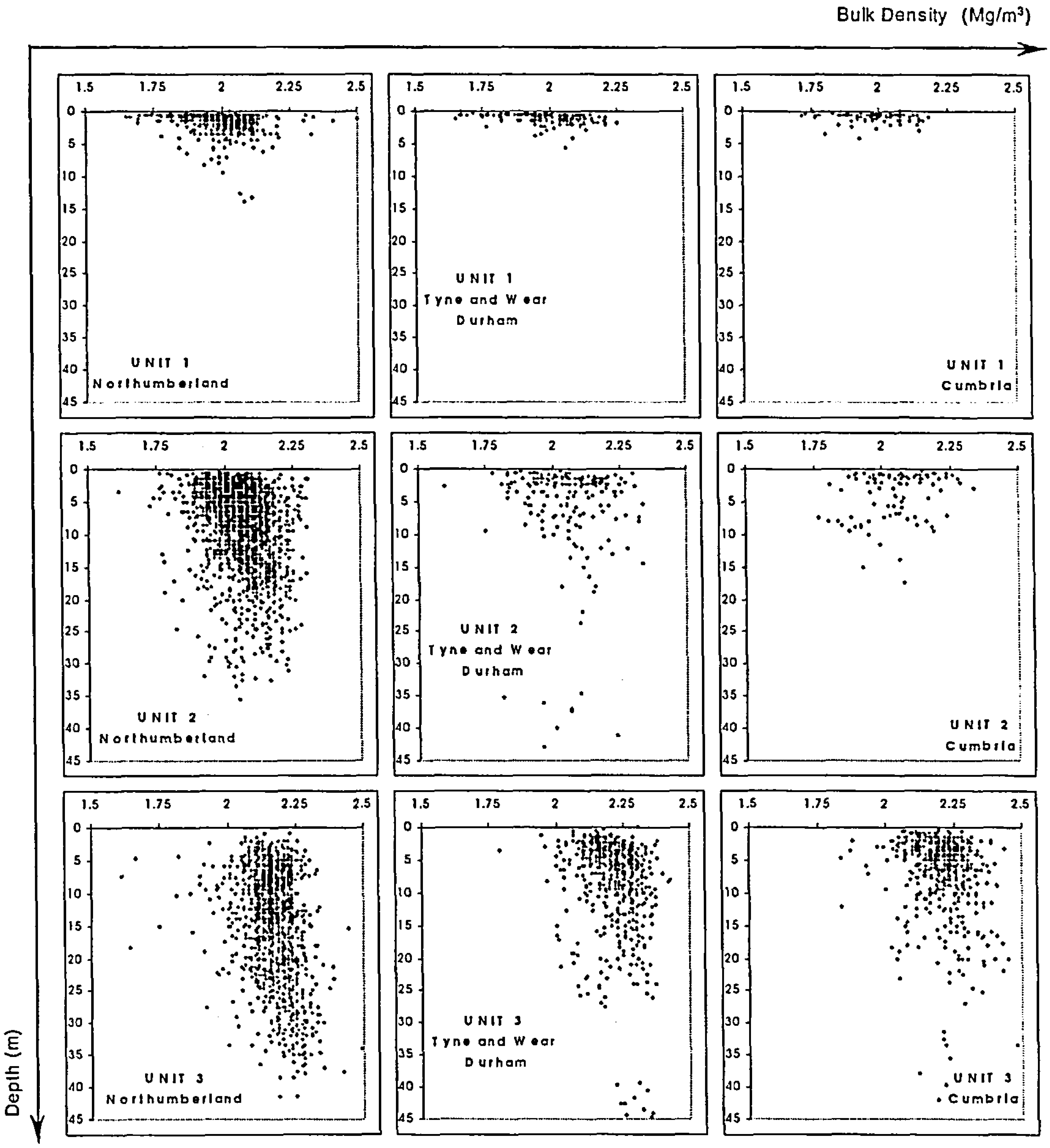


Figure 5.12: Plot of bulk density against depth for different till units.

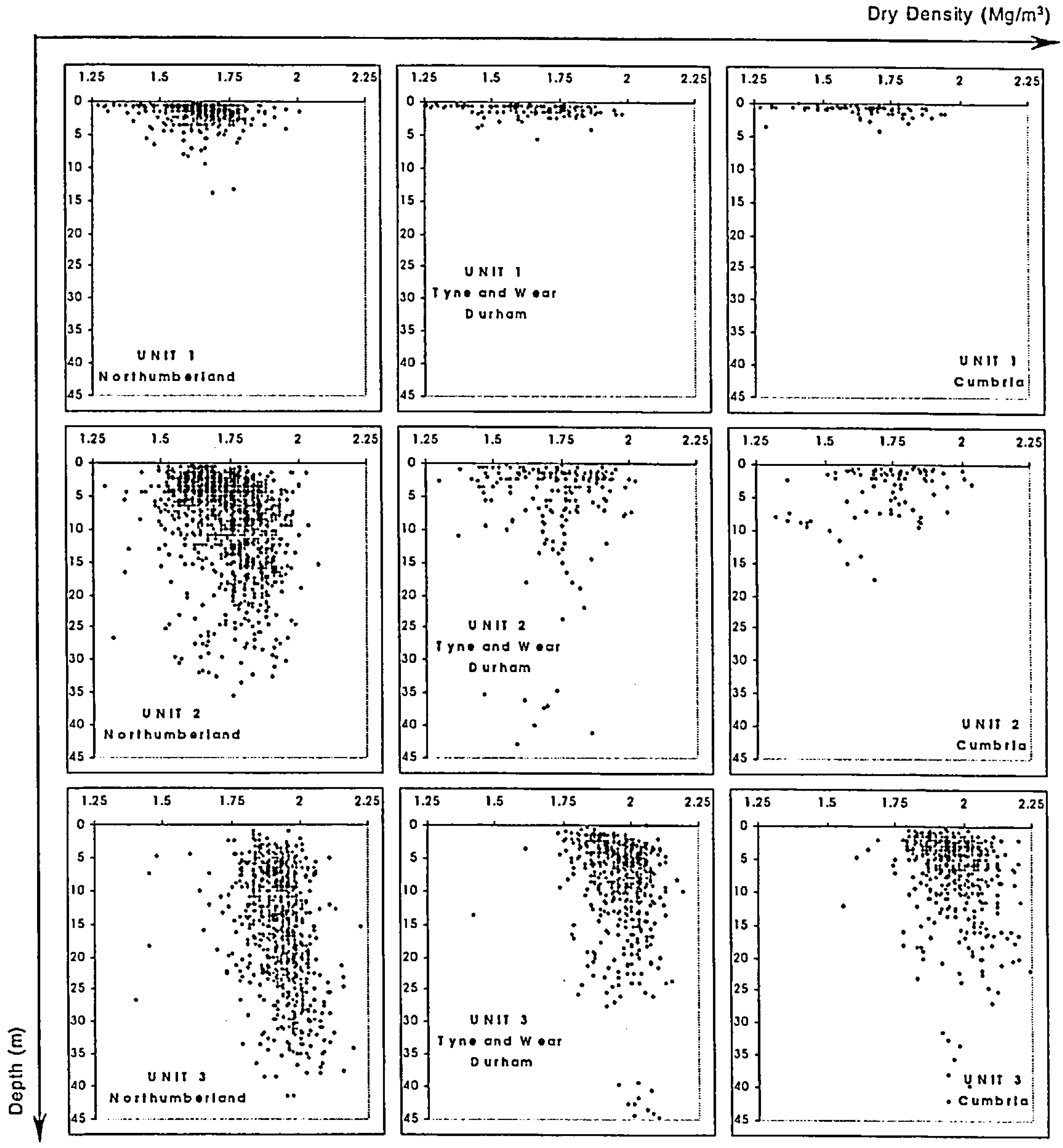


Figure 5.13: Plot of dry density against depth for different till units.

As expected from the variation in average moisture content between the glacial units, distinct differences were also found in the average bulk densities. This is demonstrated clearly in Figure 5.14.

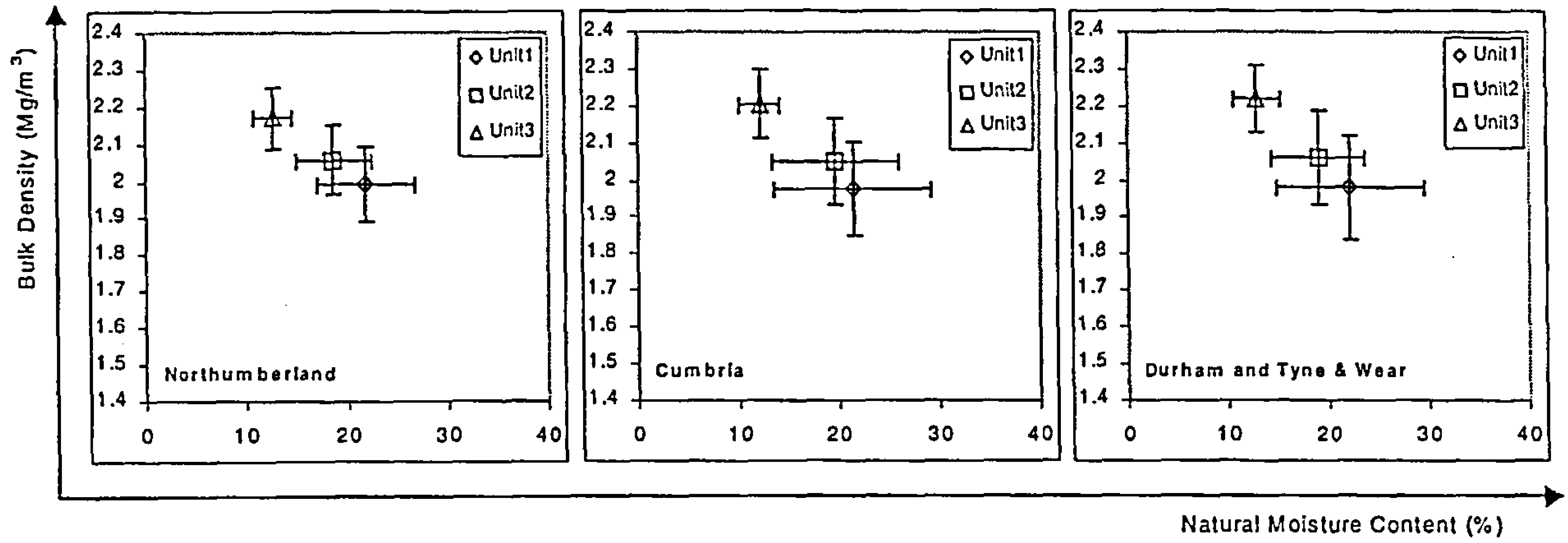


Figure 5.14: Moisture content versus Bulk Density of tills in Northern England.

It should be noted that values measured for the densities of Unit 2 do not always fall intermediate between Unit 1 and Unit 3. This reflects the difficulty in identifying an order sequence in the sites and in adopting a rigid stratigraphical model. The problem of assigning tills to units based on description can be highlighted by some of the measured values that are much lower or much higher than expected for a specific unit.

5.2.6 Shear Strength

The shear strength is the maximum resistance of a soil to shear. Strength tests are usually used for the calculation of bearing capacity, earth pressure, slope stability and the classification of soils. The shear strength can be expressed by a linear function of the normal stress with the following equation known as the Coulomb equation:

Equation 5.6 $$\tau = c + \sigma \tan\varphi$$

where c and φ are the shear strength parameters that are described as the cohesion intercept and the angle of shearing resistance and σ is the total stress. The expression was modified by Terzaghi to accommodate effective stress

Equation 5.7 $$\sigma = \sigma' + u$$

where σ' is the effective normal stress on the failure plane, and u represents the pore water pressure. Water cannot sustain shear stress, so the shear resistance of a soil arises from frictional resistance at point contacts within the soil skeleton. The greater the effective stress carried by the skeleton, normal to a potential failure plane, the greater the resistance to shear on that plane.

Equation 5.8 $$\tau_f = c' + \sigma' \tan\varphi'$$

where c' represents the effective cohesion, and φ' is the effective angle of friction.

The shear strength of a soil can be measured using various methods, such as triaxial or shear box testing, which are described in the following sections. It should be noted that before 1990 laboratory tests were carried out in accordance to BS 1377:1975, and effective strength testing procedures were introduced elsewhere (Bishop and Henkel, 1976; Head, 1986). Then these tests were subsequently introduced into BS 1377:1990. The results for all the effective stress tests are comparable since there is not much difference in any of these testing procedures.

5.2.6.1 Triaxial tests

Triaxial tests are a common method for measuring the shear strength parameters of the soil. Depending on the available samples these tests can be carried out as single stage or in multi stage. Results of the following types of triaxial tests can be found in NETDATA:

1. Unconsolidated Undrained Triaxial tests (UU). In this test a specified all-round pressure known as confining pressure is applied and then the principal stress difference known as the deviator stress is applied without permitting any drainage during the test.
2. Consolidated Undrained Triaxial tests (CU). This test permits the drainage of the specimen under a specified confining pressure until it consolidates. The deviator stress is then applied with no drainage permitted.
3. Consolidated Drained Triaxial tests (CD). In this test the specimen is permitted to drain under a specified confining pressure until consolidation is complete. With drainage still being permitted the deviator stress is then applied at a slow rate to ensure that the excess pore water is maintained at zero.

Glacial till specimens are usually 100 mm in diameter with a length to diameter ratio of 2. This size is more adequate for this type of soil in order to provide a reasonable representative sample due to the presence of various grain sizes. Details of the triaxial tests are given in BS 1377: Part 7: 1990.

The undrained shear strength of a soil depends on several factors such as the following:

- Sampling methods usually affect the water content, which the undrained shear strength depends on. Sample disturbance occurs more often in tills with large clasts.
- Many tills contain fissures, joints and foliation and the orientation of such fabric features with respect to the applied loading could affect test results. These fabric features could be well presented in larger specimens and therefore representative sampling is important.
- The rate of loading and the stress path adopted during testing is also an important factor. Dense samples tend to dilate on a shear plane, which causes high negative pore water pressures to be developed within a sample. Migration of pore water therefore occurs toward the shear plane which results in a locally high liquidity index and hence a lower strength.

For these reasons the undrained shear strength is often regarded as a shear index or a classification parameter rather than a fundamental property. The following table contains descriptions that can provide an indication of the shear strength of undisturbed clay soils.

Table 5.7: A scale in terms of shear strength (BS 5930:1990)

Descriptive term	Undrained shear strength (kN/m2)	Characteristics
Very soft	<20	Excudes between fingers when squeezed
Soft	20-40	Moulded by light finger pressure
Firm	40-75	Moulded by strong finger pressure
Stiff	75-150	Can be indented by thumb
Very stiff	150-300	Can be indented by thumb nail
Hard	>300	No impression possible with thumb

The use of undrained shear strength for foundation design purposes is usually accepted when the foundation is loaded relatively rapidly such that there should be little time for fissures to open and for the water content to change. For different glacial units it may be necessary to consider drained or undrained conditions depending on their anticipated behaviour for the design purposes.

The strength of tills is very variable which largely depends on the difficulties associated with representative undisturbed sampling and laboratory testing. Although some exceptions exist in all locations and the shear strength of the samples are much higher or lower than expected for a certain unit but based on results in Tables 5.1 to 5.3 it can be concluded that the shear strength of Unit 1 and Unit 2 are generally much lower compared to samples taken from Unit 3. The shear strength of samples from Unit 1 and 2 are similar and the soil can be classified as Firm to Stiff. Unit 3 has the largest average value of undrained shear strength and can usually be classified as very stiff. As it can be seen from Figure 5.15 the results of undrained shear strength tests are very scattered. It is suggested that the scatter of results of undrained shear strength on U100 samples of tills is the consequence of their variability, of disturbance due to sampling and the effects of fissuring or other discontinuities (Trenter, 1999). Standard test equipment can not easily deal with samples that contain boulders much in excess of medium gravel size and in many cases the excluded coarser fraction would have a significant effect on the strength results. Therefore the shear strength results are widely scattered even if the samples are collected from the same till unit and the same location. Careful sample selection and preparation could reduce this scatter but even under such circumstances the scatter could remain which reflects the heterogeneous nature of till material. Figure 5.15 shows a general trend of increasing strength with depth from the upper till through to the lower till which confirms the findings of previous research (Robertson et al, 1994; Aflaki, 1996).

The number of consolidated undrained test results available is somehow limited and the results are variable. Considering the average values shown in tables 5.1 to 5.3 it can be seen that the value of φ' in the Lower till is higher compared to the values found in the Upper till. It has been suggested that the value of φ' in drained triaxial shear reduces with increasing plasticity index (Terzaghi and Peck, 1967) which could explain the values of φ' for Unit 3. Individual results also show, in some cases, a significant cohesive strength of up to 55 kN/m^2.

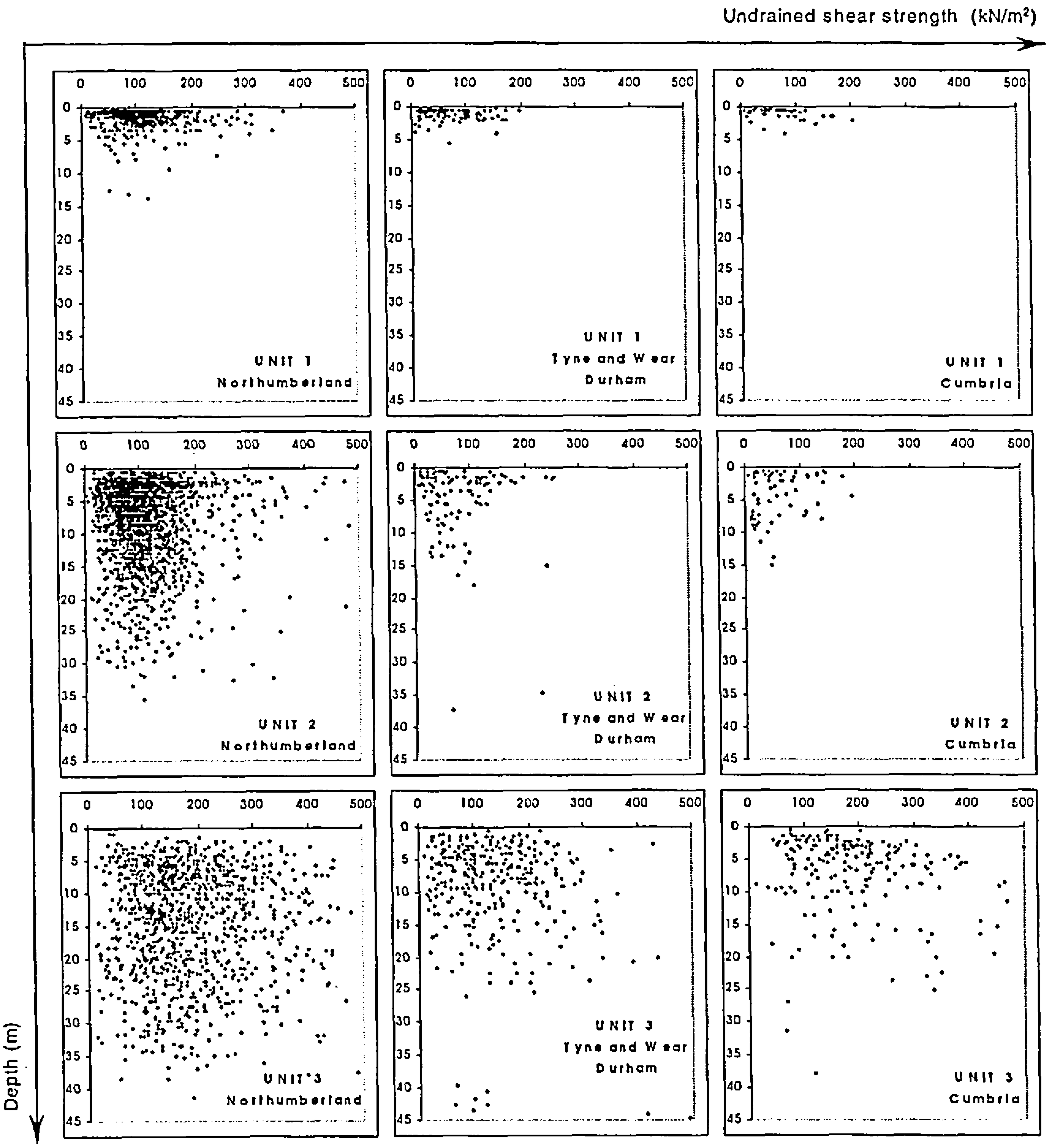


Figure 5.15: Plot of undrained shear strength against depth for different till units.

Some of the results of the triaxial tests in the site investigation reports were considered somewhat dubious since in many cases the effective strength parameters were determined from just one Mohr circle and zero cohesion seemed to have been automatically assumed. It was decided to re-interpret the results using stress path plots. The results of consolidated undrained triaxial compression tests with pore water pressure measurements have been plotted using the stress paths of effective stresses derived from the following equations:

Equation 5.9 $t' = (\sigma'_1 - \sigma'_3)/2$

Equation 5.10 $s' = (\sigma'_1 + \sigma'_3)/2$

where σ'_1 and σ'_3 are respectively the major and minor principal stresses at failure, t' is the maximum shear stress, and s' is the average effective stress. In this method any state of stress is represented by a stress point. Each data point represents a state of stress depicted by a Mohr's circle at failure. The values of c' and φ' can also be calculated from these graphs using the following equations (Head, 1994):

Equation 5.11 $t' = a' + s'.\tan\alpha'$

Equation 5.12 $\varphi' = \sin^{-1}.(\tan\alpha')$

Equation 5.13 $a' = c'.\cos\varphi'$

Figures 5.16 show the plots of t' versus s'. The approximate range of friction angle for each unit are displayed in the plots (assuming zero cohesion). As the results in tables 5.1 to 5.3 show, individual results sometimes indicate cohesive strengths of up to 64 kN/m^2 which goes against the common assumption that tills have no cohesion (Robertson et al, 1994; Trenter, 1999). This may be due to a non linear failure envelope rather than a true cohesion. This could be due to the effects of cementation, concentration of fines, or overconsolidation effects.

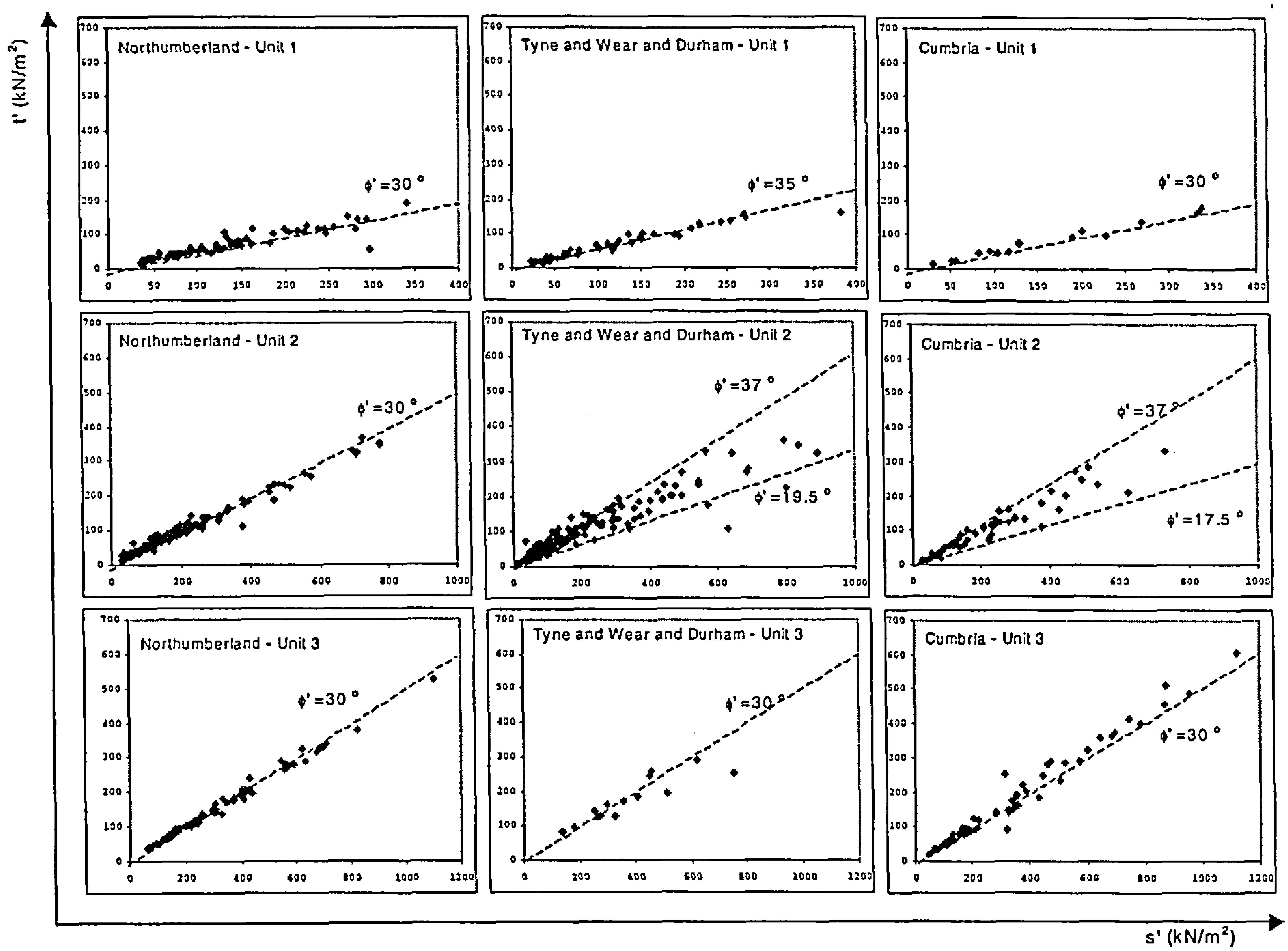


Figure 5.16: Plot of effective stress parameters using stress points for Northern England glacial tills.

5.2.6.2 Shear Box test

The Shear box test is another method used to measure the shear strength parameters of a soil. In the shear box test one portion of the soil sample is made to slide along another by the action of steadily increasing horizontal shearing force, while a constant load is applied normal to the plane of relative movement. Details of the shear box test can be found in BS 1377: Part 7:1990. The values that can be obtained from this test are briefly described as follows (Head, 1994)

- Peak strength is the maximum shear resistance which a soil can offer under defined conditions of effective pressure and drainage.
- Residual strength is the shear resistance which a soil can maintain when subjected to large shear displacement after the peak strength has been mobilised.

Residual strengths are not always easy to define since the residual state is often not reached during testing. Few data are available from shear box tests and results are very variable. The results of the tests show that in the case of peak strength both the effective cohesion and the angle of internal friction contribute to the shearing resistance of the tills. In some of the samples the peak strength is constituted only of a relatively high angle of internal friction which is clearly due to the very sandy nature of the till which is coupled with a low clay fraction. The residual strength of the tills is made up of the residual angle of friction which is usually higher for Unit 3 compared to Unit 1 and Unit 2. This is also due to the sandy nature of Unit 3. The residual angle of shearing resistance in Unit 1 and Unit 2 are usually significantly less than their peak angle of shearing resistance, which is a characteristic of stiff clays (Morgenstern, 1967). The residual and peak angles of shearing resistance of Unit 3 however are not very different. This could be due to the relatively low clay fraction of the material.

5.2.7 Consolidation characteristics

The natural loading and unloading of a soil stratum for instance during the deposition and erosion of overlying material takes place under conditions of one-dimensional compression, because lateral strains at any point are prevented by the surrounding soil. Consolidation is the time-dependent process of soil deformation due to dissipation of non-equilibrium pore water pressure. Due to the externally applied pressure the soil particles are packed closer together.

The oedometer test is a simple approach for determining the parameters which allow the assessment of the consolidation behaviour of the soil. This is required in order to estimate the settlement of a foundation beneath which the soil can be assumed to deform. The consolidation test is described in detail in BS 1377: Part 5: 1990. Laboratory tests can never fully represent actual field conditions, and it has been found for lodgement till that laboratory determinations of m_v generally lead to over-estimations of settlement (Sladen and Wrigley, 1983). One-dimensional consolidation in the laboratory, in which a load is applied vertically and lateral strain is prevented, is approximated in the field where the loaded area is large in relation to the thickness of the sediment.

Typical values of the coefficient of volume compressibility, m_v, and coefficient of consolidation, c_v, are indicated in tables 5.8 and 5.9:

Table 5.8: Typical values of the coefficient of volume compressibility and descriptive terms used. (After Carter, 1983)

Type of Clay	Descriptive term	Coefficient of Volume Compressibility (m^2/MN)
Heavy over-consolidated boulder clays and hard clays	Very low compressibility	<0.05
Boulder clays, marls, very stiff tropical red clays	Low compressibility	0.05-0.1
Firm clays, glacial outwash, lake deposits, weathered marls, firm boulder clays, normally consolidated clays at depth and firm tropical clays	Medium compressibility	0.1-0.3
Normally consolidated alluvial clays such as estuarine and delta deposits, and sensitive clays	High compressibility	0.3-1.5
Highly organic alluvial clays and peats	Very high compressibility	>1.5

Table 5.9: Typical range of values of coefficient of consolidation for inorganic soils. (After Lambe and Whitman, 1979)

Soil type	Plasticity Index	Coefficient of consolidation c_v (m^2/year)
Clays with high plasticity	>25	0.1- 1
Clays with medium plasticity	25 - 15	0- 10
Clays with low plasticity	<15	10- 100
Silts		>100

The results of oedometer tests are plotted in Figure 5.17. As this figure shows the majority of the samples are of medium to low compressibility. (Detailed oedometer test results were only available for sites in Northumberland). Although values of m_v are similar for each of the glacial units, but samples from Unit 3 show generally a lower compressibility compared to Unit 1 and 2. Based on the range of m_v values shown in Figure 5.17 and typical values shown in Table 5.8 it can be concluded that parts of each glacial units may be either normally consolidated or heavily overconsolidated. The coefficient of consolidation (c_v) is more difficult to analyse as Figure 5.17 shows no clear trends and the variations are much wider. The majority of values fall in the range of 1 to 10, which is the typical value for soils with medium plasticity. It can be seen that Unit 3 has a higher coefficient of consolidation compared to Unit1 and 2 and a number of samples from this unit have c_v values of more than 10 which is typical for soils of low plasticity.

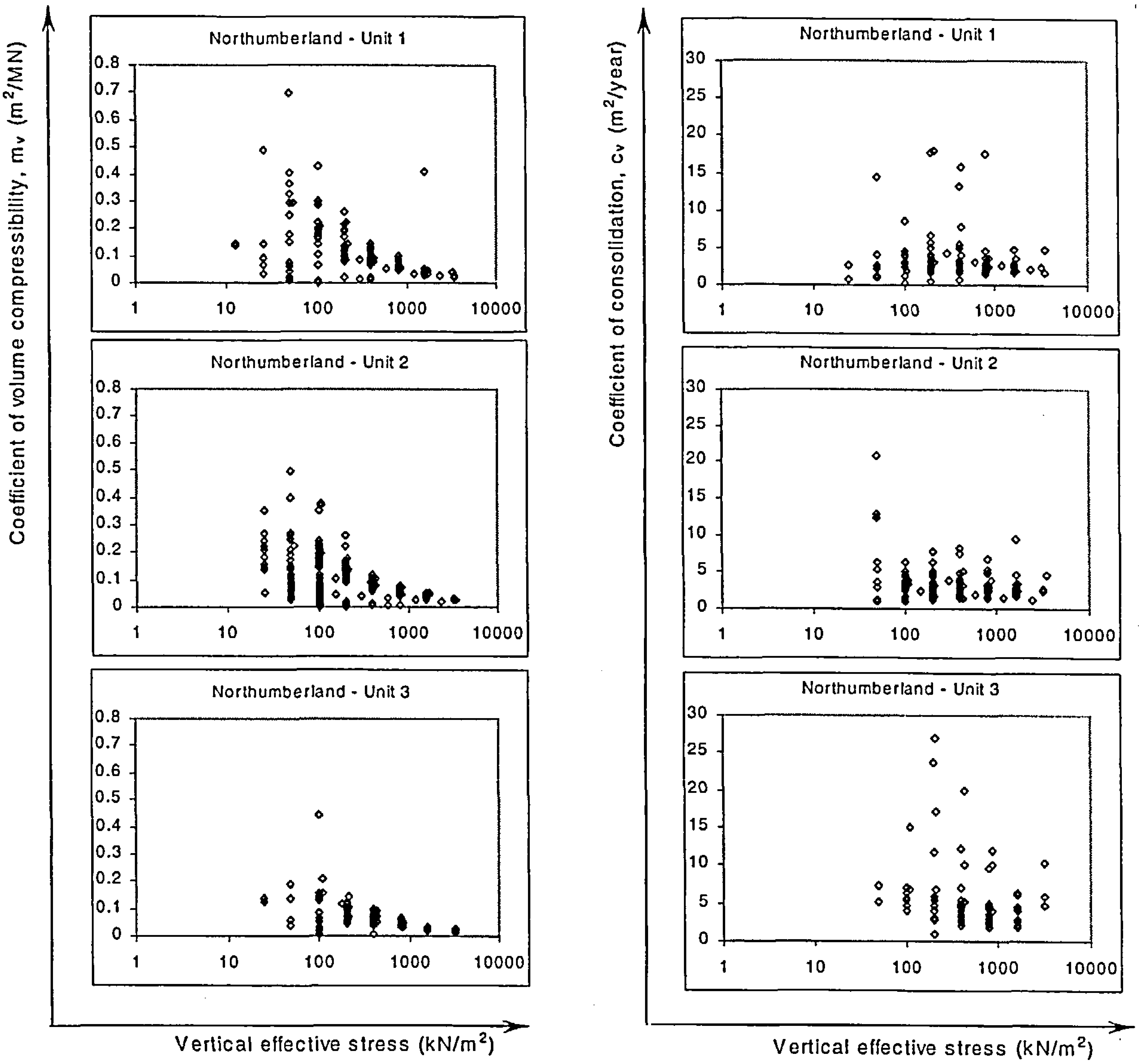


Figure 5.17: The compressibility and consolidation characteristic of tills in Northumberland

5.3 The properties of glaciofluvial deposits

One of the main difficulties in site investigations in glaciated terrains is the occurrence of material of different compositions. As mentioned in earlier chapters water-borne transport of glacial debris results in the occurrence of sediments associated with tills in preserved glacial sequences. The characteristics of these sediments can largely affect the engineering behaviour of a till dominant succession. Sheets of till often contain glaciofluvial deposits such as clay and silt laminations or lenses of sand and gravel deposited by meltwater streams whose course depends on the local topography and climate. These material were deposited under water within lakes or seas. They maybe transported directly to these water bodies by the ice or deposited into water from running streams. It is usually very difficult to predict the exact extend of such layers or lenses and their limits can only be determined by very detailed survey.

Although glaciofluvial deposits are all part of Unit 4 of the litostratigraphic model introduced by Robertson et al (1994), in this study they are divided into three groups for analysing their geotechnical parameters. These are Sand and Gravel (Unit 4-SA), Silt lenses (Unit 4-SI), and layers of laminated clay (Unit 4-LC).

Sand and gravels have normally a wide range of grain size distribution. The majority of them are granular and the variations in their engineering properties are controlled by their particle size and shape. The fine content of these material is generally low although some local pockets with high fine content may occur at some places. Classification tests are carried out on the fine fraction of these soils.

Clays and silts may occur as layers interbedded with glaciofluvial sand and gravel deposits or as pockets and lenses of clay and silt. These layers are often very compressible. The presence of soft clay and silt bands leads to a considerable difference in their engineering properties in particular their permeability. The presence of such bands reduces the bearing capacity of the soil, which results in large settlements especially under heavy loading. Results of various tests carried out on these deposits can be found in tables 5.10 to 5.12.

Table 5.10: Summary of test results for samples of Unit 4-LC.

	Northumberland					Tyne and Wear and County Durham					Cumbria				
Unit4-LC	Count	min	max	average	S.D.	Count	min	max	average	S.D.	Count	min	max	average	S.D.
Depth (m)		0.5	38.1				0.6	41.8				1.0	21.5		
ρ (Mg/m³)	874	1.45	2.30	1.99	0.09	127	1.78	2.40	2.03	0.09	33	1.73	2.26	2.02	0.10
ρ_D (Mg/m³)	674	1.19	2.05	1.61	0.11	127	1.31	1.96	1.62	0.10	27	1.19	1.97	1.68	0.16
e	874	0.29	1.29	0.66	0.12	127	0.36	0.99	0.66	0.09	33	0.36	1.24	0.60	0.16
NMC (%)	960	7.2	38.0	23.9	4.4	131	12.0	41.0	25.6	4.4	34	9.0	60.0	20.3	8.0
PL (%)	931	13.0	35.0	21.2	3.1	127	14.0	36.0	23.5	3.9	24	12.0	30.0	18.2	4.4
LL (%)	931	24.0	71.0	46.6	8.4	127	25.0	74.0	43.6	9.5	24	24.0	62.0	38.6	8.0
PI (%)	929	6.0	47.0	25.5	7.1	127	7.0	40.0	20.2	6.7	24	9.0	52.0	21.9	8.5
LI	917	-1.083	0.985	0.108	0.182	127	-0.571	0.895	0.139	0.252	24	-1.091	1.414	0.128	0.469
<425 fraction	868	17.0	100.0	95.5	8.6	128	58.0	100.0	86.5	9.7	24	72.0	100.0	93.5	8.6
Activity	864	0.06	2.18	0.27	0.10	127	0.08	0.53	0.24	0.09	24	0.09	0.53	0.23	0.08
CLAY (%)	6	15.0	55.0	31.3	14.4						1	4.0	4.0	4.0	0.0
SILT (%)	6	37.0	53.0	44.8	5.2						1	16.0	16.0	16.0	0.0
SAND (%)	6	3.0	48.0	22.7	15.2						1	40.0	40.0	40.0	0.0
GRVL (%)	6	0.0	5.0	1.2	1.9						1	40.0	40.0	40.0	0.0
CBLS (%)	6	0.0	0.0	0.0	0.0						1	0.0	0.0	0.0	0.0
c_u (kN/m²)	826	4.0	194.0	72.7	32.9	102	8.0	174.0	45.2	28.6	21.0	14.0	196.0	81.8	46.3
c' (kN/m²)	46	0.0	25.0	7.7	7.4	2	1.0	16.0	8.5	7.5	8.0	0.0	7.0	3.8	2.4
ϕ' (degrees)	46	2.0	33.0	24.2	7.7	2	2.2	22.0	12.1	9.9	8.0	3.0	31.5	20.4	7.6
c'_p (kN/m²)	51	0.0	75.0	20.3	16.0	2	19.3	32.4	25.9	6.5					
ϕ'_p (degrees)	51	6.0	38.0	23.6	6.0	2	25.5	26.3	25.9	0.4					
c'_r (kN/m²)	86	0.0	50.0	9.3	9.4	2	15.0	28.1	21.5	6.6					
ϕ'_r (degrees)	86	7.0	37.0	17.0	7.3	2	1.0	22.6	11.8	10.8					

Table 5.11: Summary of test results for samples of Unit 4-SI.

	Northumberland					Tyne and Wear and County Durham					Cumbria				
Unit4-SI	Count	min	max	average	S.D.	Count	min	max	average	S.D.	Count	min	max	average	S.D.
Depth (m)		0.5	39.6				0.2	18.5				0.4	16.1		
ρ (Mg/m³)	39	1.50	2.43	1.98	0.18	23	1.72	2.33	2.01	0.16	5	2.08	2.28	2.14	0.08
ρ_D (Mg/m³)	35	1.30	2.03	1.62	0.17	23	1.38	1.88	1.66	0.13	5	1.65	1.97	1.79	0.13
e	39	0.20	1.21	0.68	0.20	23	0.42	0.94	0.62	0.13	5	0.96	1.19	1.07	0.09
NMC (%)	44	12.0	39.0	23.8	5.3	41	9.0	36.0	22.4	6.0	6	14.0	27.0	20.5	4.4
PL (%)	37	12.0	30.0	20.9	4.0	12	17.0	40.0	23.6	6.1	6	17.0	25.0	20.0	3.3
LL (%)	37	26.0	53.0	36.4	6.5	12	23.0	53.0	35.8	6.9	6	24.0	41.0	31.3	6.1
PI (%)	37	4.0	27.0	16.1	6.2	12	5.0	17.0	12.2	3.5	6	5.0	19.0	11.2	5.4
LI	37	-0.738	2.111	0.200	0.429	12	-1.400	0.833	-0.072	0.624	6	-0.800	0.857	-0.160	0.547
<425 fraction	37	79.0	100.0	97.5	5.5	24	72.0	100.0	87.8	9.0	18	50.0	100.0	73.9	17.4
Activity	37	0.04	0.30	0.17	0.07	12	0.05	0.19	0.14	0.04	6	0.06	0.26	0.13	0.07
CLAY (%)	21	5.0	31.0	18.2	7.3	7	2.0	32.0	13.3	9.2	64	0.0	19.0	4.0	4.5
SILT (%)	21	31.0	62.0	50.7	7.1	7	46.0	86.0	57.4	12.4	64	0.0	57.0	16.2	13.5
SAND (%)	21	6.0	61.0	28.1	13.9	7	0.0	51.0	29.1	17.3	64	5.0	96.0	32.5	17.7
GRVL (%)	21	0.0	15.0	2.7	4.7	7	0.0	1.0	0.1	0.3	64	0.0	94.0	42.0	25.8
CBLS (%)	21	0.0	3.0	0.3	0.8	7	0.0	0.0	0.0	0.0	64	0.0	63.0	5.3	11.0
c_u (kN/m²)	36	11.0	237.0	87.2	54.4	22	11.0	192.0	41.5	42.2	1.0	160.0	160.0	160.0	0.0
c' (kN/m²)	2	0.0	4.0	2.0	2.0										
ϕ' (degrees)	2	3.0	21.0	12.0	9.0										
c'_p (kN/m²)															
ϕ'_p (degrees)															
c'_r (kN/m²)	3	0.0	15.0	8.3	6.2										
ϕ'_r (degrees)	3	13.0	48.0	31.0	14.3										

Table 5.12: Summary of test results for samples of Unit 4-SA.

	Northumberland					Tyne and Wear and County Durham					Cumbria				
Unit4-SA	Count	min	max	average	S.D.	Count	min	max	average	S.D.	Count	min	max	average	S.D.
Depth (m)		0.5	40.8				0.1	25.9				0.3	40.0		
ρ (Mg/m^3)	43	1.73	2.32	2.01	0.11	19	1.78	2.34	2.05	0.16	9	1.90	2.33	2.06	0.13
ρ_D (Mg/m^3)	38	1.43	2.09	1.70	0.15	19	1.45	2.09	1.72	0.19	9	1.62	2.14	1.80	0.15
e	43	0.28	0.86	0.55	0.15	19	0.28	0.84	0.57	0.16	9	0.49	1.02	0.81	0.15
NMC (%)	53	5.6	38.0	18.2	6.9	62	3.0	49.0	15.5	7.2	37	8.0	23.0	14.3	3.3
PL (%)	32	8.0	25.0	15.8	3.6	5	14.0	22.0	18.0	3.4	12	13.0	27.0	17.1	3.9
LL (%)	32	19.0	64.0	30.9	9.4	5	21.0	29.0	24.6	3.3	12	22.0	34.0	25.6	3.5
PI (%)	32	6.0	42.0	15.0	7.5	19	4.0	18.0	11.1	4.2	12	1.0	19.0	8.9	4.5
LI	29	-1.100	2.160	0.125	0.576	19	-1.400	0.833	-0.160	0.599	12	-4.000	0.500	-0.503	1.164
<425 fraction	32	51.0	100.0	89.8	12.0	19	55.0	99.0	78.4	15.9	12	50.0	100.0	67.0	15.0
Activity	32	0.06	0.42	0.17	0.08	5	0.07	0.14	0.10	0.02	12	0.02	0.26	0.14	0.06
CLAY (%)	180	0.0	26.0	6.9	5.5	89	0.0	15.0	2.4	3.8	59	0.0	19.0	3.3	3.9
SILT (%)	180	0.0	87.0	16.2	11.4	89	0.0	42.0	12.6	9.6	59	0.0	57.0	14.1	11.3
SAND (%)	180	1.0	99.0	60.1	24.1	89	4.0	93.0	44.1	28.9	59	5.0	96.0	32.2	18.3
GRVL (%)	180	0.0	90.0	14.2	21.9	89	0.0	95.0	36.6	30.4	59	0.0	94.0	44.7	24.8
CBLS (%)	177	0.0	83.0	2.6	10.3	88	0.0	59.0	4.4	9.2	59	0.0	63.0	5.7	11.3
c_u (kN/m^2)	27	4.0	536.0	141.1	130.7	15	17.0	334.0	71.3	77.9	3.0	110.0	215.0	153.3	44.8
c' (kN/m^2)	2	0.0	2.0	1.0	1.0						3.0	0.0	12.0	7.3	5.2
ϕ' (degrees)	2	29.0	36.0	32.5	3.5						3.0	31.0	37.0	33.3	2.6
c'_p (kN/m^2)	1	40.0	40.0	40.0	0.0										
ϕ'_p (degrees)	1	25.0	25.0	25.0	0.0										
c'_r (kN/m^2)	1	27.0	27.0	27.0	0.0										
ϕ'_r (degrees)	1	24.0	24.0	24.0	0.0										

The above tables show that Unit 4LC has mostly the highest moisture content compared to all the other glacial units. Similarly in Unit 4SI the silt layers have a high natural moisture content. The high moisture content in these layers results in a low shear strength of these layers.

The fine fraction of the material found in Unit 4LC and 4SI is much higher compared to the other units. Particle size distribution results indicate that the laminated clay layers are composed primarily of clay size particles with a lesser amount of silt size particles and traces of sand, while silt layers are composed primarily from silt size particles with smaller amounts of clay and sand particles. Consequently the liquid limit and plasticity index of the clay layers is much higher than those of the silt layers. The average values calculated for the Atterberg limits in Unit 4LC are also higher than that of Units 1, 2 and 3. Using the results of the tests carried out on samples from Unit 4, plasticity charts were plotted and can be found in figure 5.18. As it can be seen from the charts the samples from Unit4LC vary from low plasticity to high plasticity. Most samples taken from Unit 4SI and 4SA are of low or intermediate plasticity.

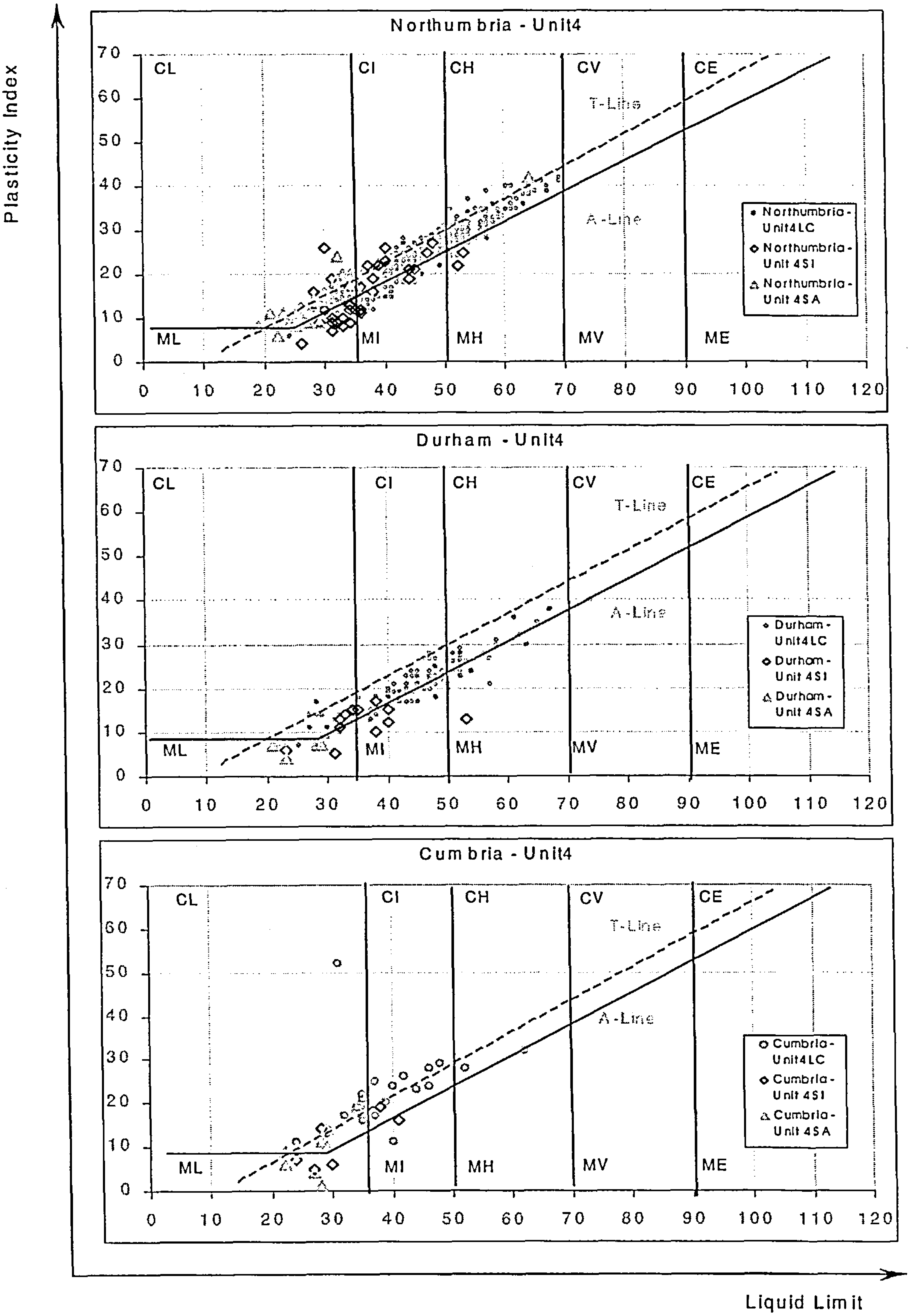


Figure 5.18: Plasticity chart for glaciofluvial deposits in Northern England.

Plots of the natural moisture content and liquidity index for Unit 4LC can be seen in Figures 5.19 and 5.20.

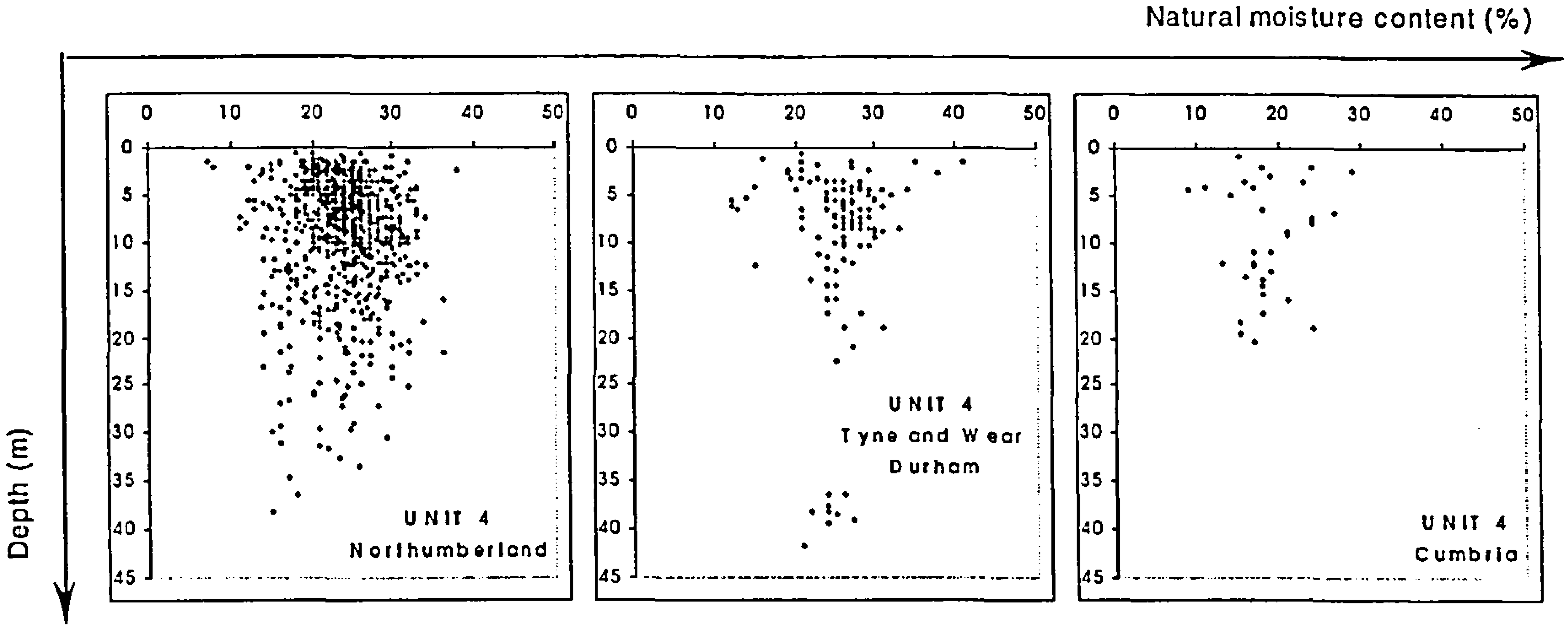


Figure 5.19: Plot of natural moisture content versus depth for laminated clays.

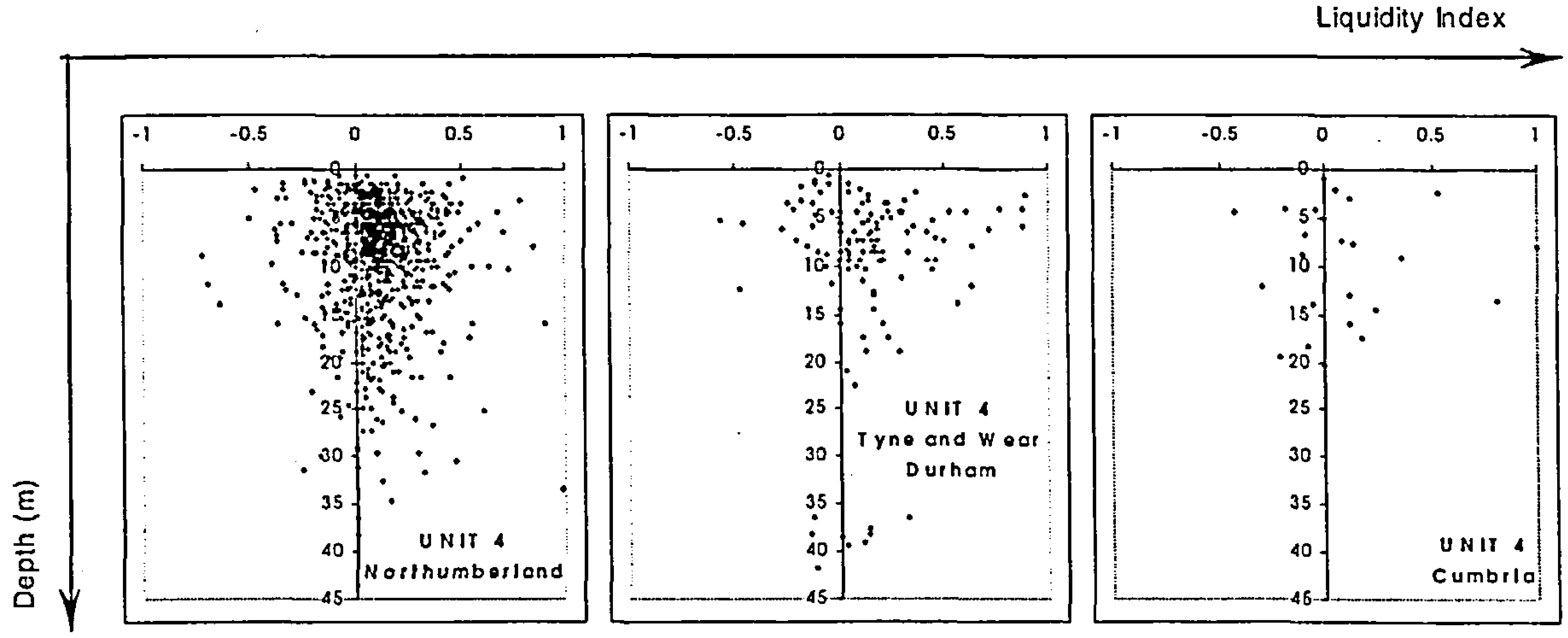


Figure 5.20: Plot of liquidity index against depth for laminated clays.

Similar to Units 1, 2, and 3 the material found in Unit 4LC are all of low activity. This could be due to the presence of inactive clay minerals in glaciofluvial clays. The activity frequency distribution curve for this unit is shown in Figure 5.21.

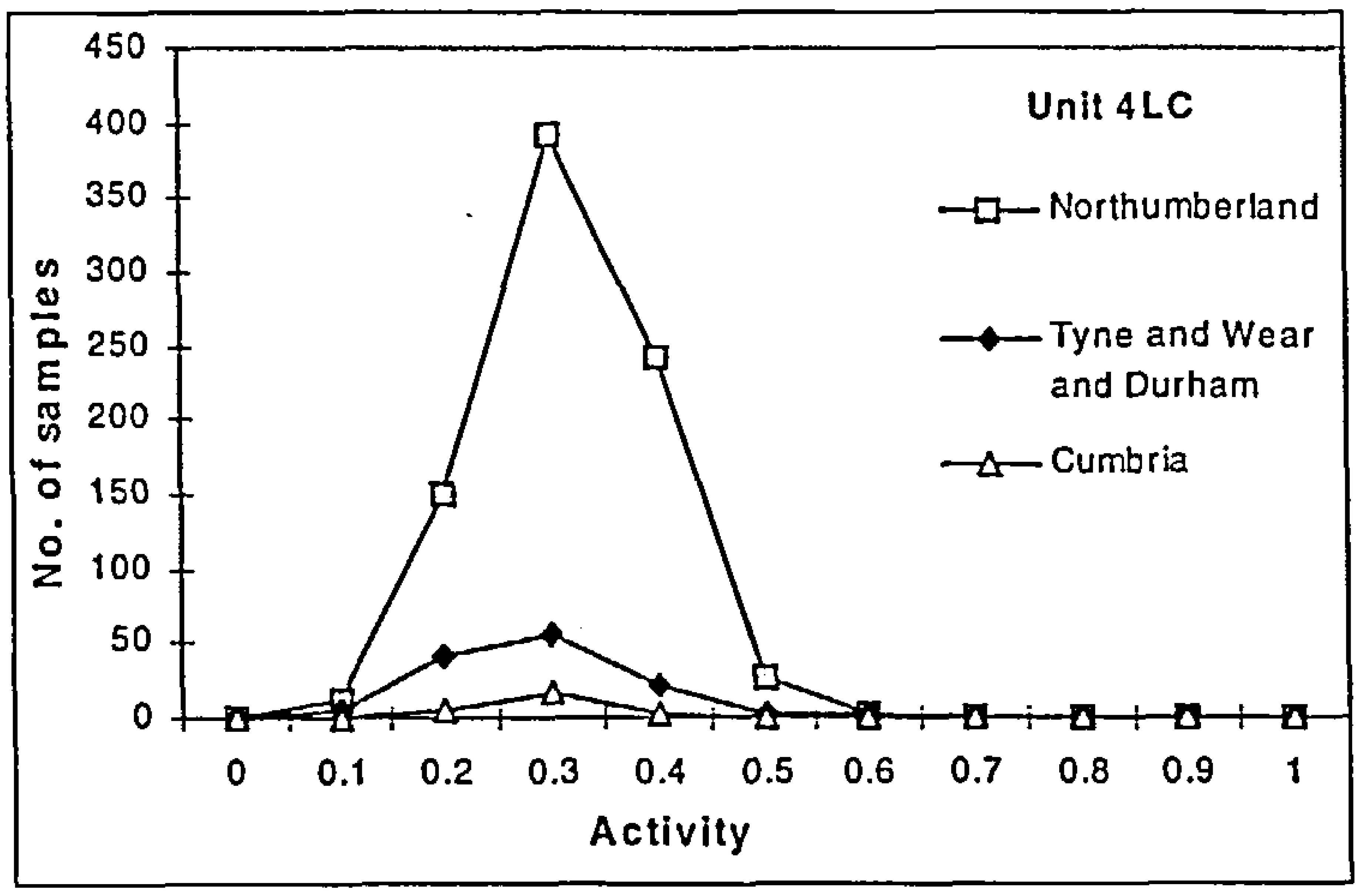


Figure 5.21: Frequency distribution for activity in laminated clays.

Tables 5.10 to 5.12 show that the bulk density of the material found in Unit 4 is comparable to that of the samples taken from Unit 1 and 2 but is less than that of Unit 3. However the void ratio of glaciofluvial clays is higher than those of the Upper and Lower Till. Figure 5.22 and 5.23 show the plots of bulk and dry density of laminated clays against depth.

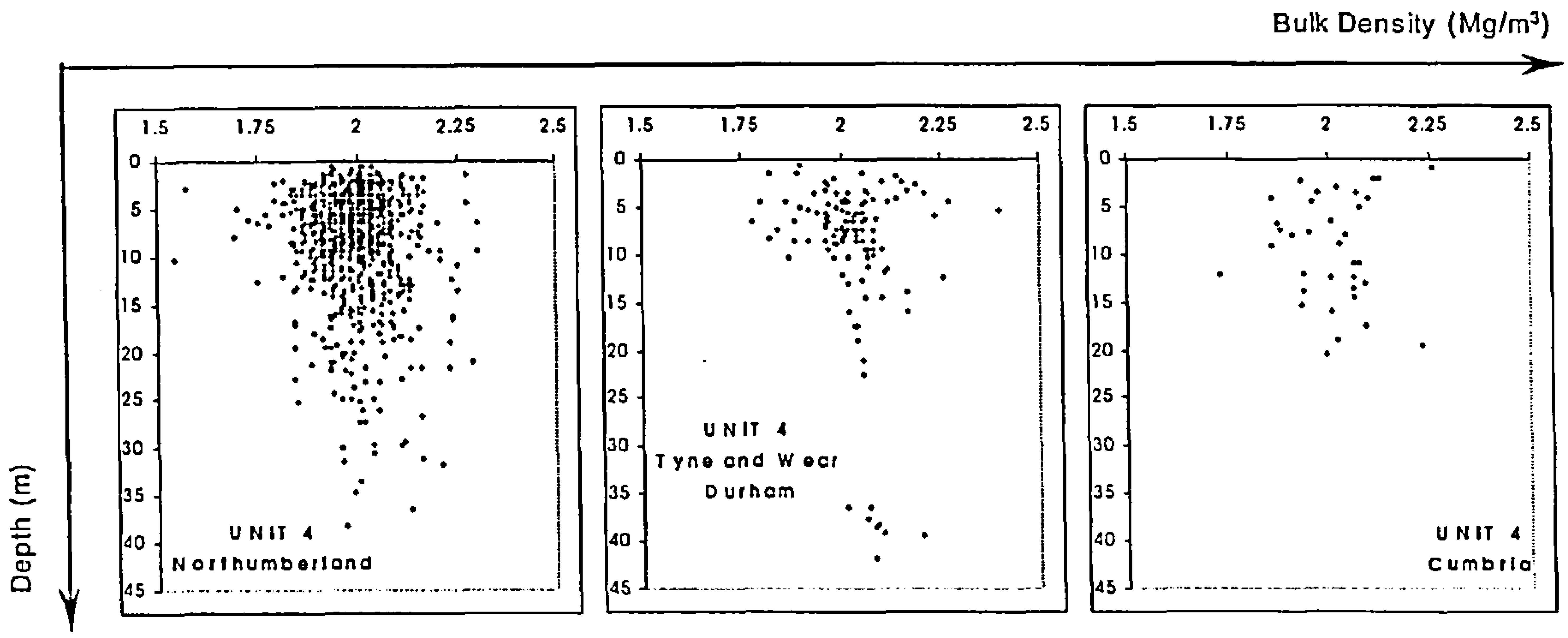


Figure 5.22: Plot of bulk density against depth for laminated clays.

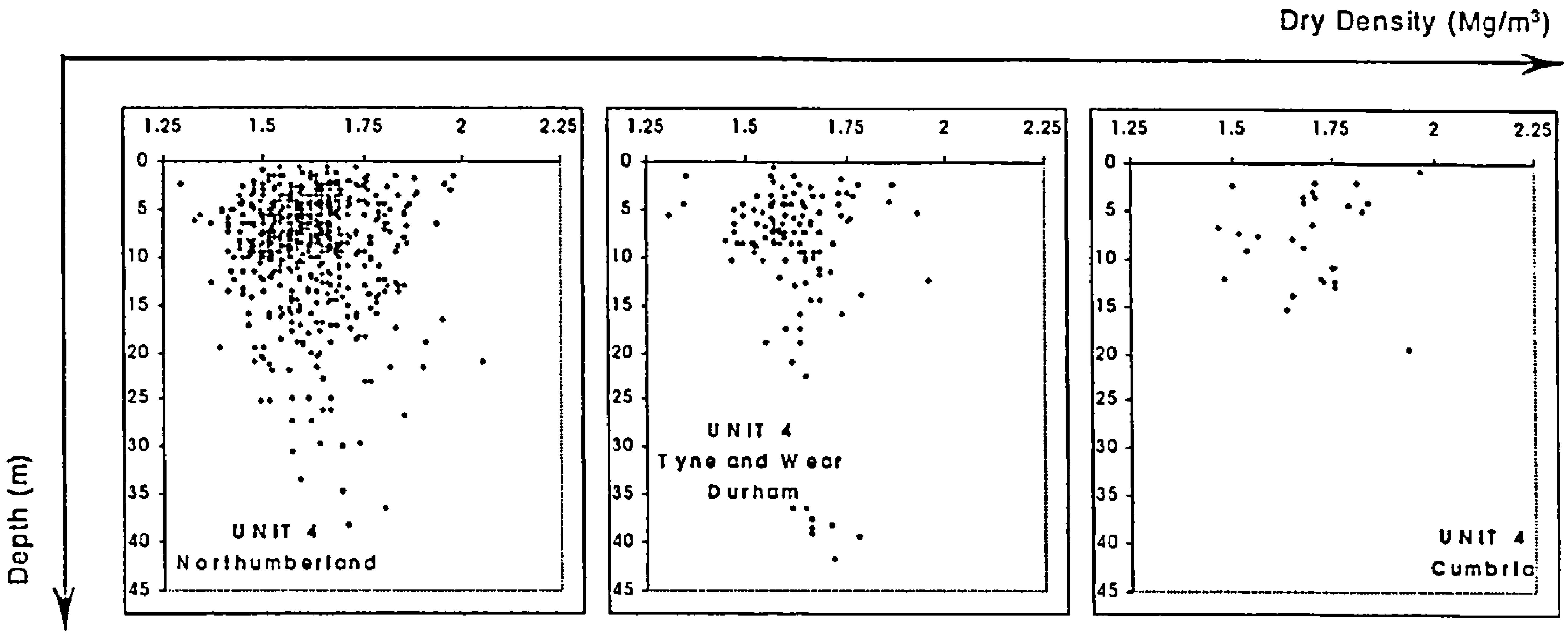


Figure 5.23: Plot of dry density against depth for laminated clays.

Problems that occur during engineering projects due to the presence of lenses of glaciofluvial material within tills have been pointed out in section 2.6. As it can be seen from tables 5.10 to 5.12 the average undrained shear strength of samples taken from Unit 4 is much lower compared to that of Units 1, 2, and 3. Some samples however appear to have much higher shear strengths than expected. Figure 5.24 shows the plot of undrained shear strength against depth for Unit 4LC.

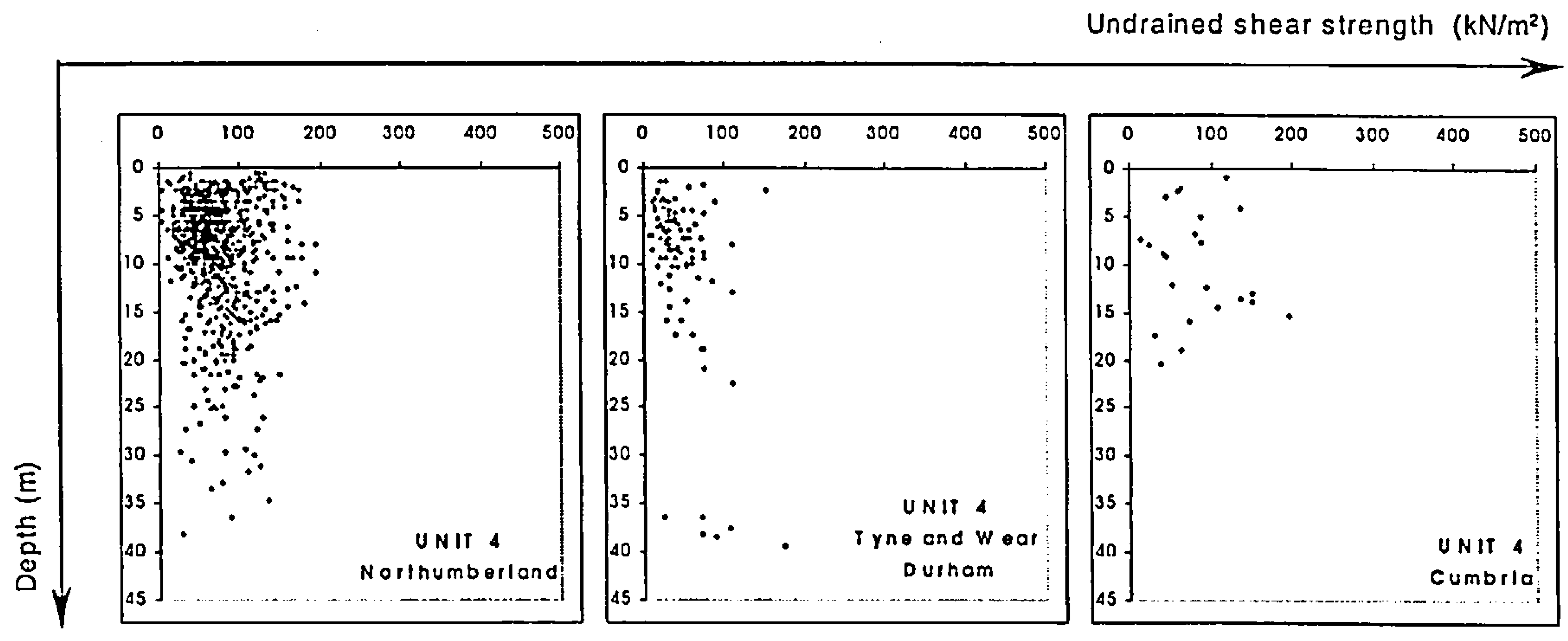


Figure 5.24: Plot of undrained shear strength against depth for laminated clays.

Using the stress path method the effective strength parameters are plotted for Unit 4LC.

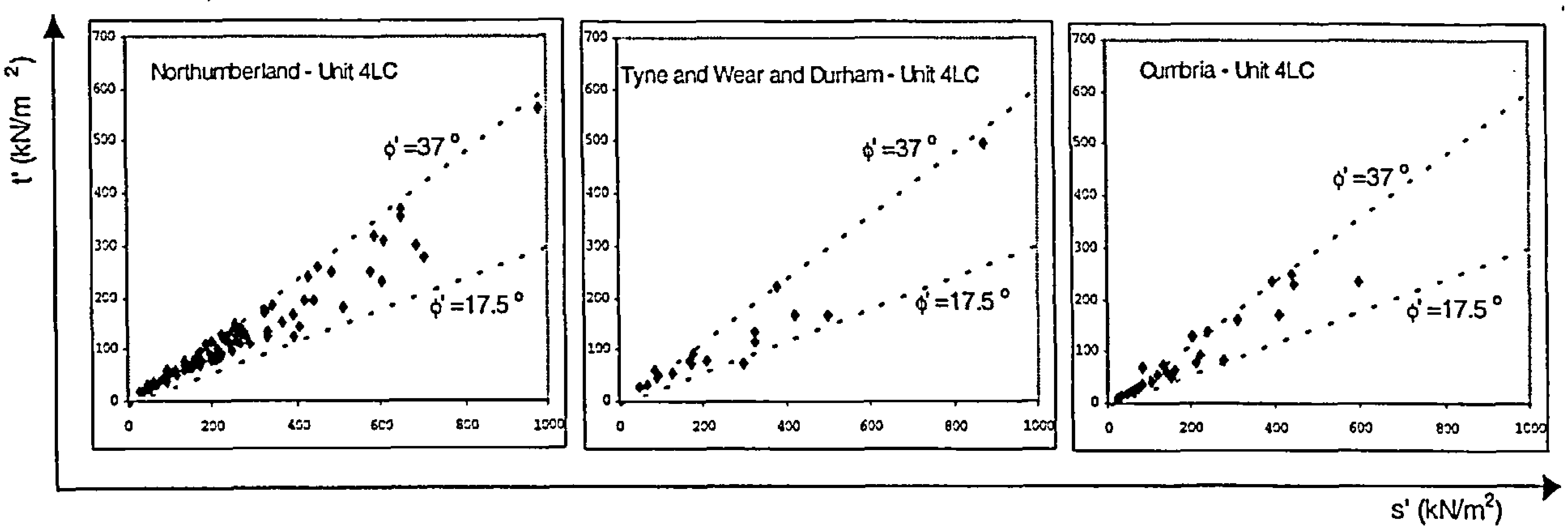


Figure 5.25: Plot of effective stress parameters using stress points for laminated clays.

The results of consolidation tests carried out on glaciofluvial samples is shown in the following graphs.

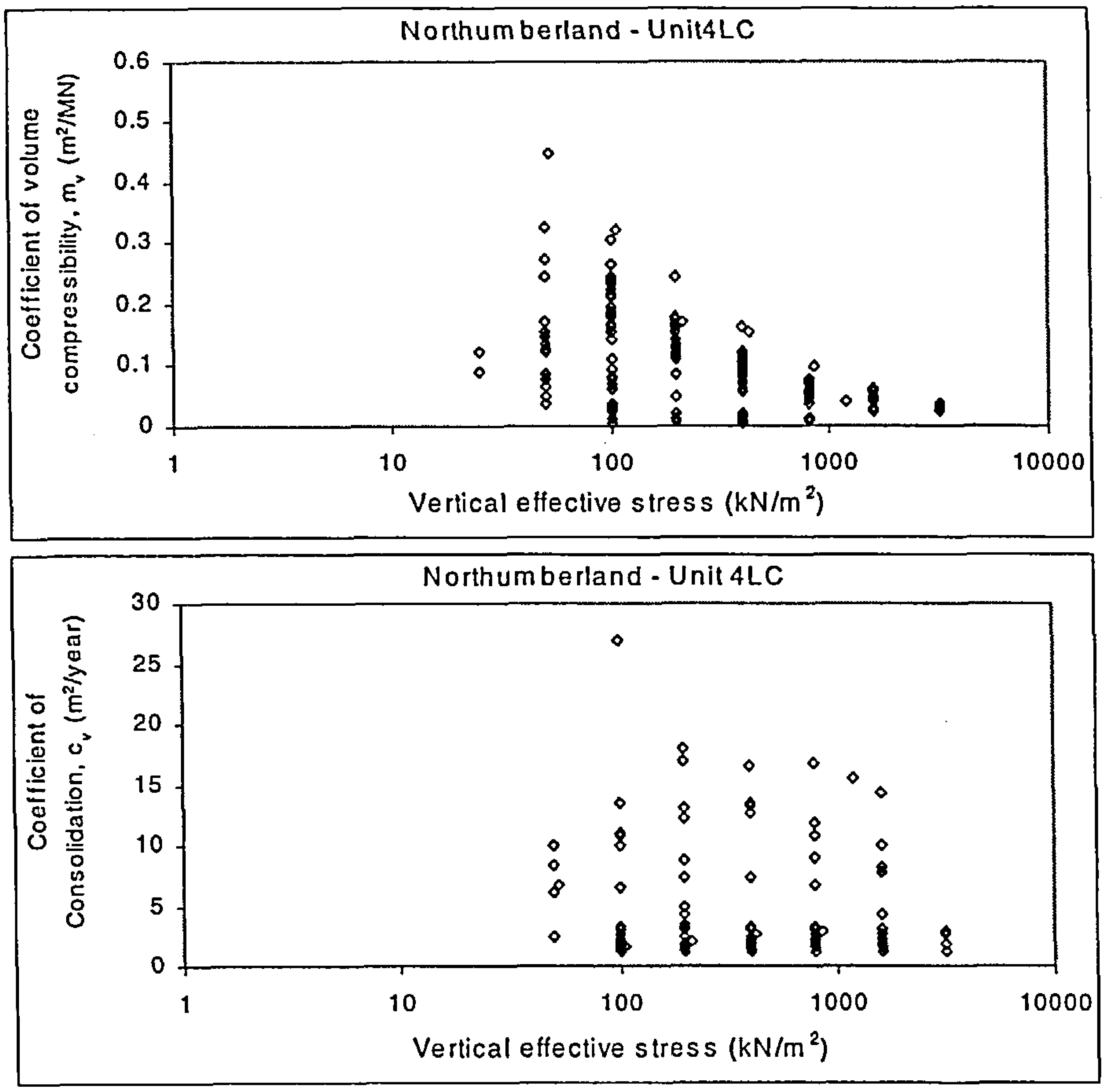


Figure 5.26: Compressibility and consolidation characteristics of laminated clays

5.4 Conclusion

It was demonstrated in this chapter that clear distinctions can be made between glacial units based from their index properties such as Atterberg limits, moisture content, and density. This makes it important not to rely only on soil description for characterising the tills. The framework for the soil model established for the sites was based on the recognition of the Upper Till and the Lower Till and their sub-division into three distinct horizons and also the presence of glaciofluvial deposits, on the basis of their index properties.

In general the glacial Units at different locations follow a similar pattern. The degree of plasticity of the tills generally decreases downwards and Unit 3 has the lowest plasticity in comparison with Unit 1 and Unit 2. The downward decrease in the plasticity from the Upper Till to the Lower Till is the result of the downward decrease in the clay fraction of the till matrix and an increase of the coarse material present in the till matrix. Unit 1 and Unit 2 are made up of much finer particles compared to Unit 3 which contains more coarse material.

Test results show that a decrease in the natural moisture content and liquidity index also follows the downward decrease in clay fraction and plasticity. Unit 3 appears to have a much lower void ratio compared to Unit 1 and 2 which could be due to the thick overburden that it carries. The compactness of the till units can also be seen from the bulk density and dry density values which show a downward increase from Unit 1 to Unit 3. The shear strength of the tills increases downwards from the Upper Till to the Lower Till with increasing bulk density and a decreasing moisture content and void ratio.

Laminated clays and silts of Unit 4 were found to have generally similar index properties to the Upper Till and Unit 1 in particular but showed a much lower shear strength which is due to their higher moisture content. Most of the tests carried out on sand and gravel lenses were particle size distributions and the results were shown in the summary tables. Other parameters such as natural moisture content and plasticity parameters derived from tests carried out on the fine content of the lenses.

The histograms prepared for the Atterberg limits of the glacial till units, illustrate that the till samples can be classified based on different till units using their index properties without the need of prior knowledge of the nature of the till material. It can clearly be seen that there is a shift in the values derived for the various geotechnical parameters of the glacial tills in North East of England and North West of England. This may arise from the inhomogenity of the tills and the effects of the difference of the rock flour in the sample. It is suggested that the mineralogy of glacial tills, especially the clay minerals, is a function of the rock source, the distance of transport and the subsequent post-depositional processes of weathering and alteration to which the tills have been subjected. These fundamental processes influence the geotechnical and engineering behaviour of the tills. Nevertheless, even if it is possible to differentiate between the different units by some of their properties, a prior knowledge of the origin of the till is required since different types of till may have similar properties.

In chapter 6 the properties of glacial tills that were reviewed in this chapter will be used in order to find correlations between them.

Chapter 6

Analysis and Correlation of soil parameters

6.1 Introduction

In the previous chapter the geotechnical parameters of the various Units found in glacial soils in Northern England were reviewed. Histograms were prepared which illustrate that the till samples can be assigned to the different till Units using their index properties without the need of prior knowledge of the nature of the till material. In this chapter the index properties, and shear strength and consolidation parameters of the glacial deposits will be intercorrelated to prove the overconsolidation of natural till deposits and to find relationships between them. Many researchers have studied the relationships between various properties of tills and a number of empirical correlations have been developed. Results from various sites stored in NETDATA will be used to evaluate existing correlations between the various parameters and to demonstrate the agreement that can be achieved.

6.2 Relationship between Index properties

The relationship between the plastic index and liquid limit was discussed in the previous chapter. Results of index tests were plotted on the Casagrande chart and it was seen that the data of all sites lie about the T-line. Data from Unit 3 tend to lie higher compared to data from Unit 1 and 2. Many attempts have been made to link Atterberg limits with other soil properties (Skempton, 1943; Bjerrum and Simons, 1960; Seed et al, 1964 a and b; Youssef et al, 1965). Some of these relationships are reviewed and discussed in the following sections.

6.2.1 The relationship between the fine fraction and the liquid limit

The clay fraction (% < 2μ) of a soil has a great influence on the engineering properties of a soil. The relationship between the liquid limit and the percentage of the clay fraction of soils was investigated and it was found that a linear correlation exists between these parameters (Davidson et al, 1952). Other researchers have also obtained linear relationships between glaciofluvial clays (Kazi and Knill, 1969) and Canadian glacial clays (Hamilton, 1966). They suggested that such a correlation is a helpful confirmation of the experimental accuracy of the particle size distribution test. This relationship was also investigated for artificial soil mixtures of pure clay and sand (Seed et al, 1964 a and b). The latter research concluded that soils having clay fractions of different activities plot on different lines. This means that if test results produce a linear relationship between the liquid limit and the clay fraction the soil samples tested have essentially the same activity and hence a similar mineralogy.

Approximate values of the activity of some clay minerals are shown alongside their liquid limit in table 6.1 (Head, 1992):

Table 6.1: Table: Typical ranges of index properties of some common clay minerals

Clay mineral	*Liquid Limit range*	*Plastic Index Range*	*Approximate Activity*
Kaolinite	40-60	10-25	0.4
Illite	80-120	50-70	0.9
Sodium Montmorillonite	700	650	7
Other Montmorillonites	300-650	200-550	1.5
Granular soils	20 or less	0	0

The relationship between the liquid limit and the clay fractions of the lower and upper tills in a number of locations in Northumberland was investigated by Thabet (1973) and is shown in figure 6.1. Data from different Units taken from NETDATA are also displayed in this figure.

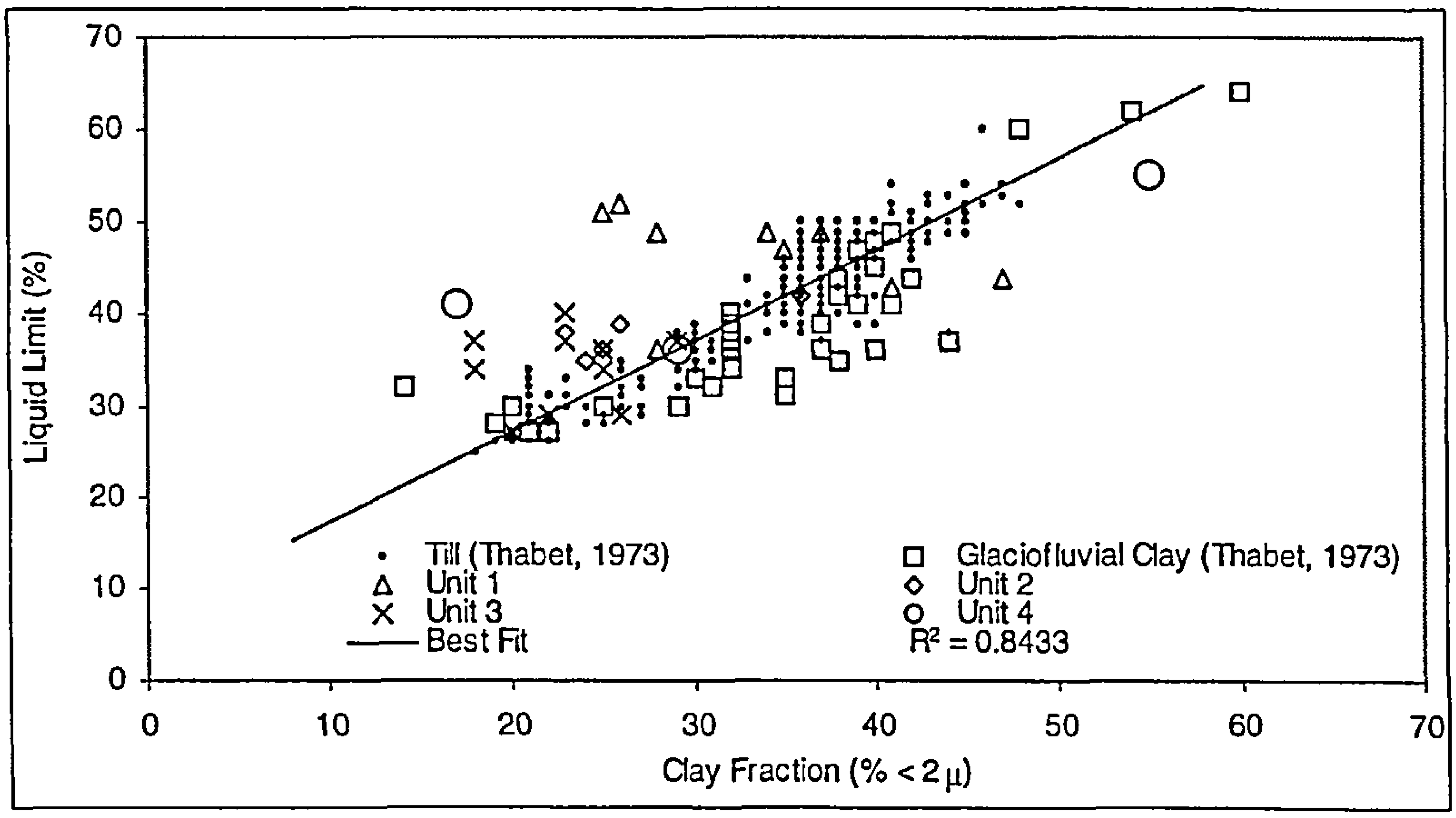


Figure 6.1: Relationship between liquid limit and clay fraction for glacial clays

This figure shows that the data lie about a linear trend line (suggested by Thabet, 1973) that shows a significant correlation which means that the liquid limit increases with increasing clay fraction. The scatter in the data could be due to the type of clay minerals, which affect the liquid limit, or due to errors in experiments. However, the trend of increasing Liquid Limit with the increase of the fine content can be seen in Figure 6.1. From the proposed linear relationship it can be concluded that the samples of glacial clays have similar activities and hence the clay content of these soils have a similar mineralogy. Figure 6.2 investigates this further using the plot of PI / fine fraction (<%425μm) versus liquid limit of the samples.

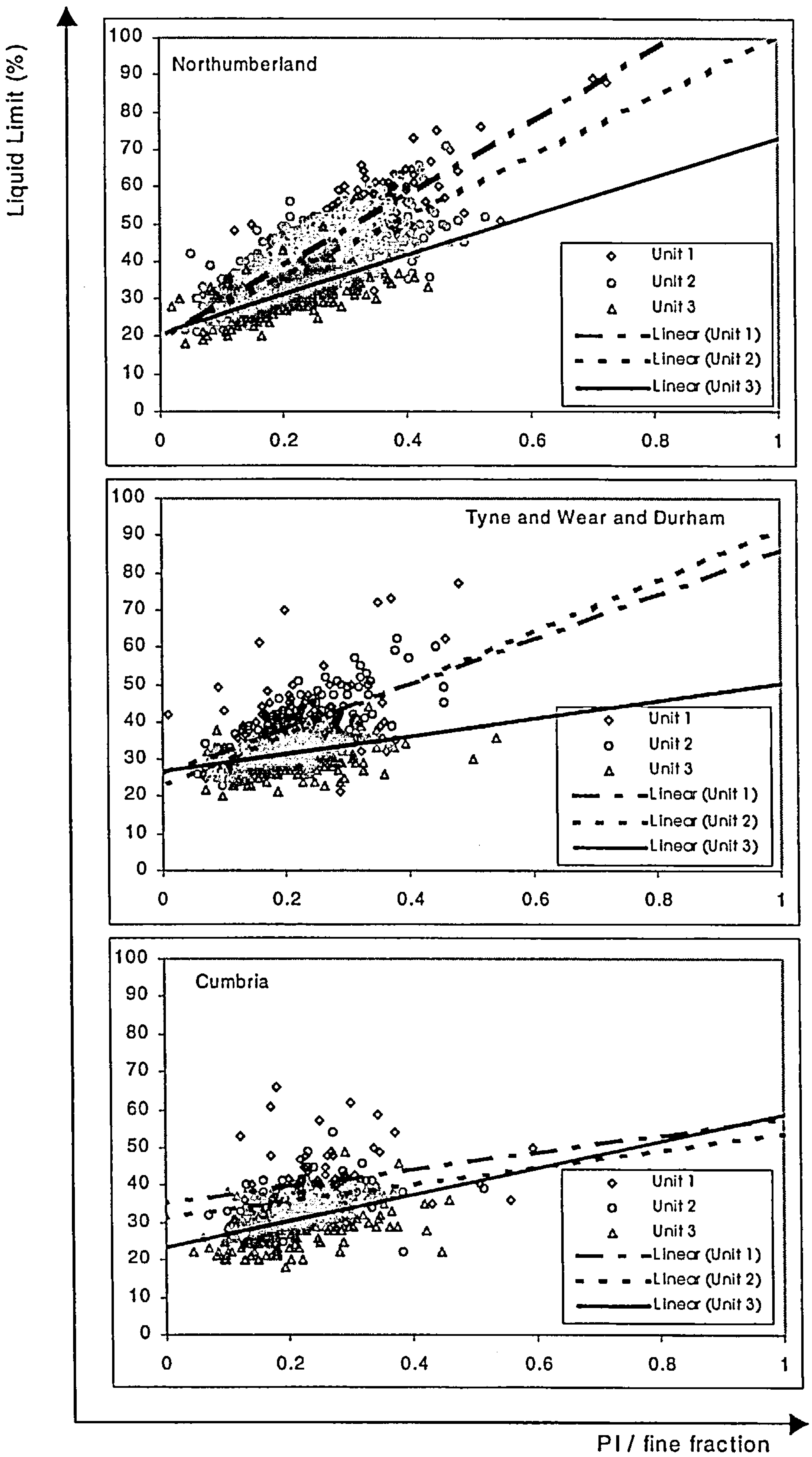


Figure 6.2: Plot of PI/fine fraction versus liquid limit.

It can be seen that the plots are different in the three areas, and Units 1 and 2 show a more similar trend compared to Unit 3. These suggest that the material of Unit 3 in any of the areas is different from the other two units which could have a similar source. It has also been suggested that a linear relationship between plasticity index and clay size exists (Skempton, 1953). This relationship is shown in Figure 6.3.

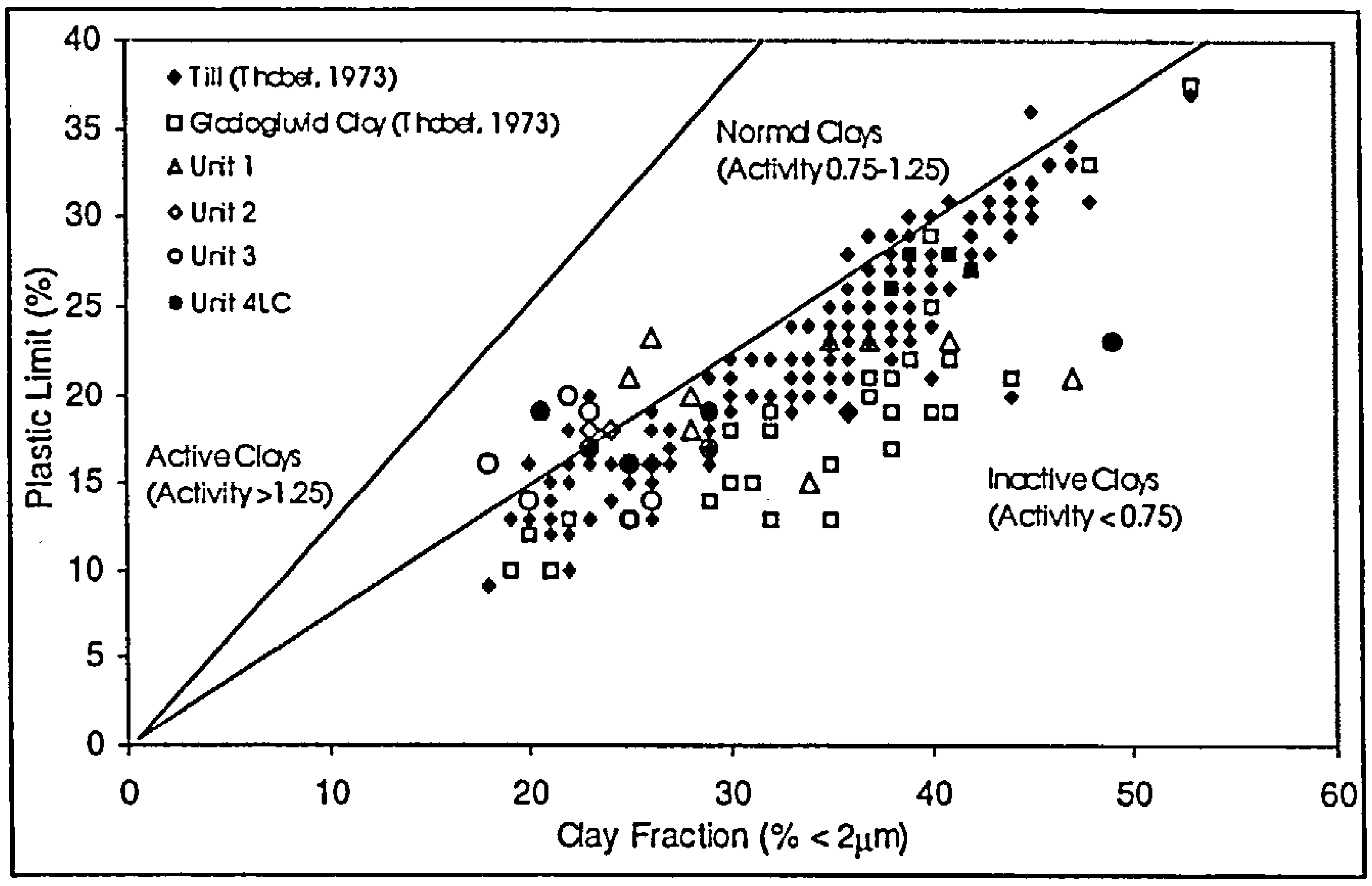


Figure 6.3: Relationship between plastic limit and clay fraction for glacial clays.

It should be noted that the data represented in Figures 6.1 and 6.3 are based on the clay fraction, whereas the results shown in Figure 6.2 are based on the fine fraction. The results represented in chapter 5 are also based on the fine fraction and show that all samples are inactive whereas the above figure suggests that some of the samples are normally active. Although the data are scattered but it can be seen that most data lie within or close to the range of inactive clays. It is suggested that soil samples that fall on one line in the activity chart, as shown in Figure 6.3, have clay fractions which contain similar assemblage of minerals (Seed et al, 1964 a and b).

6.3 Correlations between shear strength and other soil properties

Several relationships have been suggested for correlating undrained shear strength with various other soil parameters. The benefit of establishing such relationships lies in the ability to use them for predicting sensible minimum values of undrained shear strength given only basic soil index properties.

6.3.1 Relationship between undrained shear strength, moisture content and density

As already mentioned in the previous chapter the undrained shear strength of a clay till is a function of water content and an increase in water content corresponds to a decrease in shear strength. It has been suggested that in a consolidated undrained shear strength test on normally consolidated and overconsolidated samples, a linear relationship between the shear strength and the final water content exists (Henkel, 1959). This pattern has also been confirmed by Bjerrum (1954) who investigated this relationship for both undisturbed and remoulded samples. The existence of a linear relationship between the undrained shear strength and natural water content of glacial tills was also established for samples taken during the construction of the Kielder Dam on the River North of Tyne which is shown in Figure 6.4.

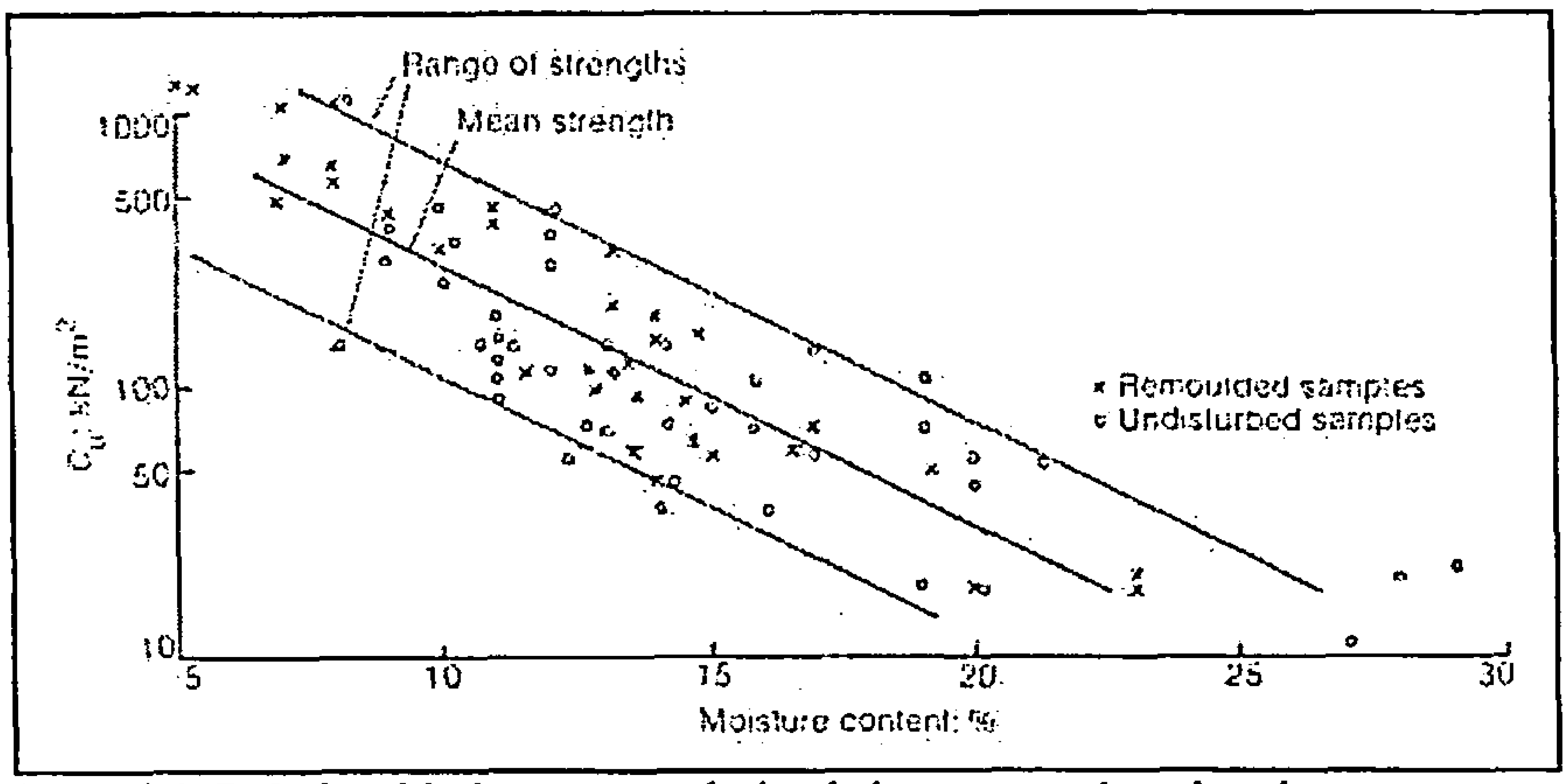


Figure 6.4: Relationship between undrained shear strength and moisture content. (after Millmore and McNicol, 1983)

The undrained shear strength is plotted against the natural moisture content in Figure 6.5 for all available data from the database. Although the data show a large scatter a trend of increasing shear strength with decreasing water content can be observed. The scatter in the data is either because of the variation in the samples or due to the presence of discontinuities and inclusions in the specimen or because of sample disturbance. It should be noted that the greater the strength of the tills the greater the disturbance because of the use of driven thick walled tubes for sampling.

The influence of bulk density on the undrained shear strength is investigated in Figure 6.6. In order to reduce the scatter in the above mentioned figures, the data were plotted separately for some of the sites in Northumberland where enough data were present. The trendline for each of the sites was established as shown in Figures 6.7 and 6.8. The values relevant to each of these lines is shown in Table 6.2.

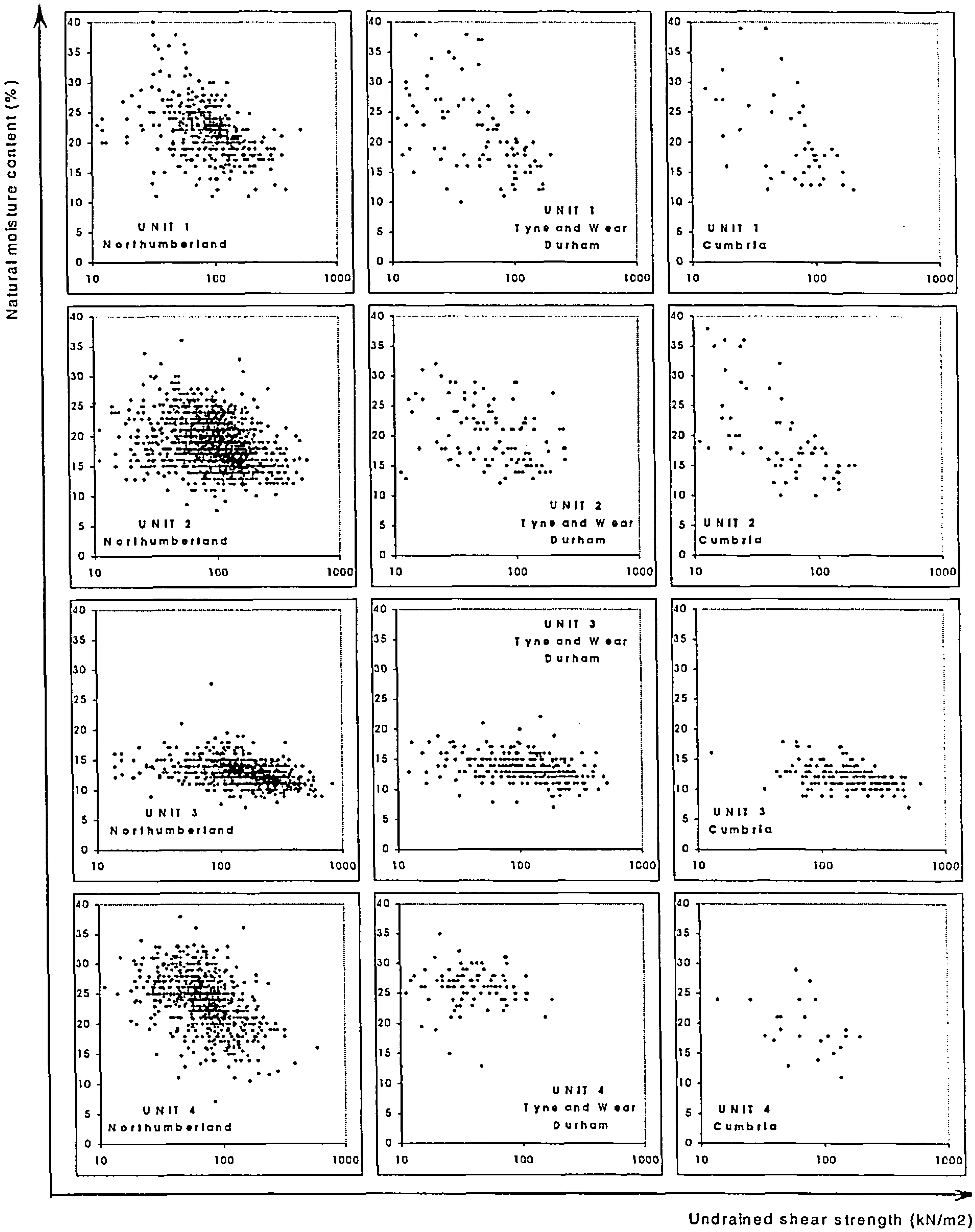


Figure 6.5: The relationship between Natural Moisture content and undrained shear strength in Northern England glacial deposits

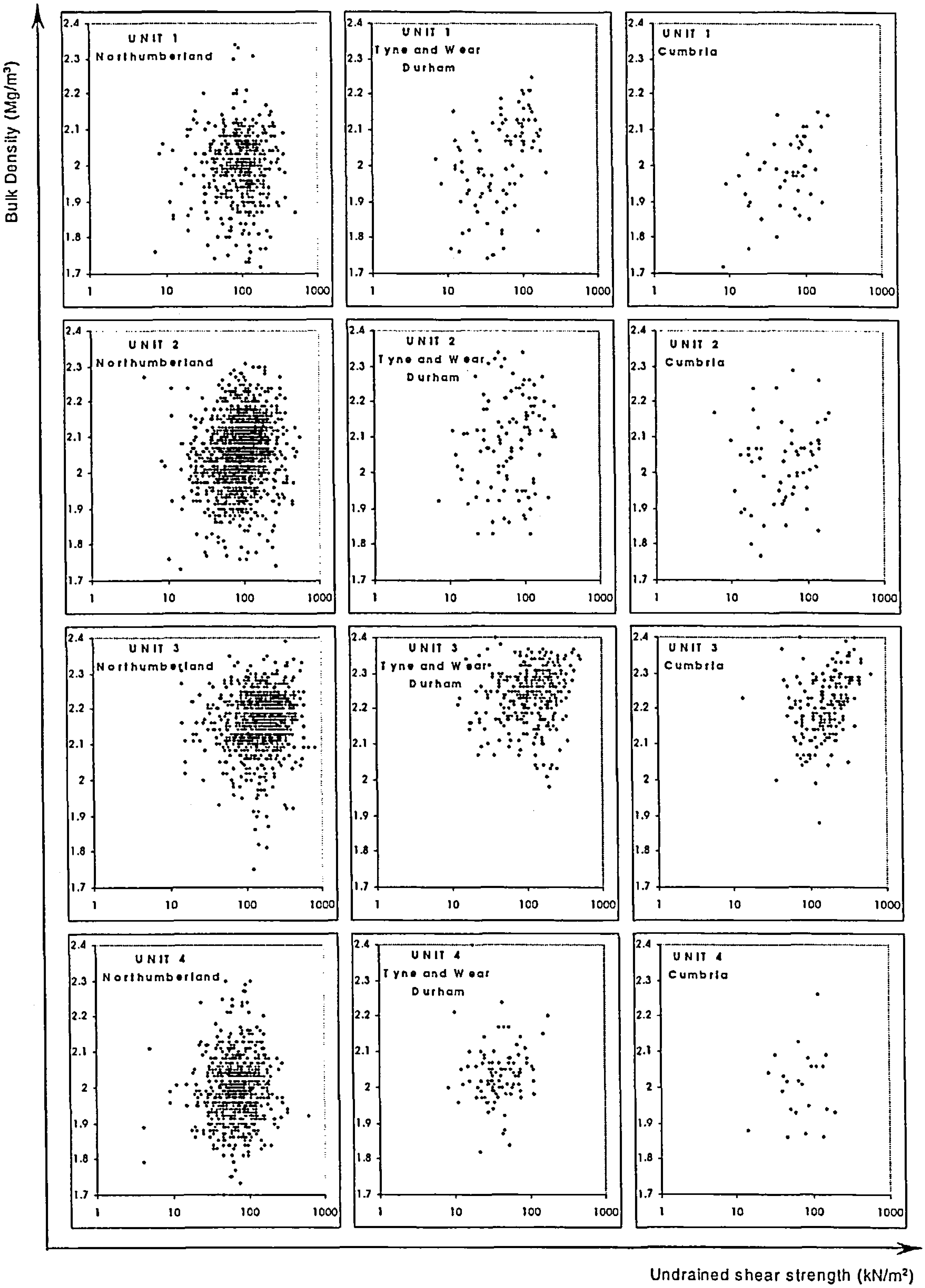


Figure 6.6: Relationship between bulk density and undrained shear strength.

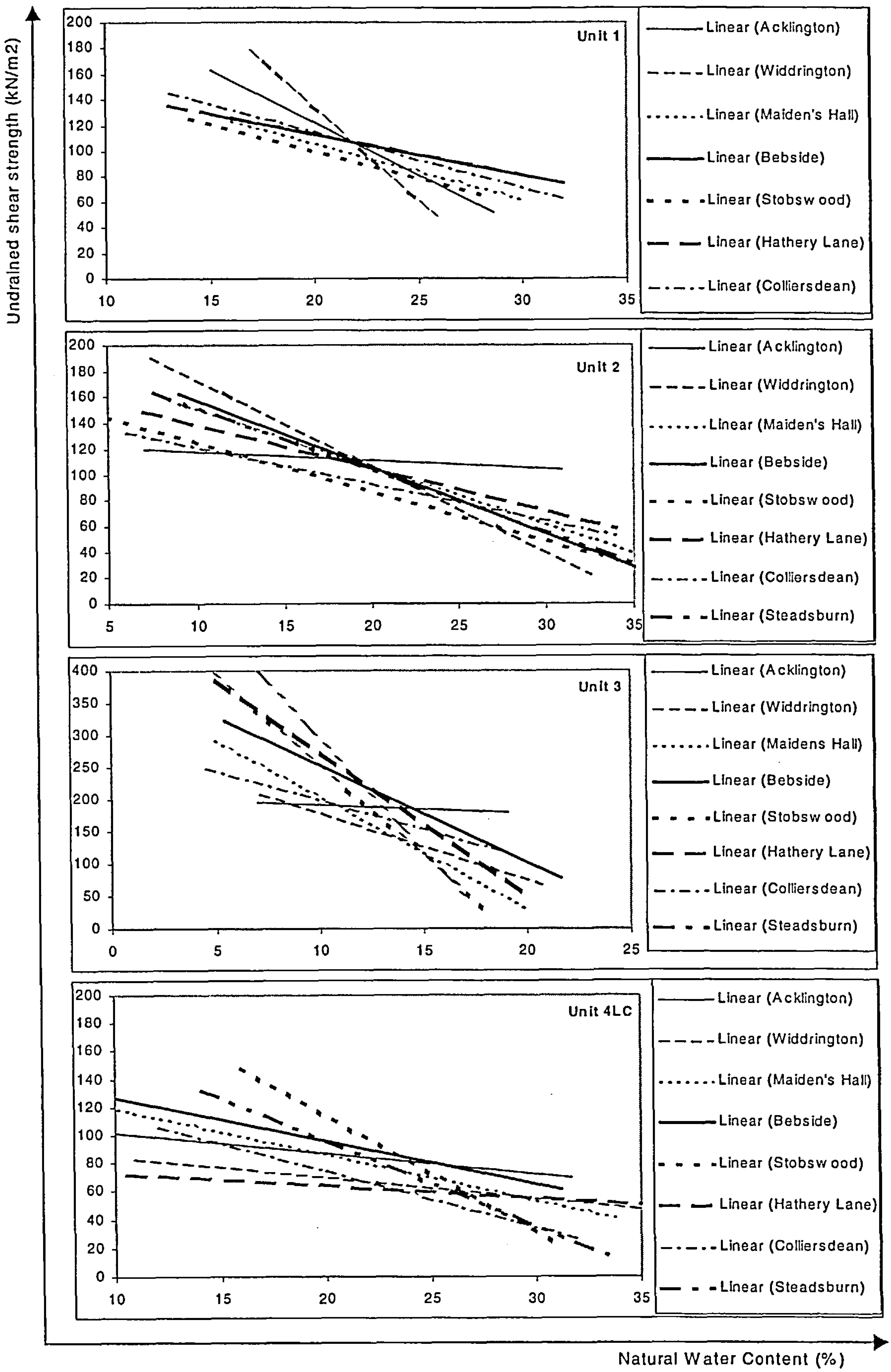


Figure 6.7: Site specific relationships between the undrained shear strength and the natural water content.

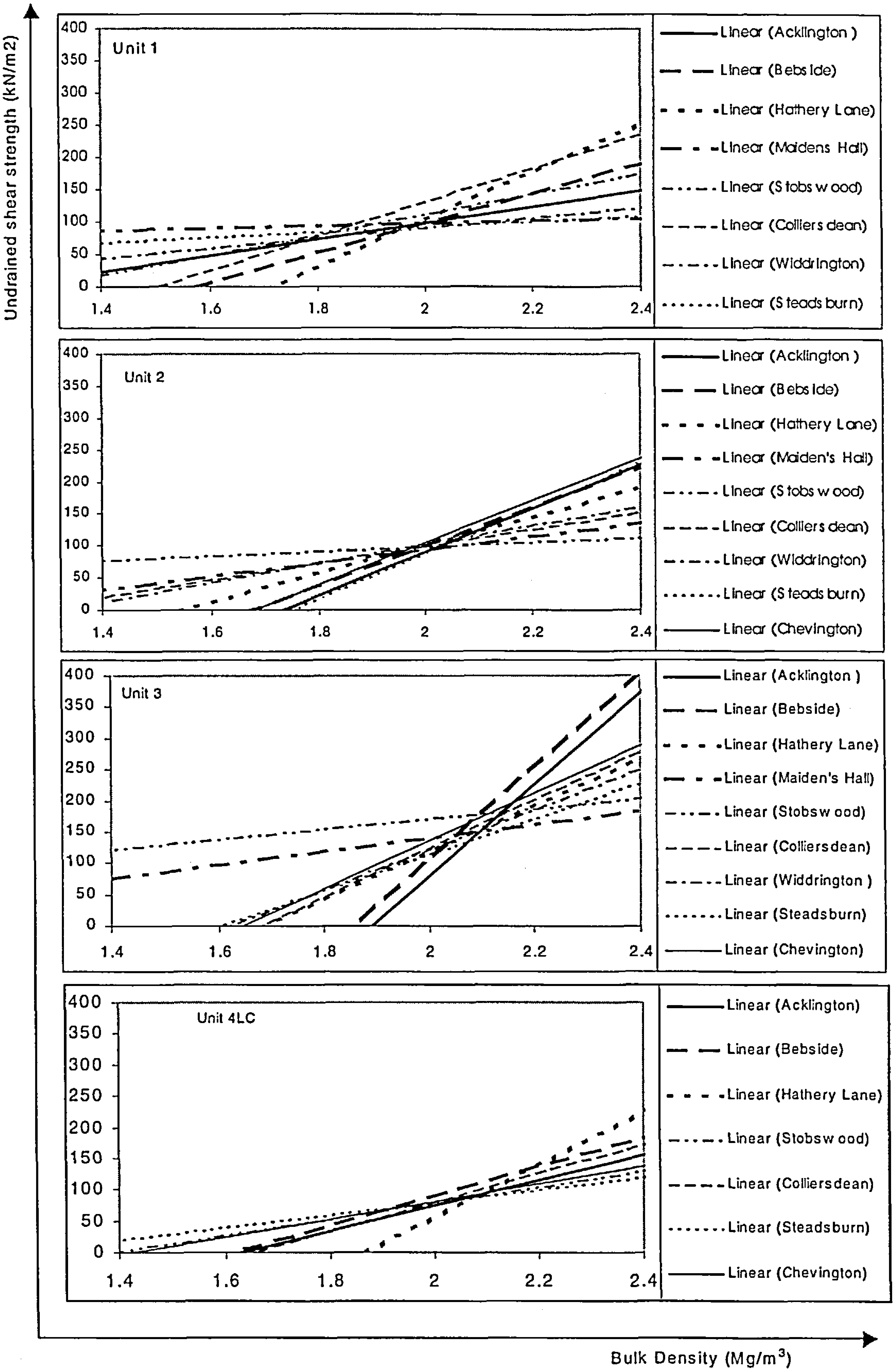


Figure 6.8: Relationship between the undrained shear strength and bulk density.

Table 6.2: Trendline information for relationships between c_u and w, and c_u and ρ.

		$c_u = m.w + c$			$c_u = m.\rho + c$		
Site	Unit	R^2	m	c	R^2	m	c
Acklington	1	0.3401	-8.1906	285.9	0.0561	124.42	-151.19
	2	0.0026	-0.6787	124.36	0.1412	340.04	-589.16
	3	0.0014	-1.1706	202.53	0.1661	733.5	-1388
	4	0.0613	-1.4995	116.9	0.2141	202.57	-330.36
Bebside	1	0.0778	-3.1507	175.64	0.148	229.41	-361.2
	2	0.3842	-5.5657	217.17	0.2276	307.08	-515
	3	0.2192	15.16	404.42	0.2132	744.85	-1383.9
	4	0.1924	-3.0739	157.17	0.195	235.06	-380.11
Stobswood	1	0.1221	-4.2873	185.59	0.0567	155.94	-200.18
	2	0.0366	-3.8459	163.75	0.002	36.993	24.851
	3	0.3103	-29.233	537.05	0.0021	81.305	9.2959
	4	0.1201	-8.309	280.73	0.0619	128.4	-177.12
Maidens hall	1	0.1962	-4.4754	195.81	0.0021	19.79	57.618
	2	0.1101	-3.4576	162.05	0.0306	104.27	-116.3
	3	0.1154	-17.493	379.85	0.0089	108.02	-75.916
	4	0.2033	-3.4189	155.28	-	-	-
Steadsburn	1	-	-	-	0.001	39.598	13.667
	2	0.1765	-4.8441	200.7	0.3191	353.47	-618.41
	3	0.5257	-34.518	636.83	0.0135	287.37	-460.68
	4	0.1185	-4.5087	171.48	0.0606	101.04	-121.4
Hathery lane	1	0.0525	-3.1717	176.99	0.1996	370.05	-636.36
	2	0.0649	-3.513	175.31	0.0634	223.23	-345.51
	3	0.1095	-22.388	497.54	0.0437	376.18	-635.74
	4	0.0793	-0.8723	80.957	0.5303	423.91	-791.72
Colliersdean	1	0.1459	-4.3303	201.88	0.1685	263.82	-395.78
	2	0.0624	-2.8797	150.87	0.0358	131.6	-164.41
	3	0.0853	-10.084	296.2	0.0553	387.7	-650.85
	4	0.1469	-3.9801	154.14	0.3452	231.61	-382.44
Chevington burn	1	-	-	-	-	-	-
	2	-	-	-	0.3967	329.65	-554.19
	3	-	-	-	0.0803	382.34	-629.1
	4	-	-	-	0.152	141.41	-200.97
Widdrington	1	0.4962	-14.82	430.1	0.0852	77.201	-63.06
	2	0.1339	-6.6856	240.84	0.0361	149.23	-196.48
	3	0.1179	-10.297	281.81	0.0479	321.85	-521.77
	4	0.0098	-1.4544	99.614	-	-	-

The scatter was reduced by considering each site separately, and the trendlines follow similar patterns. However, the correlation coefficient R^2 for each of the trendlines is very different from one site (or unit) to another. This indicates the extreme variability of the conditions and the properties of the soils in different locations.

6.3.2 The relationship between undrained shear strength and liquidity Index

As pointed out earlier the water content is an important parameter in controlling the shear strength of a soil. At a given effective stress, if the water content decreases the liquidity index will also decrease. Hence when the liquidity index is plotted against the logarithm of undrained shear strength a similar pattern is obtained as in the relationship between the undrained shear strength and water content. Research was carried out in order to find the relationship between the undrained shear strength of remoulded clay with its liquidity index (Skempton and Northy, 1952; and Wroth and Wood, 1978). Figure 6.9 shows the relationship between liquidity index and undrained shear strength. Further research has shown that test results from lodgement till also follow the same pattern (Sladen and Wrigley, 1983). Lodgement tills are often taken to be insensitive (sensitivity is the ratio of undisturbed to remoulded shear strength) or of low sensitivity, so close correlations between undrained shear strength and liquidity index are usually expected.

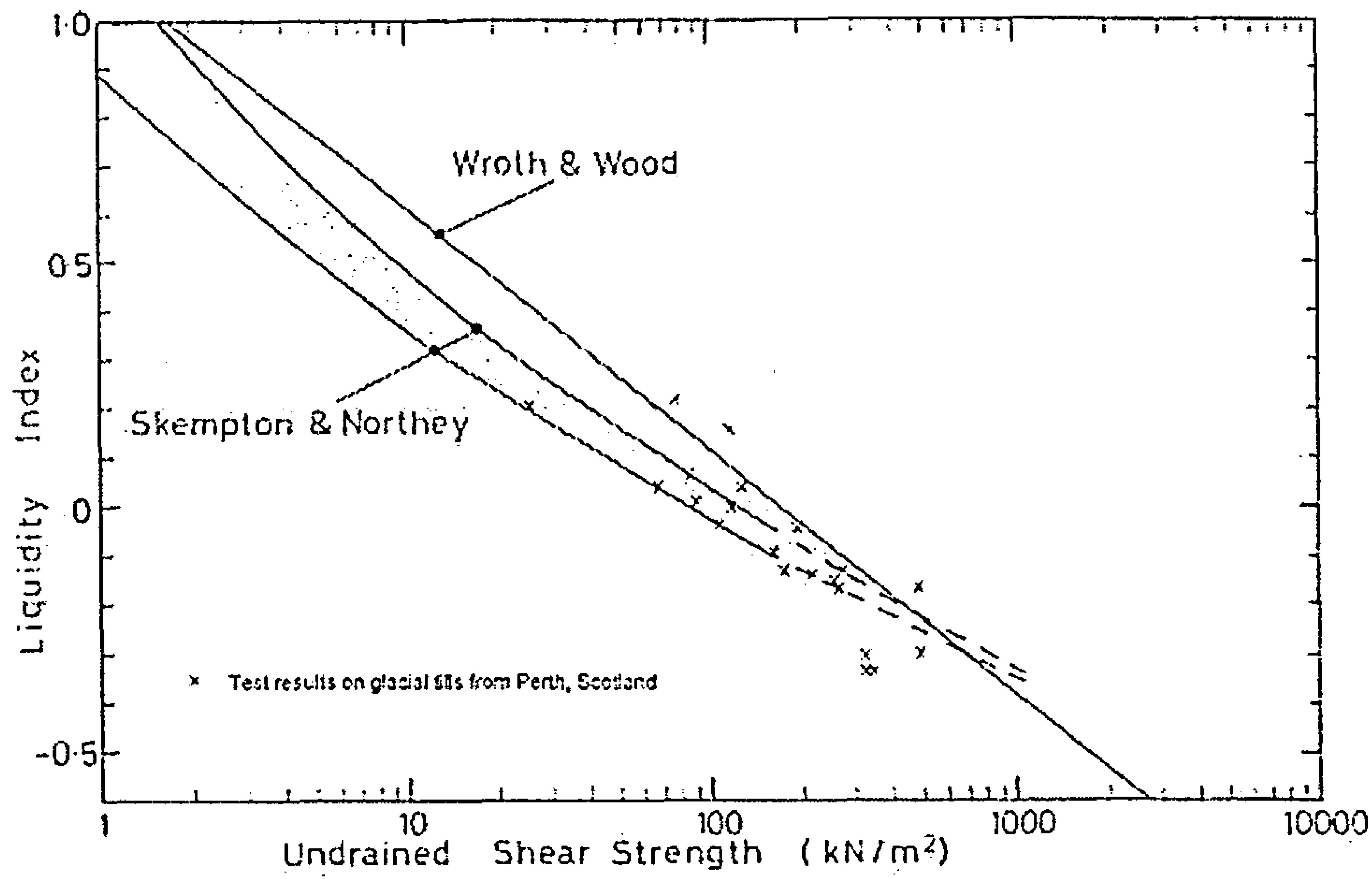


Figure 6.9: Relationship between liquidity index and undrained shear strength (after Skempton and Northy, 1952; Wroth and Wood, 1978; and Sladen and Wrigley, 1983)

Using the data from the database the liquidity index is plotted against the undrained shear strength of the tills in North of England. Figure 6.10 also shows the linear relationship suggested by Wroth and Wood (1978).

As it can be seen in Figure 6.10 the data show a large scatter, similar to the relationship between natural water content and undrained shear strength (Figure 6.5). However they lie close to the suggested line and follow the same trend which is the decreasing value of undrained shear strength with the increasing value of liquidity index. It has been suggested that the scatter in the plot of liquidity index against undrained shear strength could be attributed to errors in the determination of liquidity index which is sensitive to errors in the measurements of liquid and plastic limits (Sladen and Wrigley, 1983).

It is found that for normally consolidated clays, undrained shear strength is proportional to effective overburden pressure. This is because in terms of effective stress, shear strength is a frictional phenomenon and depends on the confining pressure. If the constant of proportionality between shear strength and effective overburden pressure is known then shear strength can be inferred from effective overburden pressure, which depends on the depth. It is suggested that the ratio of undrained shear strength to effective overburden pressure depends on the liquid limit or plasticity index of the clay (Skempton, 1948). In general the higher the liquid limit the greater the ratio of undrained shear strength to effective overburden pressure. Figure 6.11 explores the relationship between this ratio and the liquidity index. It is expected that this relationship should be similar for Unit 1 and 2 because of the similar source of material. It can be seen however that although most trendlines for the sites in each unit are similar and parallel, the two units show different trends. This could be due to the effect of weathering.

In order to reduce the scatter in Figures 6.10 and 6.11, the data were divided into smaller groups based on the locations. Trendlines for a number of locations in Northumberland were produced for each site and are shown in Figures 6.12 and 6.13. Table 6.3 shows the relevant information to each of the lines shown in these figures.

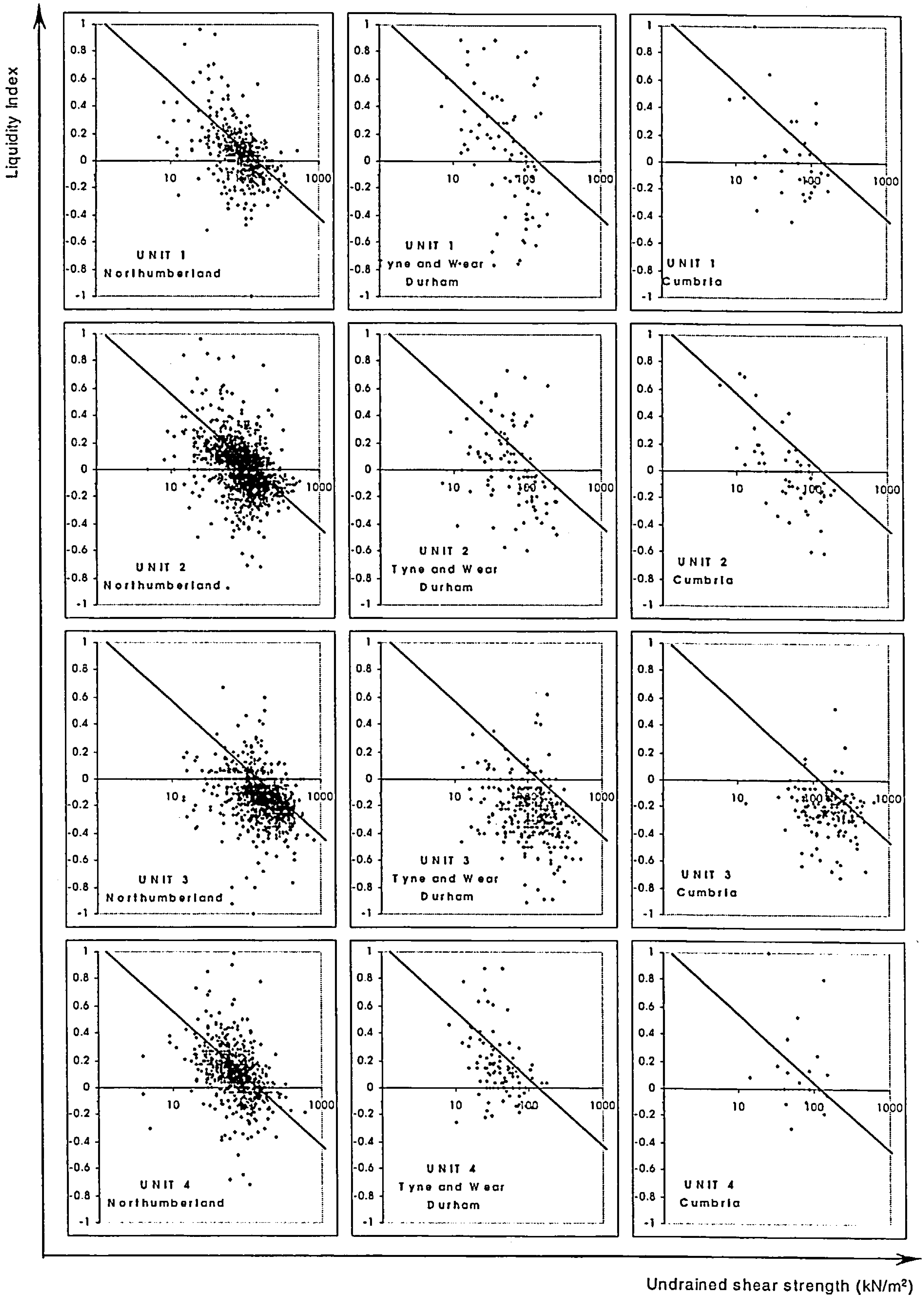


Figure 6.10: Relationship between liquidity index and undrained shear strength in Northern England glacial tills
Line shows suggested relationship by Wroth and Wood, 1978.

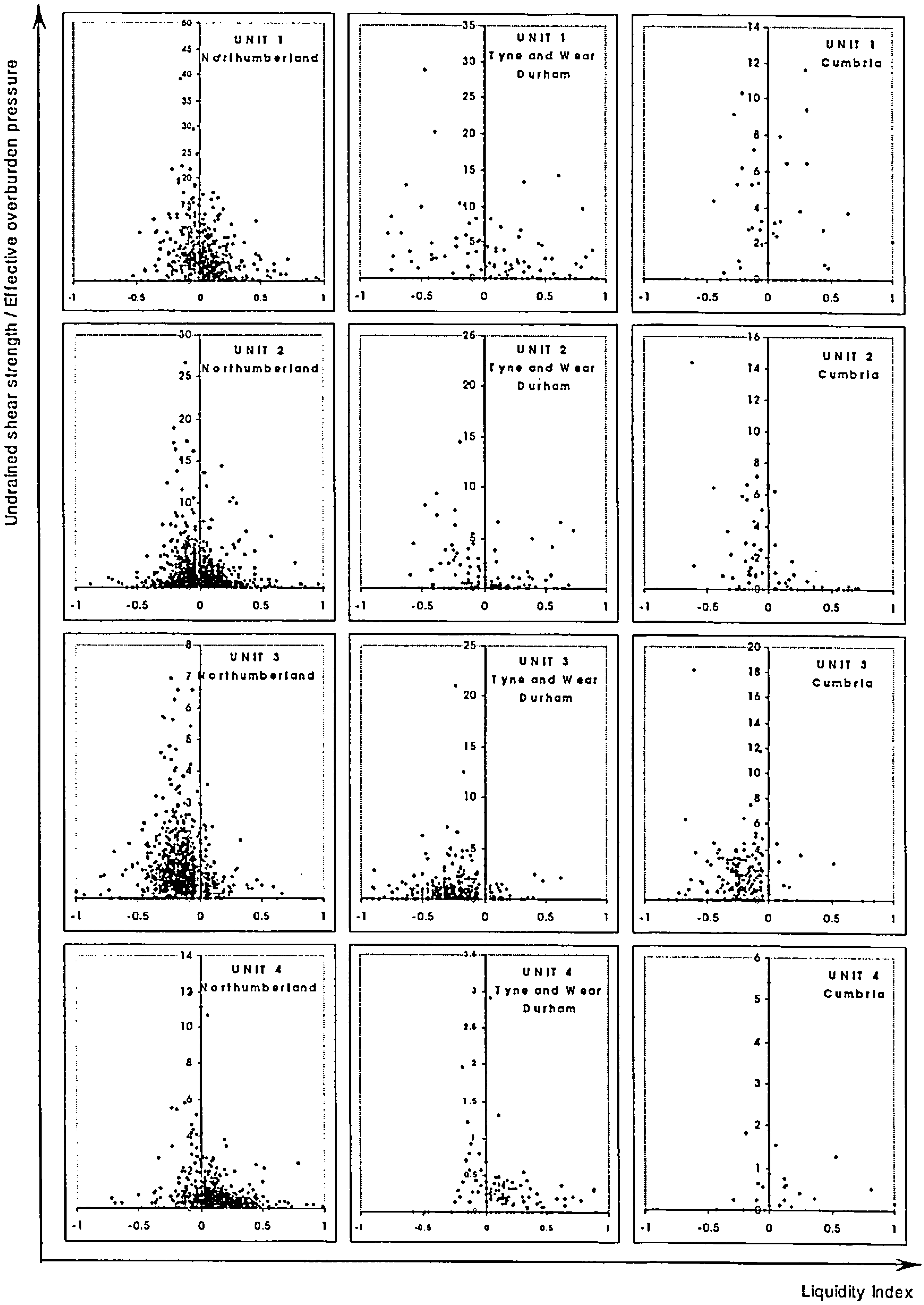


Figure 6.11: Plot of Liquidity Index versus the ratio of undrained shear strength / effective overburden pressure.

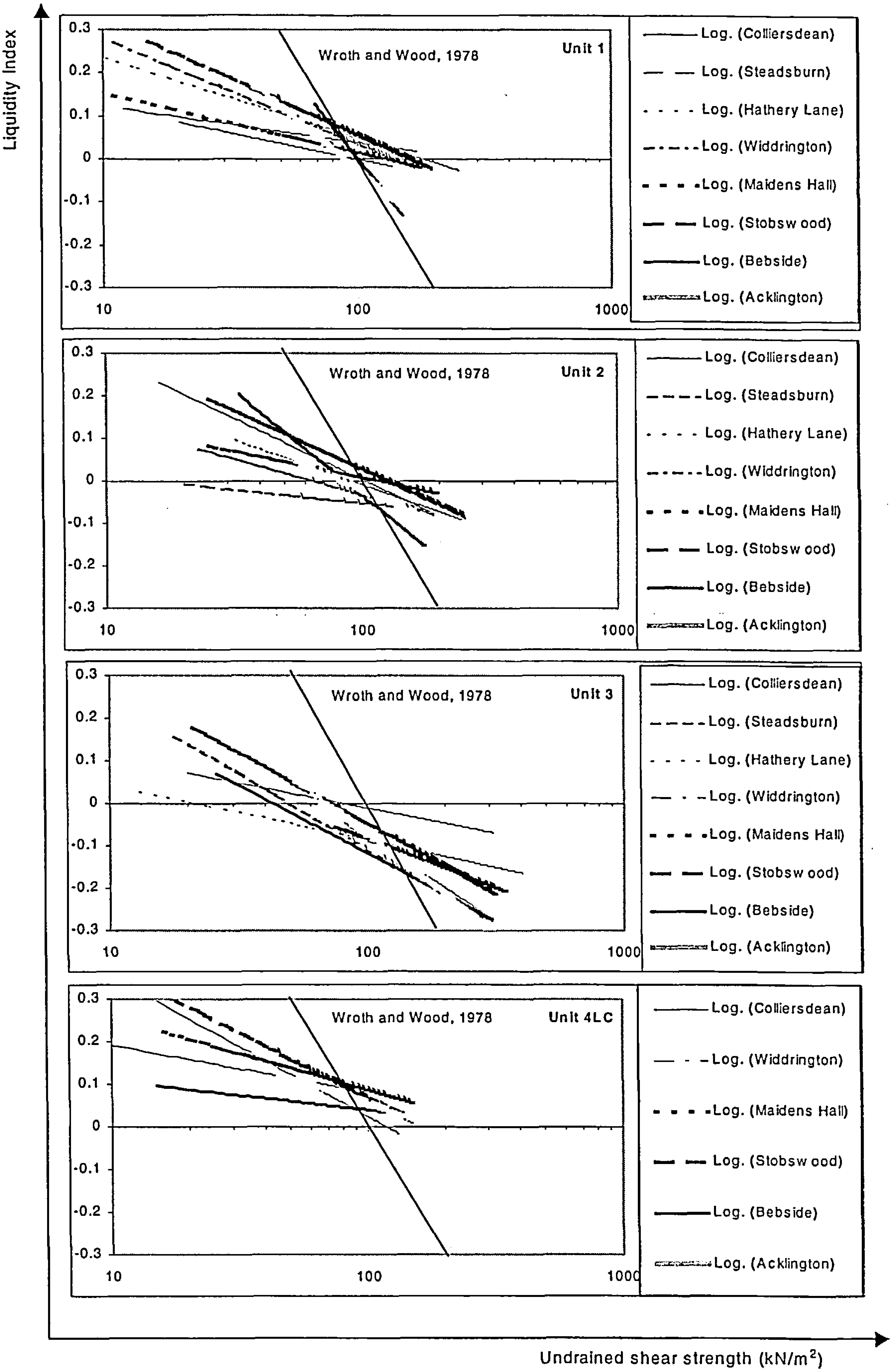


Figure 6.12: Relationships between liquidity index and undrained shear strength for each site in Northumberland

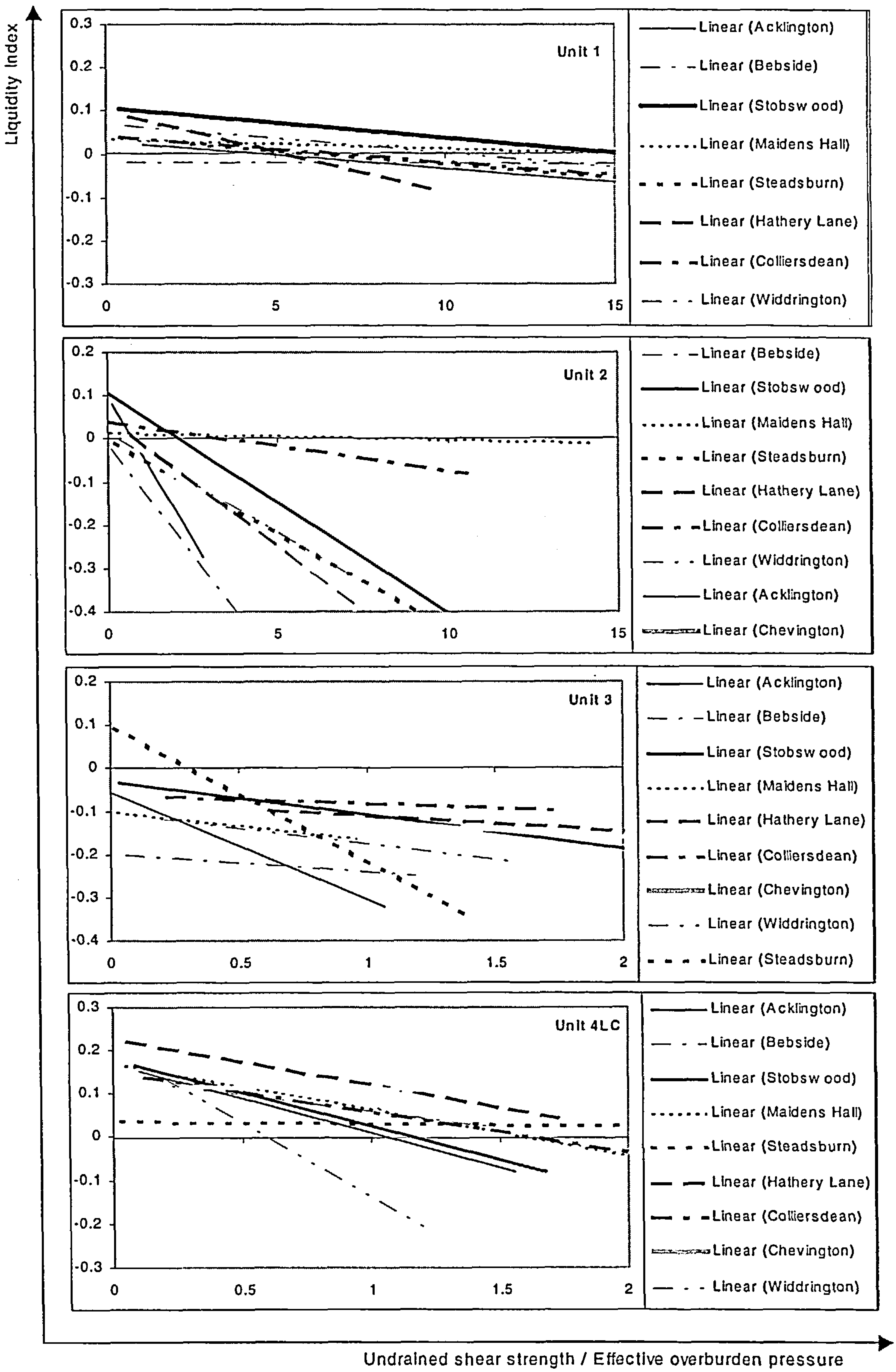


Figure 6.13: Relationship between the undrained shear strength/Effective overburden pressure ratio and Liquidity Index for sites in Northumberland.

Table 6.3: Trendline information for relationships between c_u and LI, and c_u/σ'_v and LI.

		$c_u = m.\ln(LI) + c$			$c_u/\sigma'_v = m.LI + c$		
Site	Unit	R^2	m	c	R^2	m	c
Acklington	1	0.3485	0.2115	0.9471	0.0528	-0.0062	0.0288
	2	0.052	0.1143	0.5059	0.2366	-0.1347	0.1
	3	0.1957	-0.2049	0.8698	0.1911	-0.2495	0.0549
	4	0.0337	-0.0906	0.4716	0.0736	-0.3652	0.4646
Bebside	1	0.2158	-0.3219	1.4842	0.007	-0.0004	-0.0173
	2	0.2345	-0.2129	0.9462	0.0363	-0.1022	-0.0151
	3	0.1019	-0.1396	0.5254	0.0121	-0.0427	-0.1979
	4	0.0027	-0.0301	0.1776	0.0904	-0.0759	0.1355
Stobswood	1	0.18	-0.1149	0.5849	0.0755	-0.0069	0.1065
	2	0.3696	-0.1197	0.5794	0.1175	-0.0512	0.1069
	3	0.4105	-0.1453	0.6229	0.1244	-0.0792	-0.0297
	4	0.179	-0.135	0.6876	0.1865	-0.155	0.1805
Maidens hall	1	0.02	-0.0598	0.2899	0.0066	-0.0021	0.0357
	2	0.0235	-0.0539	0.256	0.008	-0.0017	0.0135
	3	0.0871	-0.1004	0.3798	0.0095	-0.0669	-0.0987
	4	0.0603	-0.0756	0.4338	0.0613	-0.1063	0.17
Steadsburn	1	0.0481	-0.0527	0.2419	0.0446	-0.006	0.0377
	2	0.0151	-0.0278	0.0767	0.0363	-0.0443	0.0124
	3	0.4734	-0.1555	0.6091	0.0191	-0.3185	0.1
	4	-	-	-	0.001	-0.0058	0.0368
Hathery lane	1	0.291	-0.0812	0.4223	0.0479	-0.019	0.1014
	2	0.2092	-0.0913	0.4113	0.0466	-0.061	0.0531
	3	0.1059	-0.0562	0.1735	0.0444	-0.0356	-0.0748
	4	-	-	-	0.1603	-0.1052	0.2266
Colliersdean	1	0.1488	-0.0368	0.2067	0.1463	-0.0061	0.0411
	2	0.233	-0.1241	0.5758	0.0044	-0.0113	0.0392
	3	0.1593	-0.0509	0.2247	0.018	-0.022	-0.061
	4	0.4511	-0.1433	0.6831	0.0188	-0.0934	0.1521
Chevington burn	1	-	-	-	-	-	-
	2	-	-	-	0.0494	-0.0611	0.0405
	3	-	-	-	0.0049	-0.0324	-0.0941
	4	-	-	-	0.0004	-0.0078	0.1201
Widdrington	1	0.1433	-0.1071	0.5287	0.0377	-0.0067	0.071
	2	0.0371	-0.0739	0.309	0.0211	-0.0462	0.0142
	3	0.0841	-0.1682	0.6933	0.0387	-0.0712	-0.1053
	4	0.0623	-0.0482	0.3029	0.3808	-0.3411	0.2025

6.4 The relationship between drained strength and plastic index

The strength of saturated soil in terms of effective stress is usually described by means of Mohr-Coulomb failure criteria. Effective stress parameters can be obtained either from drained shear box or triaxial tests or from consolidated undrained triaxial tests with pore pressure measurements.

Research has shown that the peak angle of friction tends to decrease with increasing plasticity. (Gibson, 1953, Terzaghi and Peck, 1967). The existence of these relationships arises because both plasticity index and shear strength reflect the clay mineral composition of the soil. As the clay mineral content increases, plasticity increases and shear strength decreases.

Figure 6.14 shows the trendlines suggested by Terzaghi and Peck (1967), for undisturbed clay samples, and Vaughan and Walbancke (1975), for samples of lodgement till, in addition to the results of some other research carried out on Glacial tills.

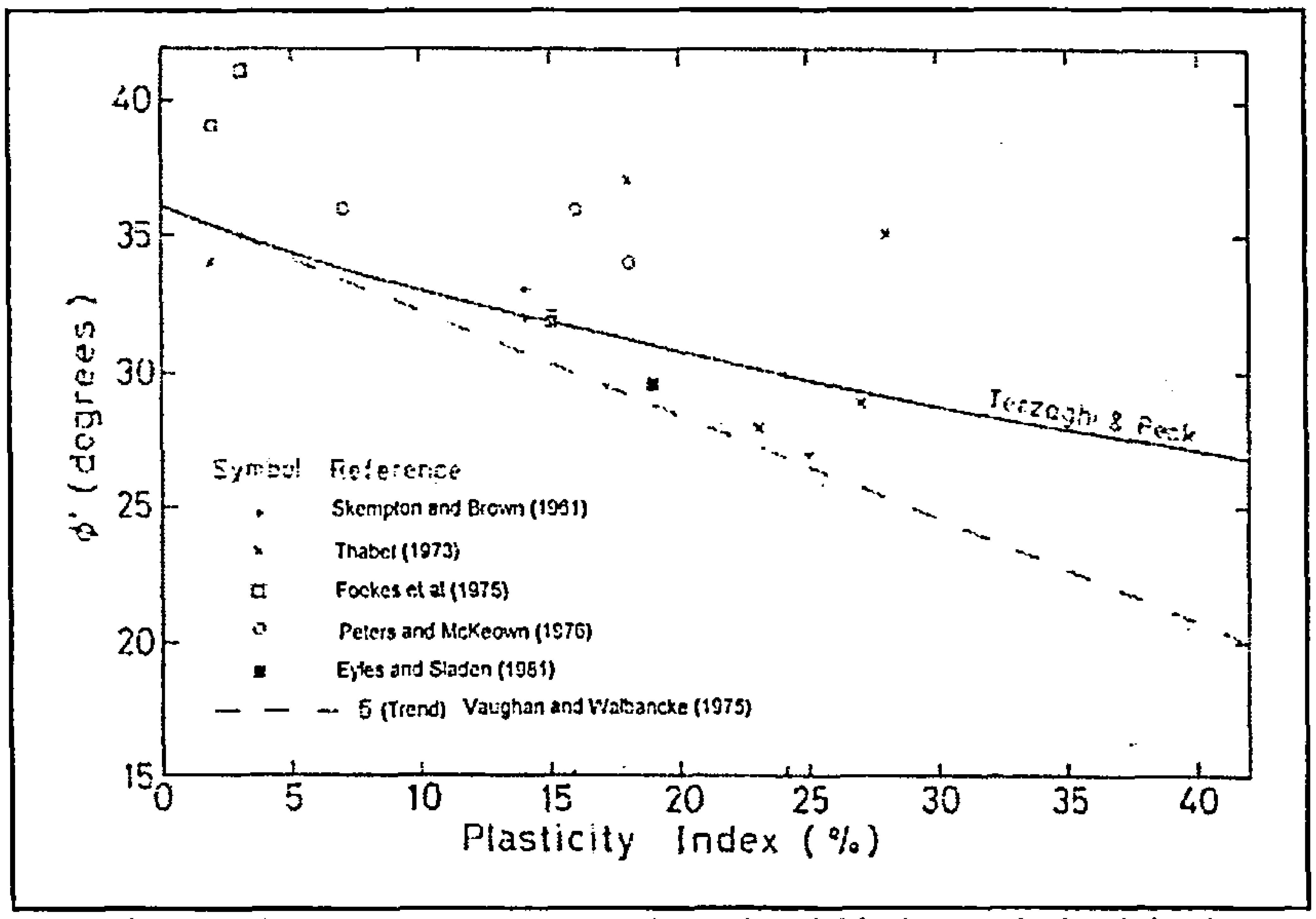


Figure 6.14: Relationship between peak angle of friction and plasticity index (taken from Sladen and Wrigley, 1983)

A similar trend can be seen in Figure 6.15 where the results of drained triaxial tests, stored in NETDATA, are plotted against their plasticity index. It can be seen that the majority of these results lie between or close to the two suggested trendlines as shown in Figure 6.14. This confirms the existence of a relationship between the two parameters. However, since the peak strength of a soil will be influenced by any structure the soil may contain and its density prior to shearing, neither of which are reflected in the plasticity index, such a correlation should be used with care (Sladen and Wrigley, 1983).

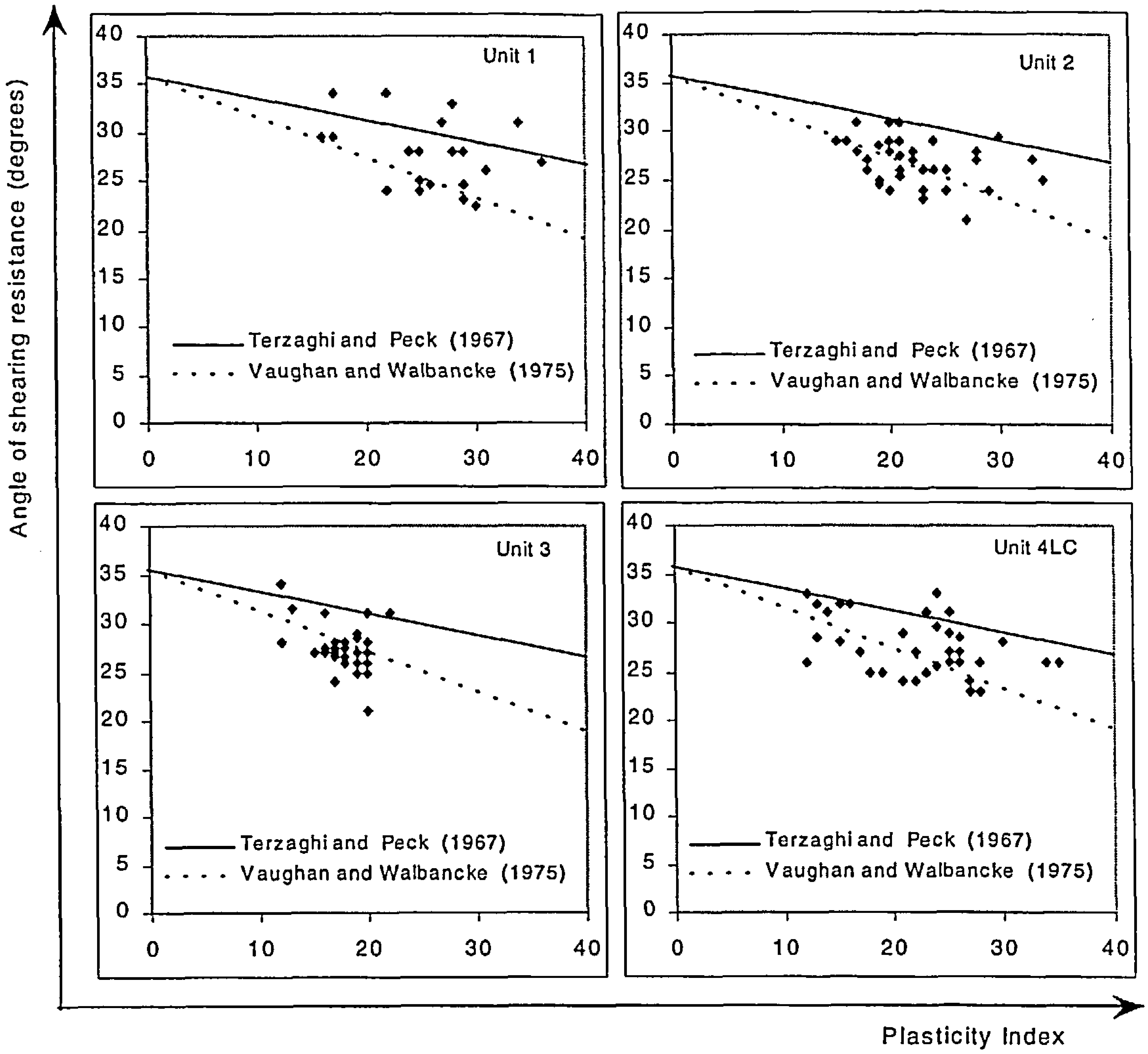


Figure 6.15: Relationship between the peak angle of shearing resistance derived from drained triaxial tests and plasticity index for Northumberland glacial Units

The residual strength of a homogeneous soil is independent of structure and density prior to shearing (Bishop et al, 1971) and dependent on grading and mineralogy (Kenny, 1967). Both grading and mineralogy are reflected in the plasticity index and therefore a correlation between PI and the Residual Angle of Friction (RPHI) can be expected for soils of similar geological origin (Voight, 1973). Figure 6.16 shows published values of residual shear strength for lodgement tills plotted against plasticity index. It can be seen that that the residual strength of the soils decreases at a plasticity index of about 20% to 25%. It has been suggested that this decrease of residual strength is the result of different modes of shear (Lupini et al, 1981). Low plasticity soils behave essentially as granular material in which the residual strength is high and brittleness is low, mainly due to dilation in the failure zone within which no preferred particle orientation occurs. Soils with higher plasticity index have a low strength shear surface of strongly oriented platy particles which results in drained brittleness (Sladen and Wrigley, 1983).

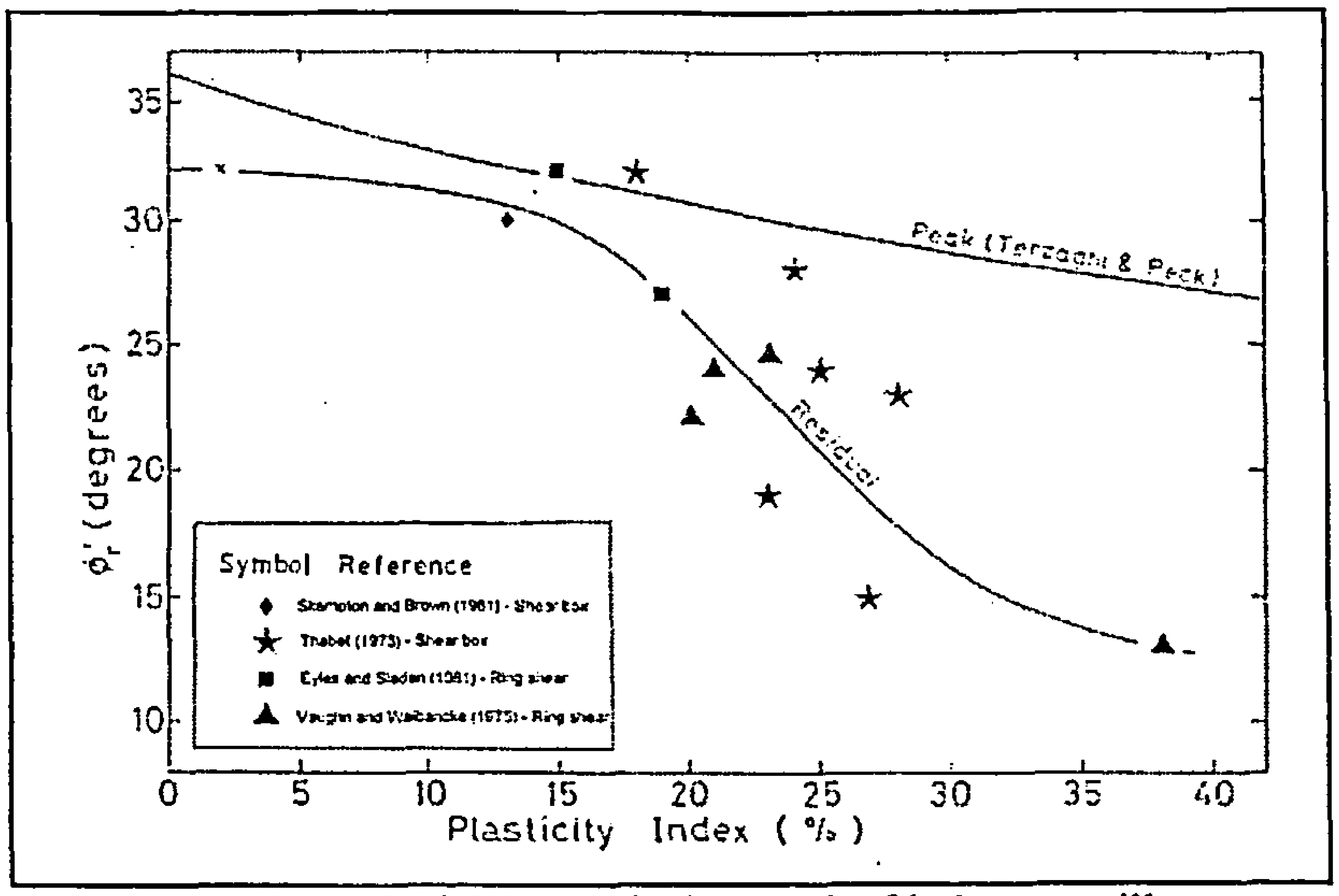


Figure 6.16: The residual strength of lodgement tills
(taken from Sladen Wrigley, 1983).

Figure 6.17 shows the peak and residual angle of friction of various samples from Northumberland stored in NETDATA, derived from shear box tests, plotted against their plasticity index.

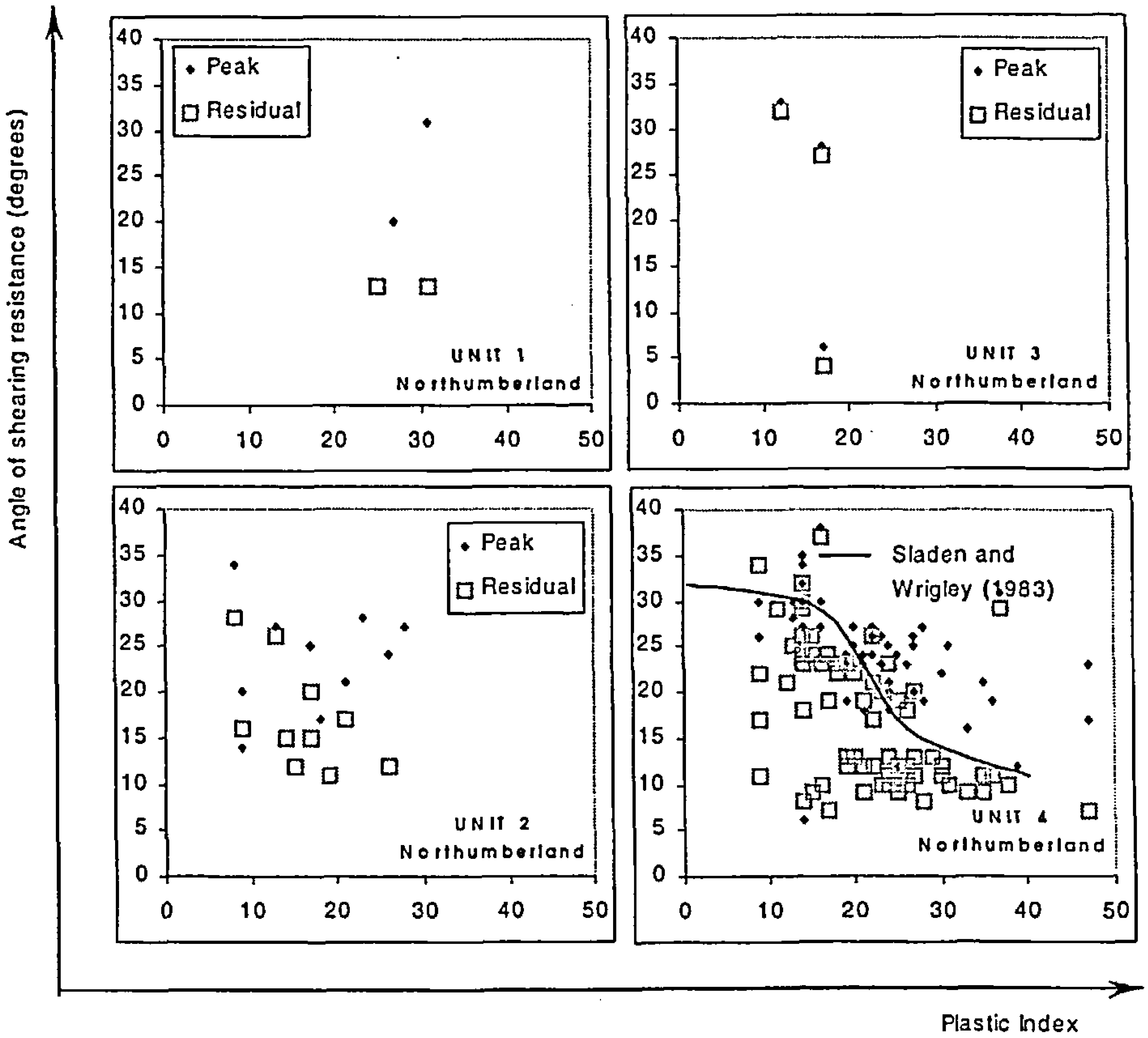


Figure 6.17: Peak and residual angle of friction derived from shear box tests plotted against plasticity index for glacial tills in Northumberland.

Research has shown that the cohesion of lodgement till decreases with increasing angle of shearing resistance (Thorburn and Reid, 1973). This may be the result of the fact that the Mohr-Coulomb line is curved. Each set of triaxial tests used to produce values of c' and φ' are interpreted as a linear relationship dependant on c' and φ'. As the confining pressure increases c' will increase and φ' will reduce. Figure 6.18 shows this relationship together with results of other research on glacial tills.

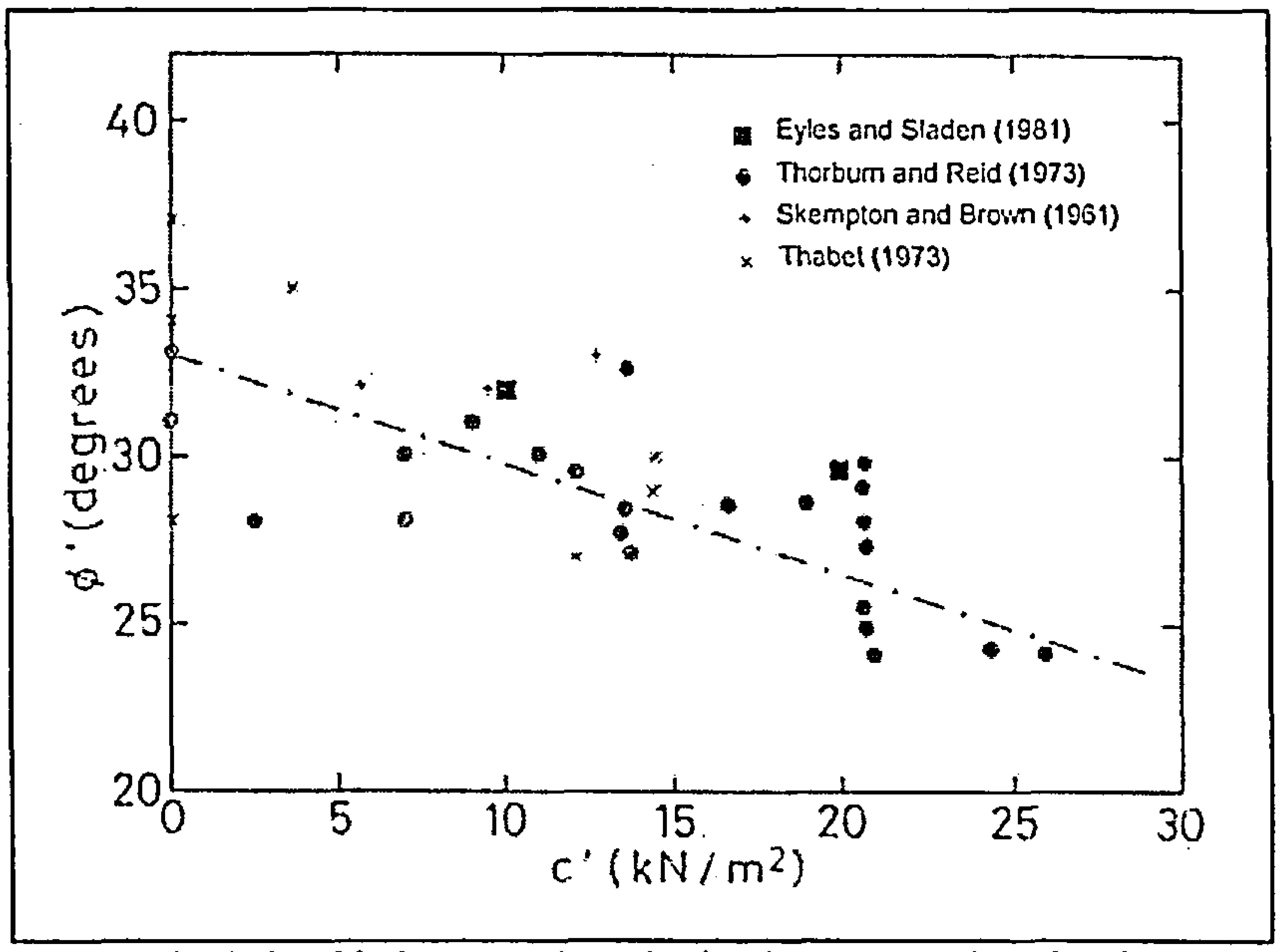


Figure 6.18: Suggested relationship between the cohesion intercept and angle of shearing resistance.

Figure 6.19 shows the peak strength results of drained triaxial tests along with the relationship suggested by Thorburn and Reid (1973). As it can be seen the data from all units are rather scattered and do not lie close to the suggested line. The quality of the data depends on the quality of the samples, the sample structure and content, and also the testing procedure. Therefore the variation in the values of c' and φ' could be dominated by these facts. Therefore these values should be treated with caution. This is clearly shown in Figure 6.19.

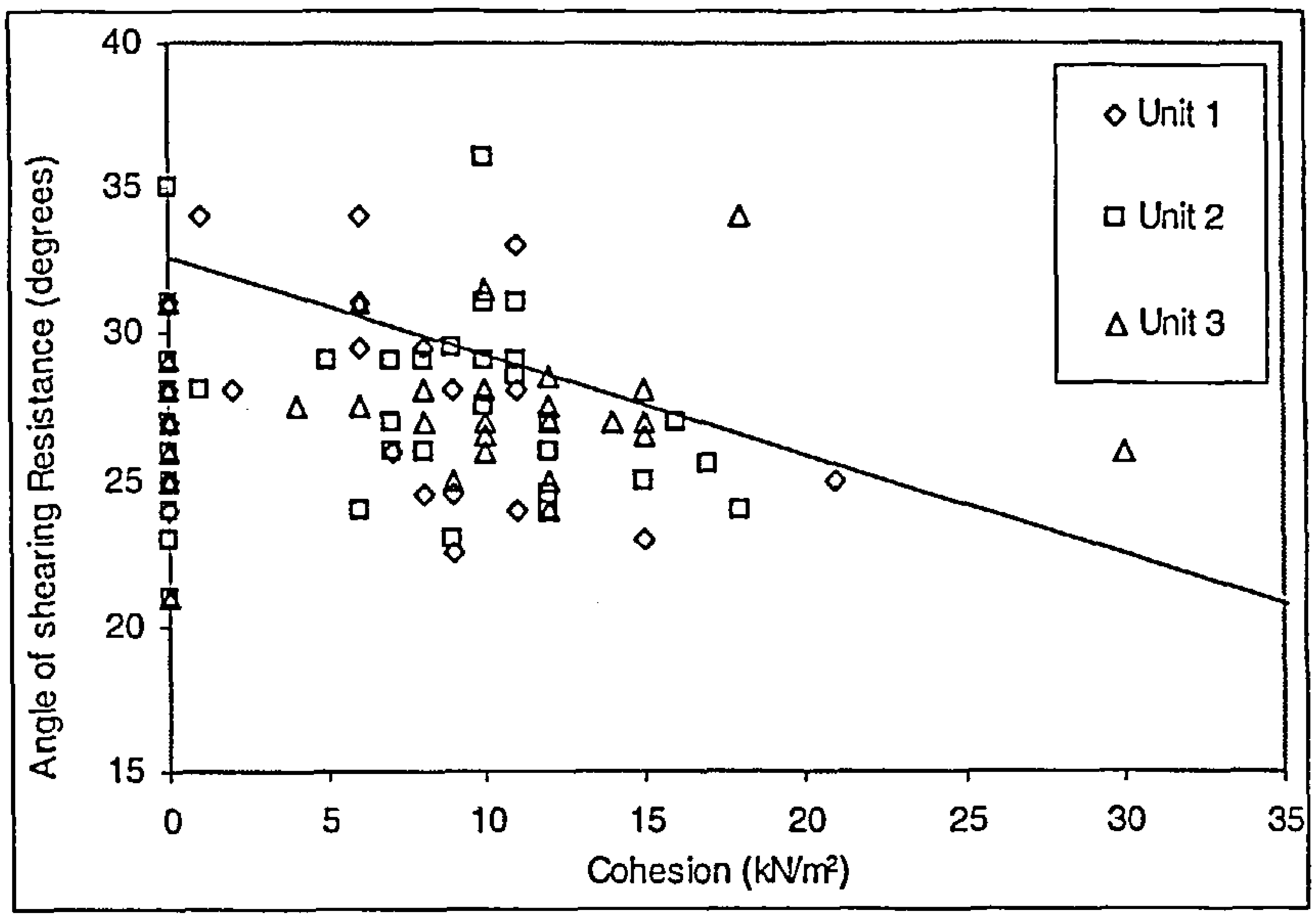


Figure 6.19: Relationship between the cohesion intercept and angle of shearing resistance for glacial units in Northern England.

6.4.1 The relationship between drained shear strength and fine fraction

It has been suggested that an optimum grading exists which would produce the minimum void ratio and the maximum angle of shearing resistance for granular tills (McGown, 1975). This effect was also studied by other researchers on different soils (Skermer and Hillis, 1970). The influence of percentage fines is displayed in Figure 6.20 where the results of the above mentioned research are demonstrated.

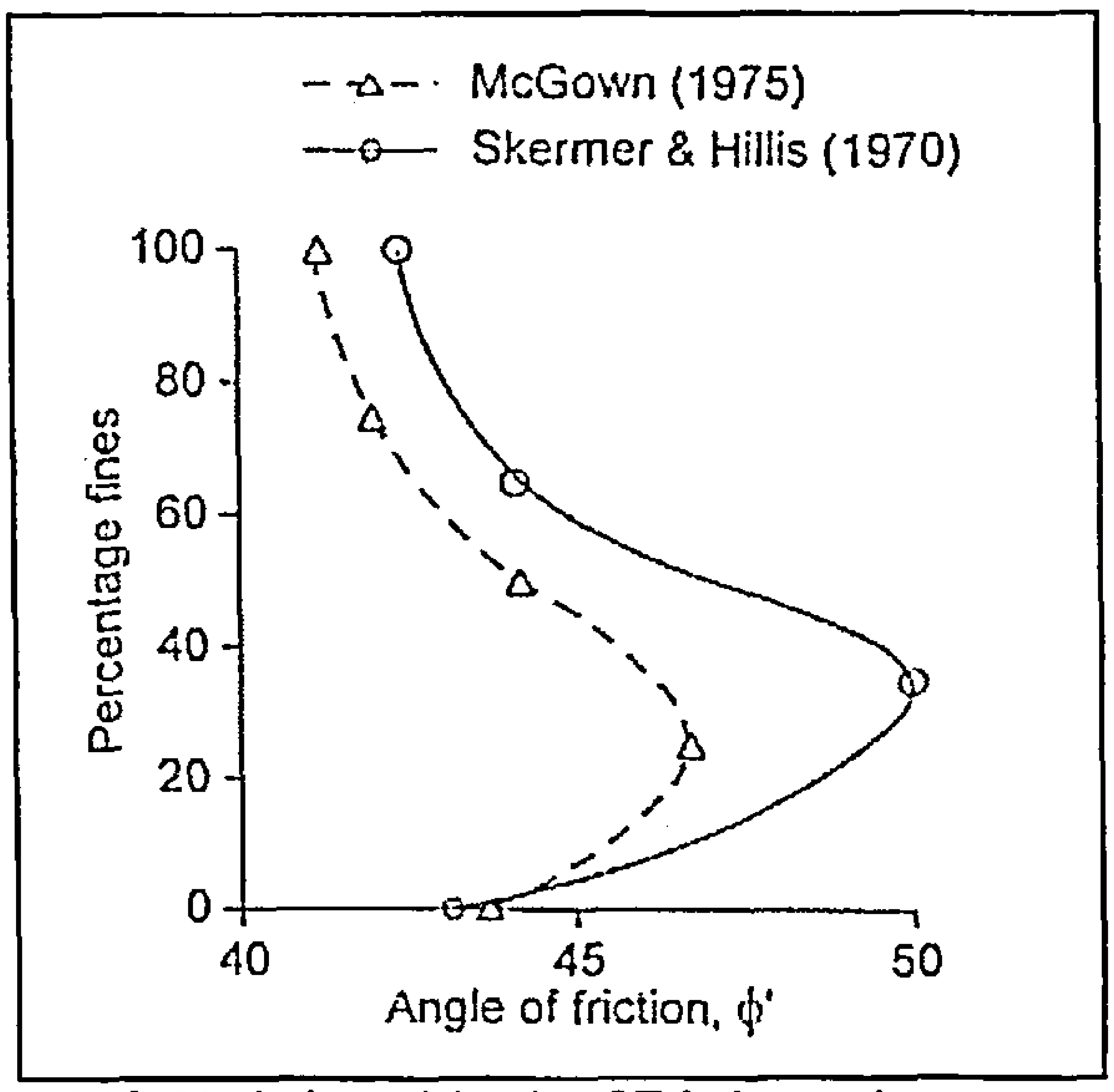


Figure 6.20: Variation of Angle of Friction and percentage fine

Figure 6.21 shows the plot of angle of friction against percentage fines for samples from Northumberland. It can be seen that the data are very scattered and their range is different from those shown in Figure 6.20, which suggests that the glacial units in Northumberland, despite their density and particle size distribution, do not comply with the optimum grading.

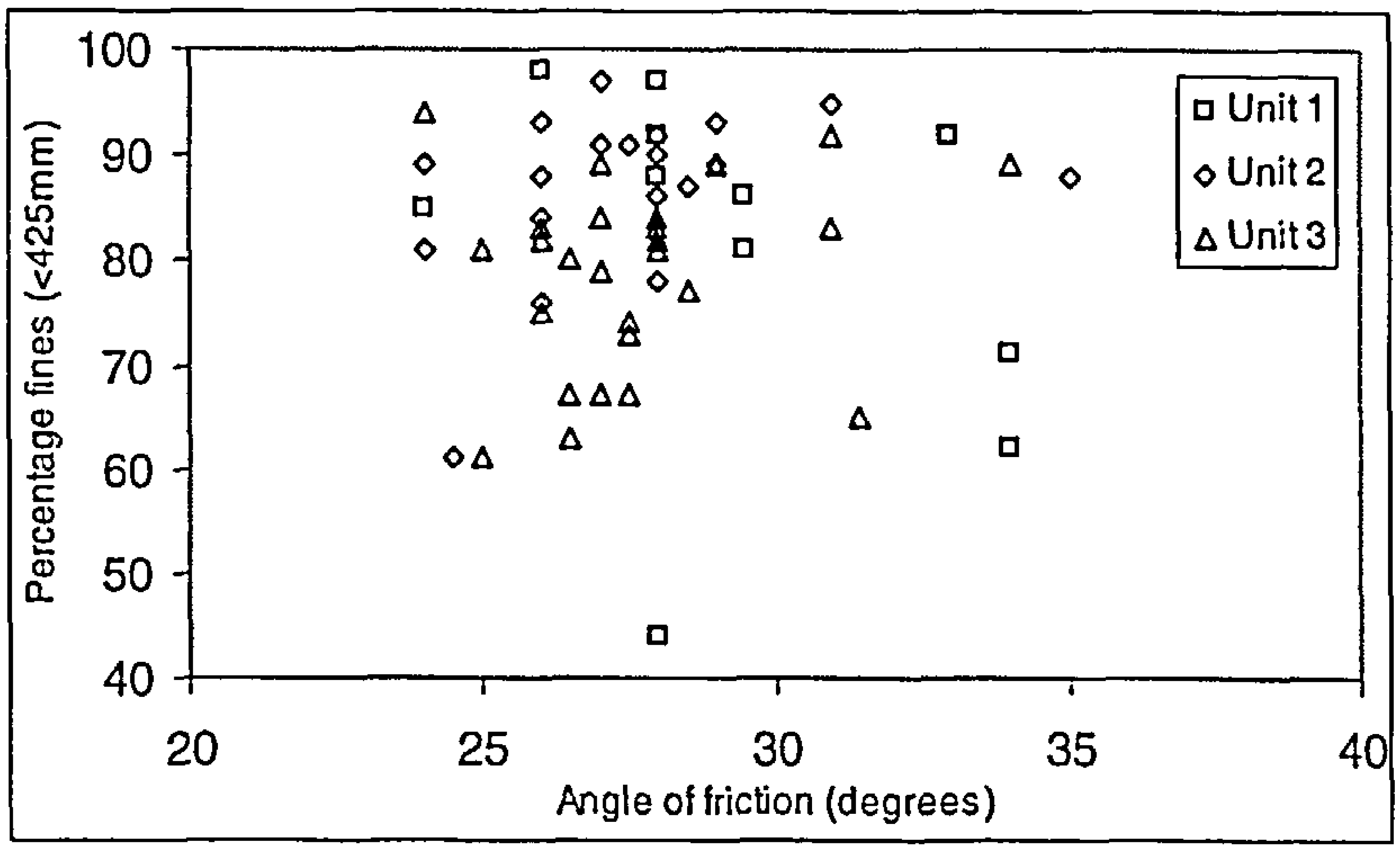


Figure 6.21: Angle of friction against percentage fines in glacial units of Northumberland.

6.5 Consolidation parameters

Consolidation is a time dependent process in which pore water is squeezed out of the voids and the soil particles are packed closer together by applying an external pressure. The oedometer test is a relatively simple approach based on the theory of one-dimensional consolidation for determining the parameters which allow the consolidation behaviour of a soil to be assessed. The results of oedometer tests carried out on several samples from the different till units in Northumberland are presented in the Figures 6.22 and 6.23:

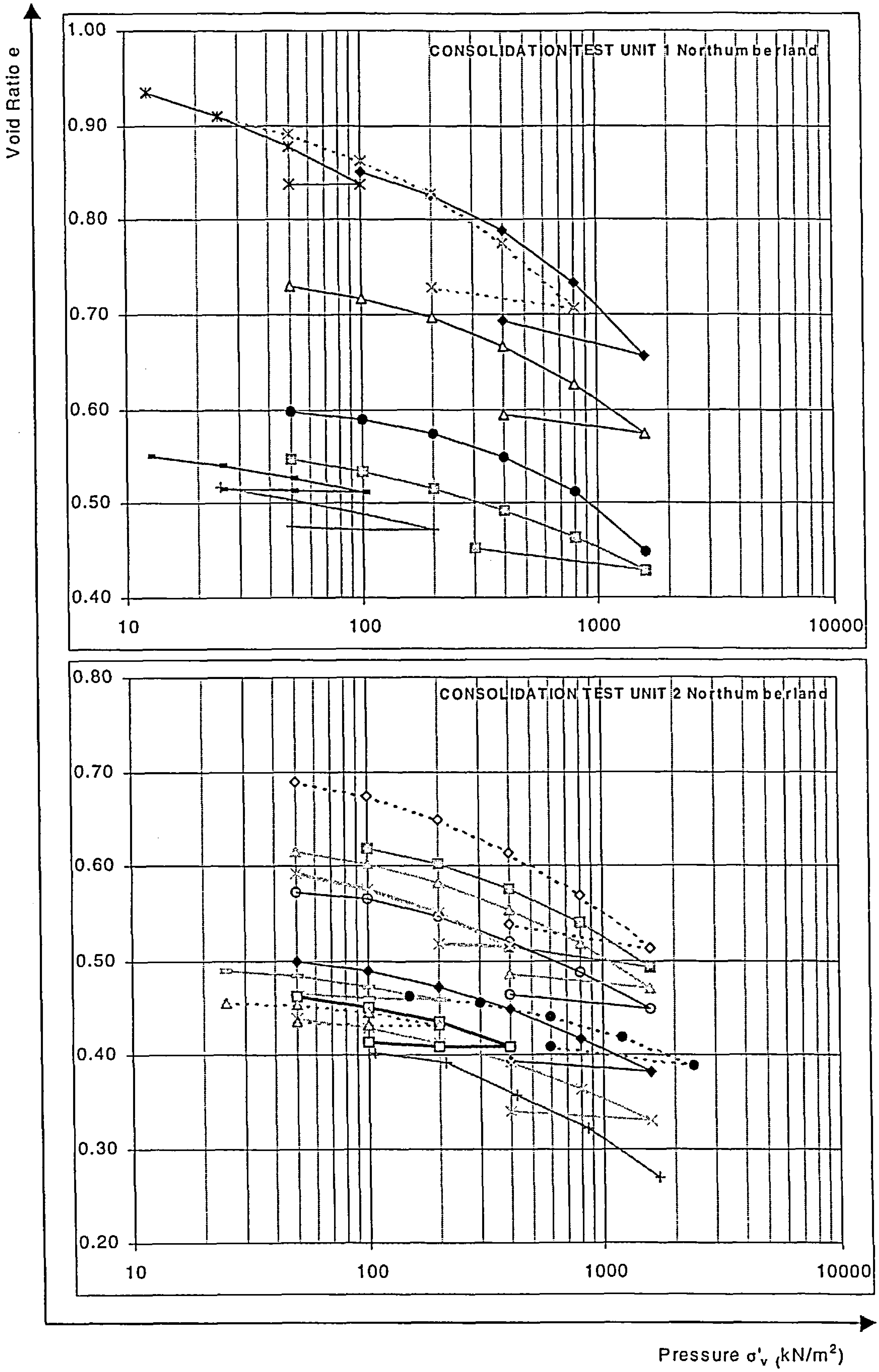


Figure 6.22: The plot of void ratio against pressure for tills from Unit 1 and 2 in Northumberland

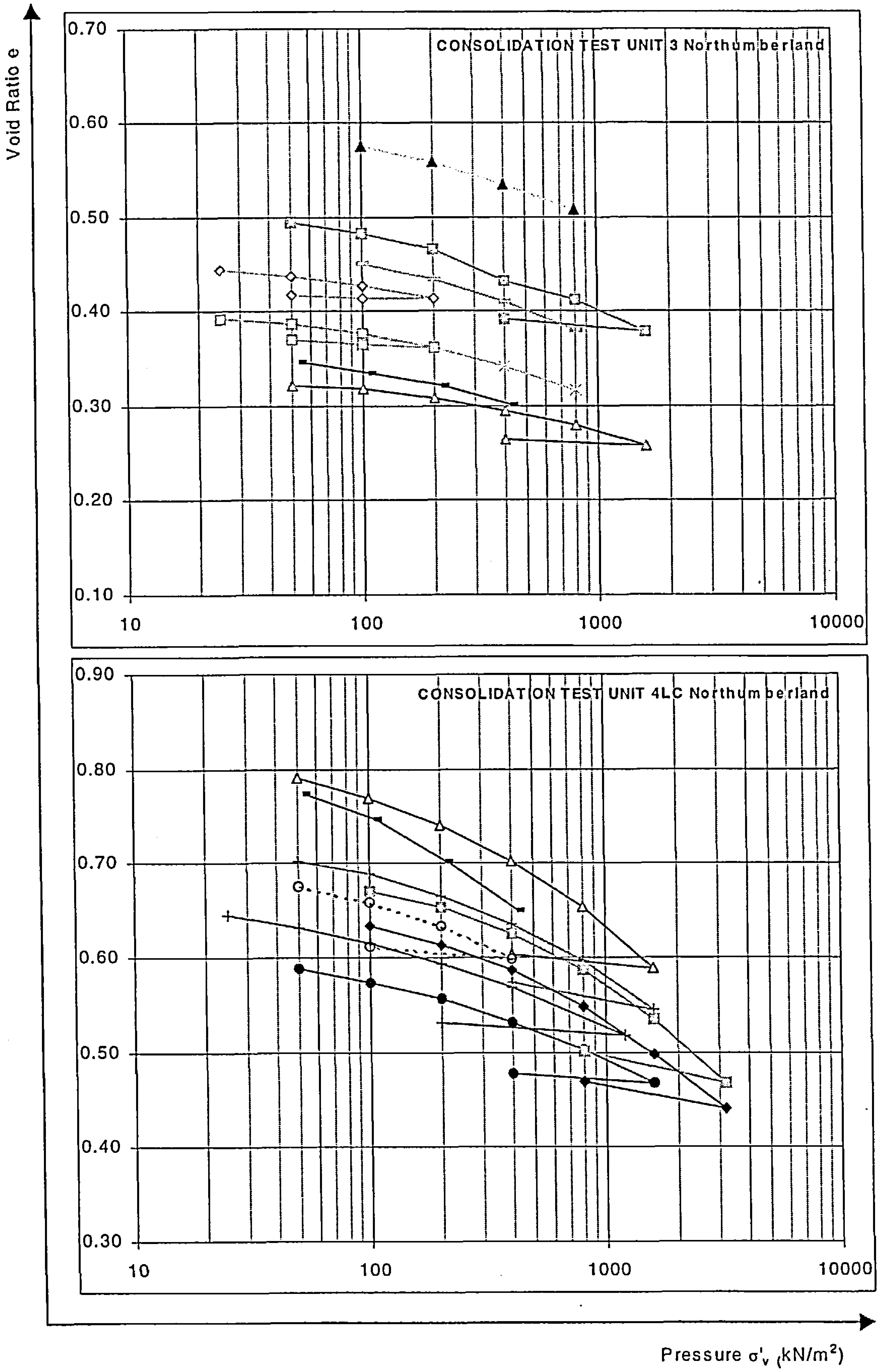


Figure 6.23: The plot of void ratio against pressure for tills from Unit 3 and 4LC in Northumberland

Using the above figures an attempt was made to estimate the preconsolidation pressure (σ'_c) on void ratio-pressure curves using the method proposed by Casagrande (1936) as described by Craig (1997). In most cases it was difficult to identify σ'_c with certainty. The ratio of the preconsolidation pressure to the effective overburden pressure is called the Overconsolidation Ratio (OCR) was calculated for samples from Northumberland. The results vary between 2 to 32 for Unit 1, 0.7 to 7 for Unit 2, 0.35 to 5 for Unit 3 and 0.26 to 5 for Unit 4LC. It can be concluded that all glacial units are to some extent overconsolidated. However, there are indications that some parts of the tills may be either normally consolidated or heavily consolidated. It should be noted that the consolidation pressure in the tests on the samples may have been insufficient to bring the soil to true normal compression.

One method which provides a useful means of assessing the degree of overconsolidation of natural clays is the use of the intrinsic compression line (ICL) as suggested by Burland (1990). This line can be achieved by plotting the void index (I_v) against the log σ_v'. The co-ordinates of this line can be represented by the following equation:

Equation 6.1 $I_v = 2.45 - 1.285\,(\log_{10}\sigma_v') + 0.015\,(\log_{10}\sigma_v')^3$

This line can also be constructed directly using the following equation:

Equation 6.2 $I_v = (e-e^*_{100}) / (e^*_{100}-e^*_{1000}) = (e-e^*_{100}) / C_c^*$

where e^*_{100} and e^*_{1000} are the void ratios corresponding to the effective vertical pressure at 100 kPa and 1000 kPa respectively, and C_c^* is the intrinsic compression index. Using the void ratio at liquid limit (e_L)the values of e^*_{100} and C_c^* can be calculated as shown below:

Equation 6.3 $e^*_{100} = 0.109 + 0.679e_L - 0.089e_L^2 + 0.016e_L^3$

and

Equation 6.4 $C_c^* = 0.256e_L - 0.04$

These equation were used in order to calculate the void index for the samples shown in figures 6.22 and 6.23 and to plot Figure 6.24. The specific gravity (G_s) used for the calculation of e_L was assumed to be 2.69 as suggested by Aflaki (1996) for glacial tills from Northumberland.

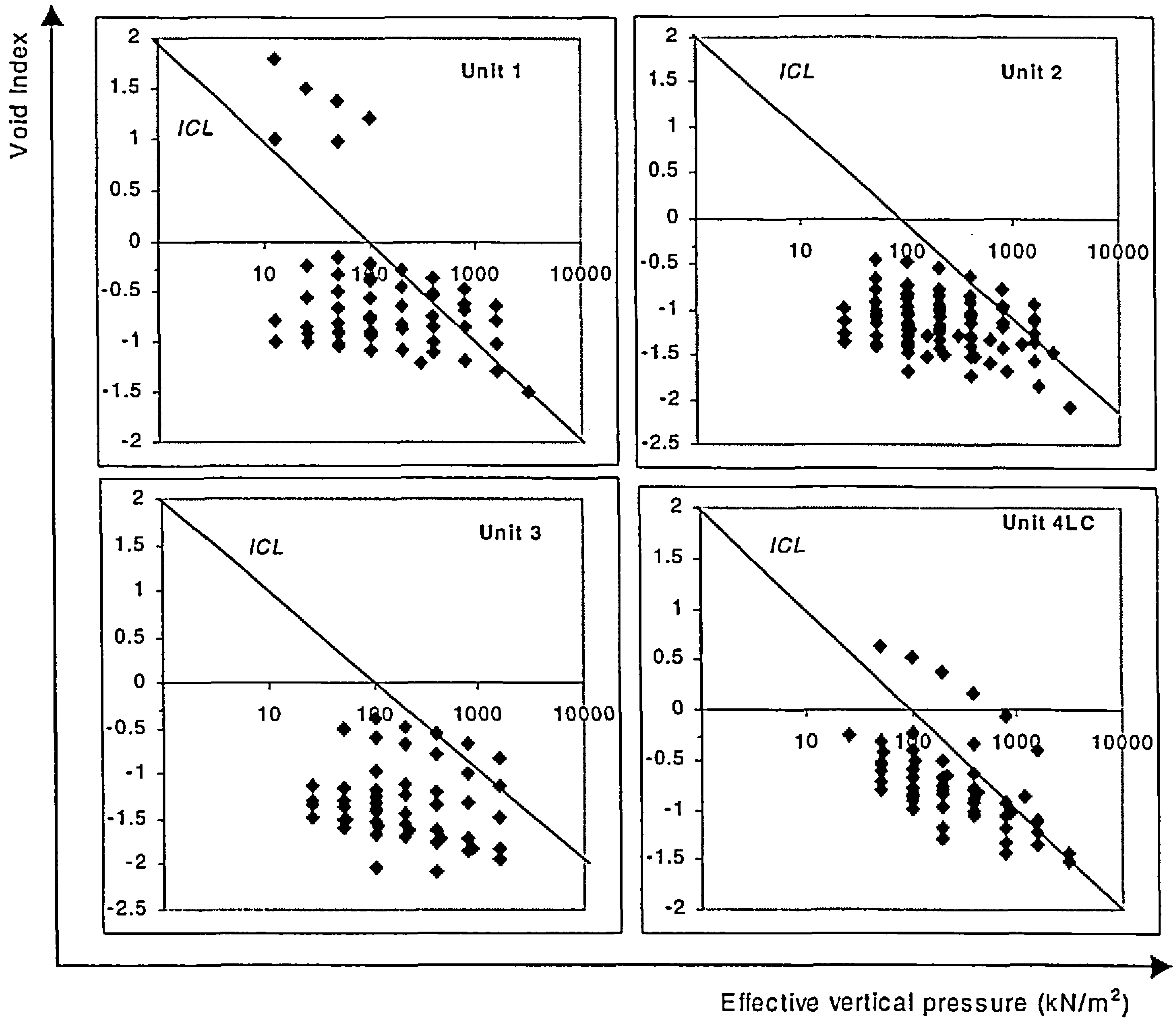


Figure 6.24: The intrinsic compression line proposed by Burland (1990) and data from NETDATA

It can be seen that most data points lie to the left of the Intrinsic compression line which suggests that these samples are overconsolidated.

6.5.1 Compression Index and Atterberg Limits

The compression index determined from oedometer tests defines the change in void ratio of normally consolidated till with applied stress. It is the slope of the straight portion of the normal compression component e-logσ'v plot. It can be calculated from the following equation:

Equation 6.5 $$C_c = \frac{e_0 - e_1}{\log(\sigma'_1 - \sigma'_0)}$$

Since the compression index is used for settlement analysis a significant correlation with index properties would be useful tool for engineering practice. Various correlations were introduced between the compression index and the index properties of soils. These were mainly derived statistically and are briefly reviewed below:

Skempton (1943) proposed the following relationship between the compression index and the liquid limit for normally consolidated clays:

Equation 6.6 $$C_c=0.007(LL-10)$$

Terzaghi and Peck (1967) proposed a similar relationship, based on research with clays of low and medium sensitivity:

Equation 6.7 $$C_c=0.009(LL-10)$$

It is suggested that in general the empirical equations reported above should be best used on a site-specific basis (Trenter, 1999). In this study an attempt was made to correlate the compression index with index properties of tills. C_c was calculated using equation 6.5 and details of the available oedometer tests. As it can be seen from figures 6.25 and 6.26 that generally a poor correlation exists between the compression index and the liquid limit and there is a considerable scatter but with a tendency for the compression index to increase with increasing liquid limit. Similarly when the compression index is plotted against the natural moisture content there seems to be a tendency for the compression index to increase with increasing moisture content.

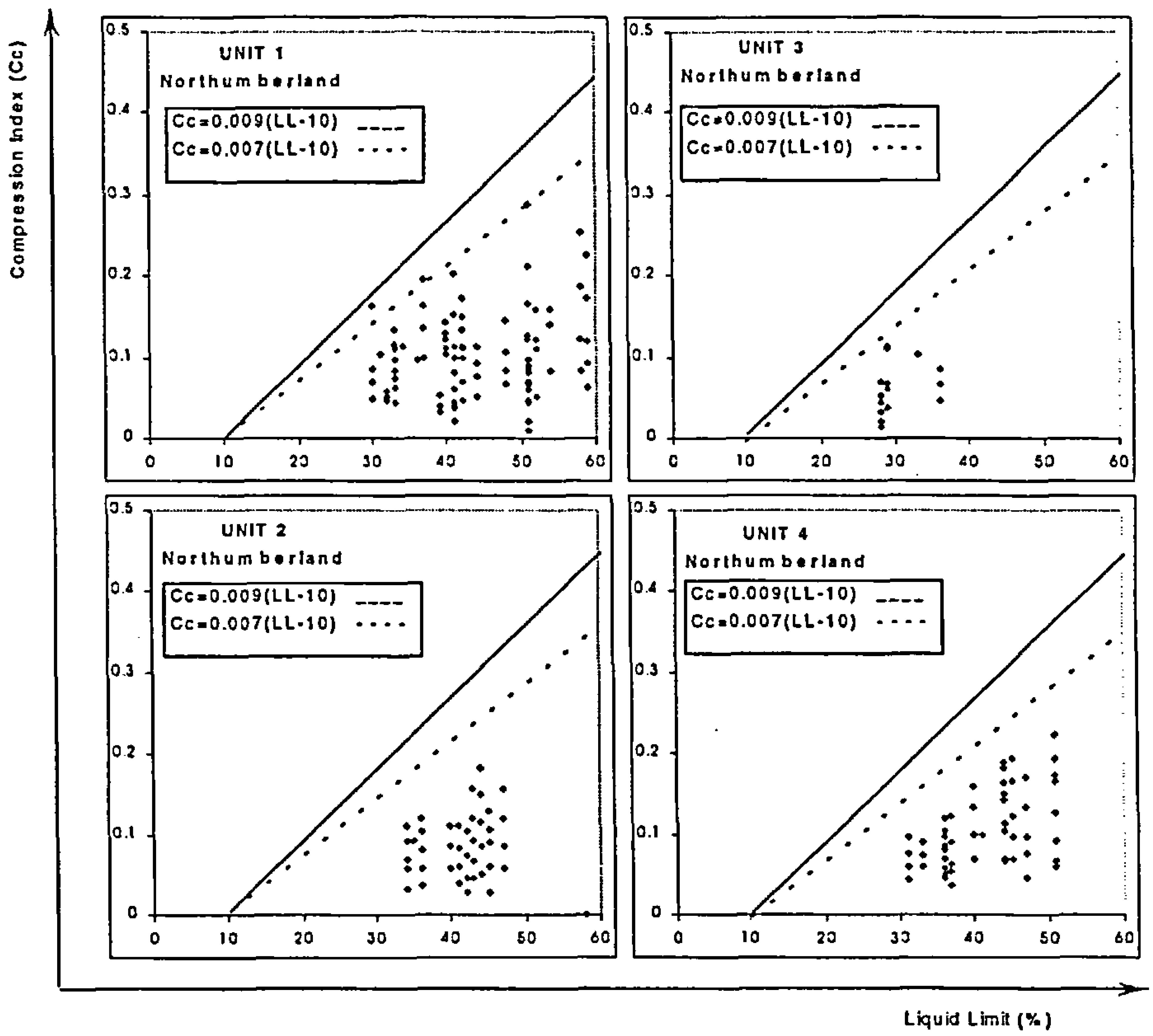


Figure 6.25: Compression Index against Liquid Limit

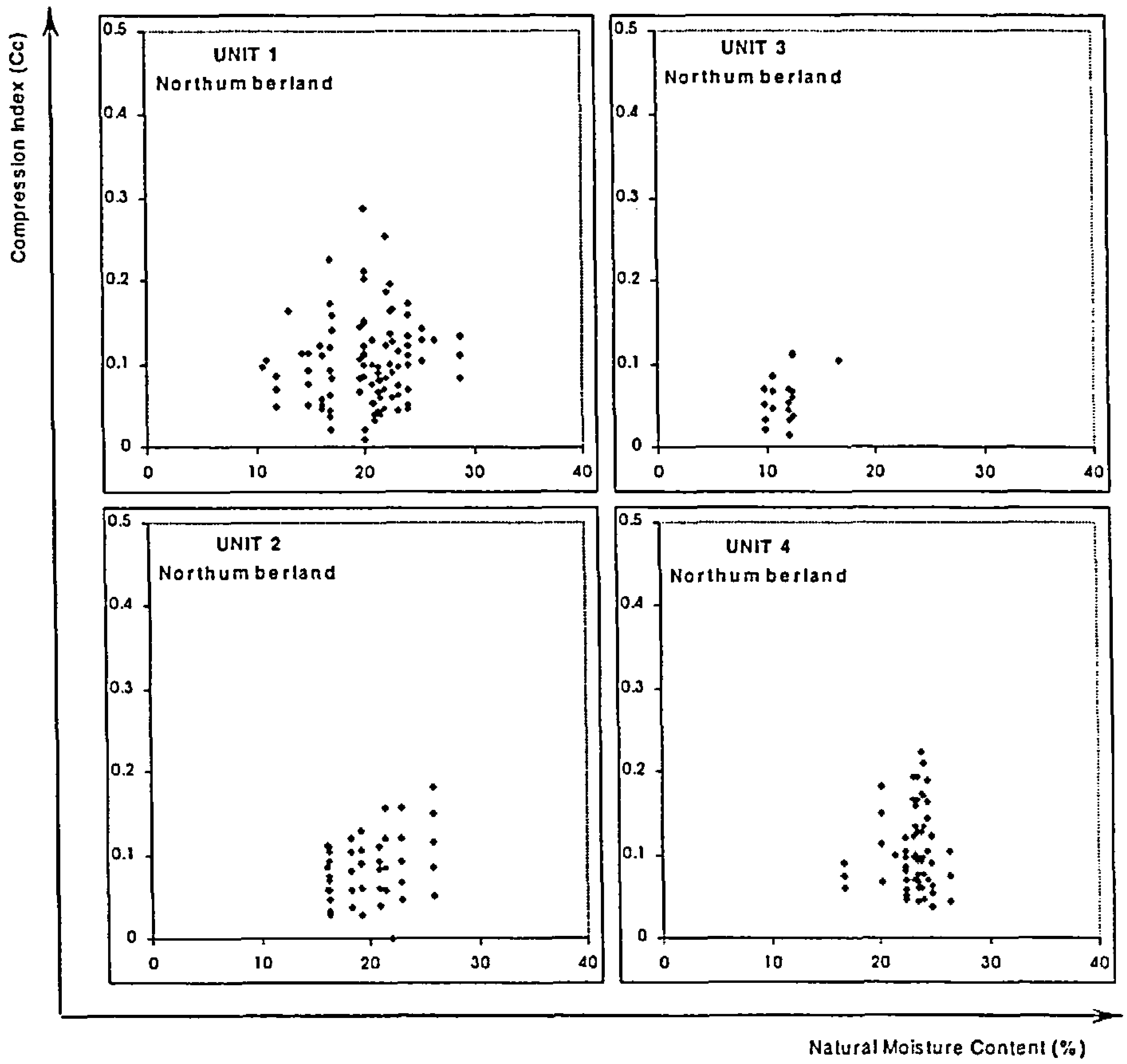


Figure 6.26: Compression Index against Natural Moisture Content

A relationship was suggested between the plastic index and the compression index (Little, 1996):

Equation 6.8 $Cc=0.005\,(PI)(Gs)$

Where Gs is the particle density and if the typical value of Gs=2.67 is inserted into the above equation it will result in the following relation (Trenter, 1999):

Equation 6.9 $Cc=0.013\,PI$

Figure 6.27 shows the relationship between the Compression Index and Plastic Index for the glacial units in Northumberland.

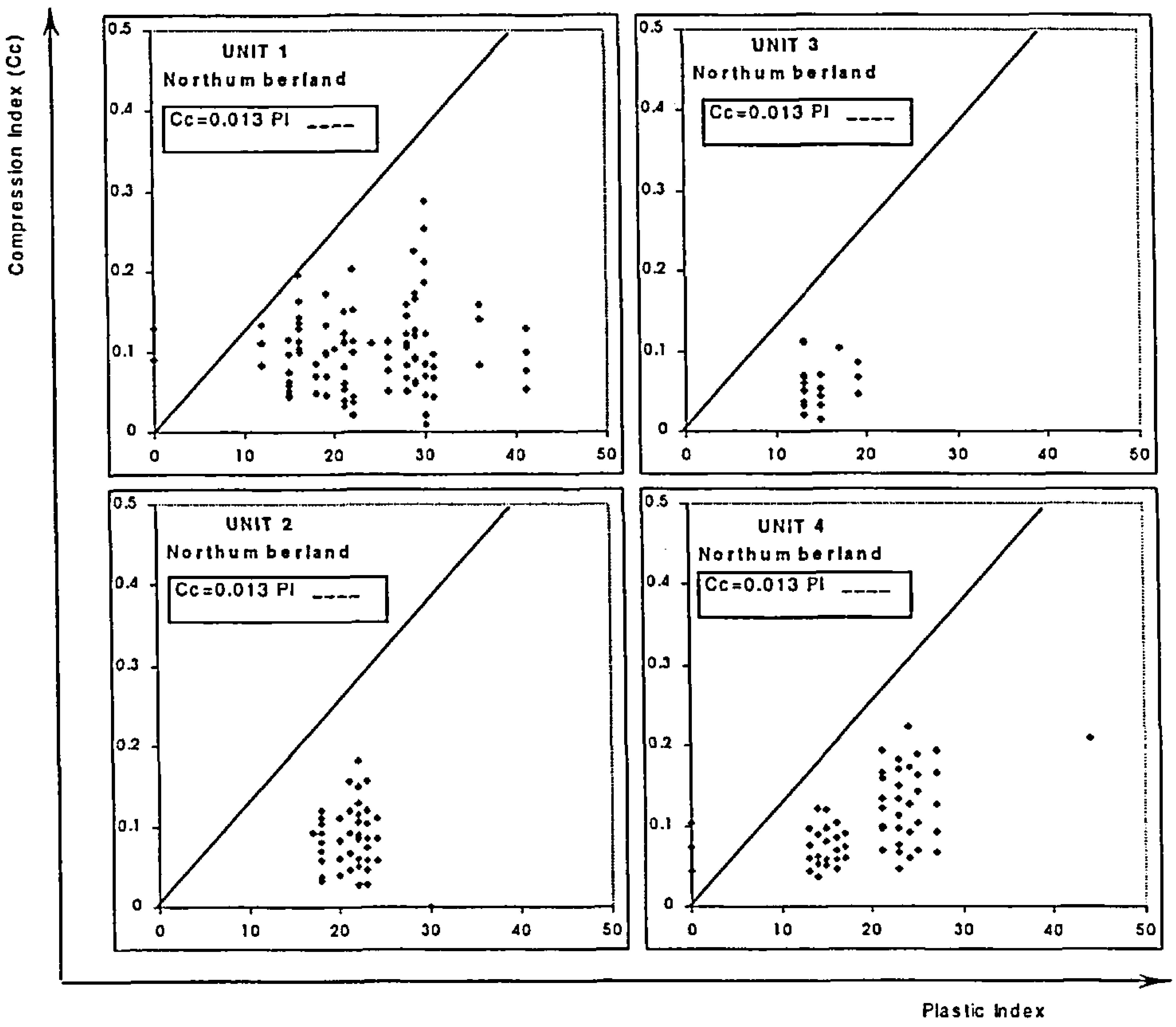


Figure 6.27: Compression Index against Plastic Index

It can be seen that generally a poor correlation between the compression index derived from oedometer tests and empirical equations exists. In this regard it is stated that four important factors namely the consolidation pressure, initial void ratio, existence of structure and sample disturbance may affect the relationship between the compression index and the index properties of a soil and therefore any correlation will be limited (Tsuchida, 1994).

6.6 Summary

This chapter studied the correlation between the results of index tests and other soil properties which included correlations between shear strength parameters and consolidation parameters with index properties of the soil.

It was found that the liquid limit generally increases with increasing clay fraction, which confirmed the finding of other researchers. The relationship between shear strength and some index properties was investigated and it was confirmed that the undrained shear strength tends to increase with decreasing moisture content and liquidity index.

It can be concluded that due to the variability of the material it is very difficult to establish empirical equations that would define the relationship between the different parameters of the glacial units. It was seen that by limiting the analysis to samples from specific sites better correlations might be found between the geotechnical parameters.

An attempt was made to estimate preconsolidation pressures from oedometer test results. It proved to be difficult to measure these values with certainty as the consolidation pressure in the tests on the samples may have been insufficient to bring the soil to true normal compression. Plots of void index against pressure however suggest that the samples from different units may have been overconsolidated.

The following chapter will investigate the potential of Neural Networks for classifying the different till units and its potential to correlate and predict various parameters.

Chapter 7

Classification and prediction of geotechnical parameters of glacial till using Neural Networks

7.1 Introduction

Artificial Neural Networks (ANN) have steadily been developed and used as problem-solving and decision-making tools for complex problems. As already mentioned in Chapter 2, many researchers have investigated the potential of ANN's as a tool for supporting the modelling of engineering systems. They are biologically inspired devices, developed for mapping a set of inputs into a set of outputs. Neural Networks consist of a collection of processing units, referred to as neurons, that pass around activations that are filtered and modified by the connections between the processing units. The neurons are arranged into two or more layers and interact with each other through weighted connections. Neural networks work by feeding in some input variables, and producing some output variables by adjusting the connection weights within their structure.

The multi-layer structure and the non-linear activation functions used in Neural Networks provide a tool that can be used where some known information exists, and some unknown information is sought. It should be noted that not every problem can be solved by a neural network. An important requirement for the use of a neural network is the existence of a relationship between the inputs and outputs. This relationship may be noisy where some factors may not be represented in the input set, and there may be an element of pure randomness but it must exist (Fausette, 1994). Neural Networks are used in cases where the exact nature of the relationship between inputs and outputs might not be known, otherwise they could be modelled directly.

The success of Neural Networks can be attributed to their flexibility and ease of use. They are capable of modelling complex and non-linear functions. For many years, linear modelling has been the commonly used technique in most modelling domains, since linear models had well-known optimisation strategies. Where the linear approximation was not valid, which was frequently the case, the models suffered accordingly (Michie et al, 1994). Neural networks learn by example. Once representative data are gathered, the network invokes training algorithms to automatically learn the structure of the data. To do this the user of the network needs some knowledge of how to select and prepare data, how to select an appropriate neural network, and how to interpret the results.

This chapter reviews the development of neural networks in more detail and will also explain how they function. Using data from the NETDATA relational database, which has been reviewed in previous chapters, the potential of Neural Networks are investigated for solving classification problems and to predict the undrained shear strength of glacial till samples.

7.2 Stages for using neural networks

By plotting the input against the output of a network a solution surface can be created. The objective of training a Neural Network is to provide an acceptable approximation to this targeted surface. The intention is not simply to train a network to reproduce the solutions to the examples in the training set, but rather to find a generalised solution applicable to all examples of the problem that could be of interest. Some values used as training patterns might contain errors, for instance due to inaccurate measurements or because the targeted solution changes with time. Hence an exact fit of the solutions with the training patterns could fail to provide a generalised solution. A more acceptable solution will be one that provides a closer approximation to the test patterns while still making a good fit to the training points and follow a general trend implied by the training patterns. The number and configuration of the hidden neurons, the number of training patterns, the type of network and the training algorithm adopted will ensure that a neural network provides the most appropriate degree of generalisation. It should be noted that typically Neural Networks are unable to produce accurate solutions far outside the training domain, since there is no information provided on the form of the solution surface at this region.

The development of a neural network involves several stages. First the variables to be used as the input parameters must be identified which requires an understanding of the problem and knowledge in that specific field. The next stage involves gathering the data for use in training and testing the neural network. This requires a data set of case records containing the input patterns and the expected solution. The training set must provide a representative sample of the data containing the various distinct characteristics of the problem that the neural network is likely to encounter in the finished application. The next step is to design the structure of the neural network. A neural network is characterised by its network topology, the connection strength between neurons, node properties, internal controls, and the updating rules. The above steps will be discussed in the following sections.

7.2.1 Learning in neural networks

A simple network has a feedforward structure where signals flow from inputs through any hidden units and eventually reach the output units. Neurons are arranged in a distinct layered topology. The input layer is not really neural and only serves the purpose of introducing the values of the input variables. Each of the hidden and output neurons are connected to all units in the preceding layer.
To train neural networks, learning algorithms, also known as learning rules, are developed. The learning algorithm specifies an initial set of weights and indicates how weights should be adapted during use to improve performance by minimising errors. By sequentially applying a set of inputs while adjusting network weights according to a predetermined procedure, the network weights gradually converge to the values that are able to produce the desired, or at least consistent, set of outputs. The minimisation procedure is designed to find the global minimum of errors.

Since the relation between the weights and the errors is non-linear, it is impossible to derive an analytical solution and therefore, the global minimum usually relies on an interactive process of learning algorithm that searches the error surface to reach the global minimum (Michie et al, 1994). Learning algorithms are broadly categorised as supervised and unsupervised, with many paradigms implementing each method.

There are different ways that learning models can be classified. The main broad paradigms of learning are briefly reviewed below (Zeidenberg, 1990; Ghaboussi et al, 1991):

- In supervised learning, the network user assembles a set of training data, which contains examples of inputs together with the corresponding outputs. Training data are usually taken from historical records. During training the network output is compared to the target output for a given input, and the error is computed and fed back so that weights can be changed according to an algorithm that tends to minimise the error. The process is repeated until the error for the entire training set is as low as that required. After learning, the weights are usually not changed further, unless something new must be learned. If the network is properly trained, it has then learned to model the function, which could be unknown, that relates the input variables to the output variables. This function can subsequently be used to make predictions where the output is not known.

- Unsupervised learning occurs without the use of training sets and the network learns to classify the input into sets without being told what it has to learn about the presented input. It does the clustering on the basis of intrinsic statistical properties of the set of inputs, which means that the training process employs the statistical methodology to group similar patterns of output into classes. The Neural Network must discover regularities and similarities among the input patterns on its own. Without the availability of a target output in this method, the network only computes outputs that are grouped corresponding to the changes of inputs. The weights are adjusted to produce the most consistent outputs.

When the network is executed, the input variable values are placed in the input units and then the hidden and output layer units are progressively executed. Each of them calculates its activation value by taking the weighted sum of the outputs of the units in the preceding layer, and subtracting the threshold. The activation value is passed through the activation function to produce the output of the neuron. When the entire network has been executed, the outputs of the output layer act as the output of the entire network.

Several linear and non-linear functions can be used to activate the nodes and to control the output for the node. For instance the Hard Limiter is a threshold function, the Threshold Logic is a linear function and the Sigmoid and Hyperbolic Tangent are non-linear functions. Figure 7.1 shows the form and method of calculation of these common functions that are used in neural networks.

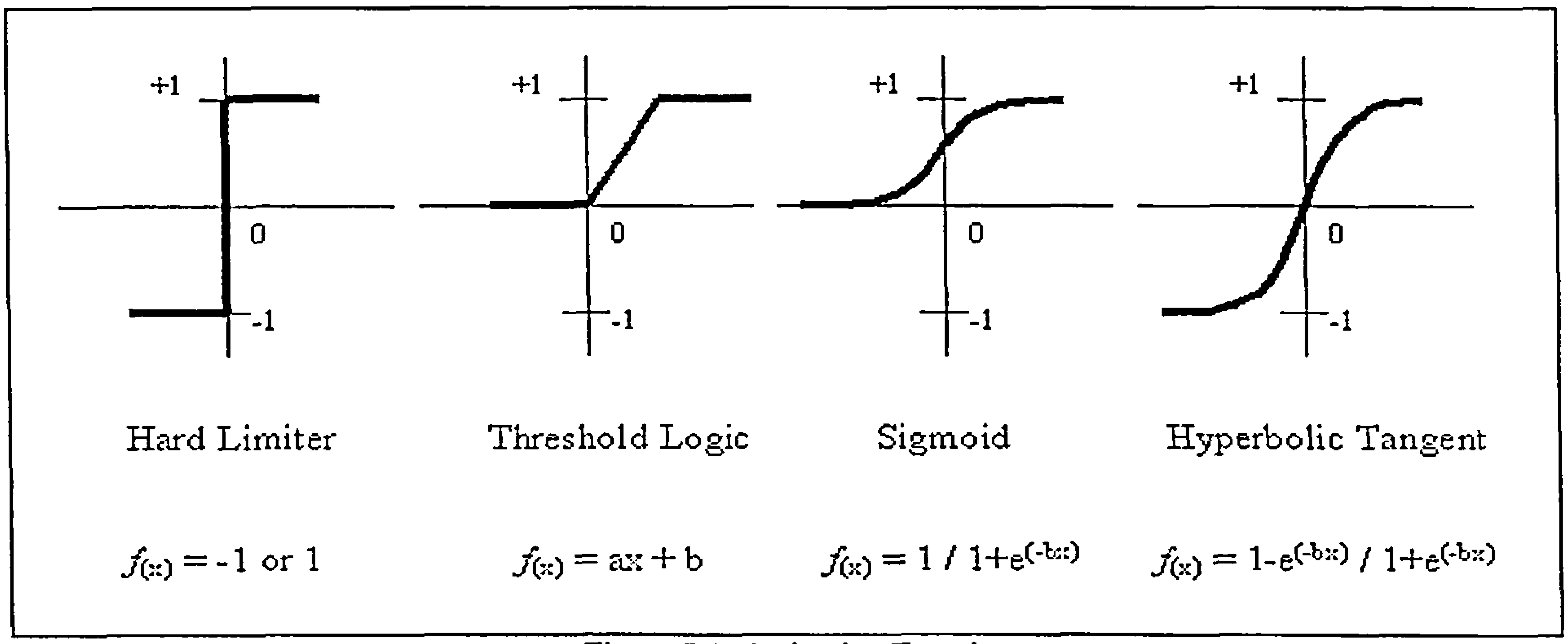


Figure 7.1: Activation Functions

All these functions produce different types and ranges of output. They are also called Squashing Functions because they compress the range of outputs, so that they never exceed some limits regardless of the value of input signals. For example, as shown in Figure 7.1, the sigmoid function allows outputs in the range of 0 and 1 and the output range for the hyperbolic tangent function is -1 to 1.

Several types of neural networks are known. In this study the back-propagation method was used for the design of the Networks. This method is explained in detail in the following section.

7.2.2 Back propagation

Back-propagation also known as the generalised delta rule is a gradient descent method to minimise the total squared error of the output computed by the neural network. It is a supervised learning technique that compares the responses of the output units to the desired response, and readjusts the weights in the network so that the next time that the same input is presented to the network, the network's response will be closer to the desired response (Zeidenberg, 1990). The nature of the back-propagation training method means that a back-propagation network, which is a multi-layer, feedforward neural network trained by back-propagation algorithm, can be used to solve problems in many areas.

The aim is to train the network to achieve a balance between the ability to respond correctly to the input patterns that are used for training, a process known as memorisation, and the ability to give reasonable response to input that is similar but not identical to that used in training, known as generalisation. (Fausette, 1994).

The training of a network by back-propagation involves three stages (Wasserman, 1989); the feedforward of the input training pattern, the calculation and back-propagation of the associated error, and the adjustment of the weights. Each presentation of one training case and subsequent modification of connection strengths is called a cycle; and a set of cycles, made up of one cycle for each training case is called an epoch. Each cycle can be explained in a few steps. In the first step, for the training case to be learned, the network is presented with the input pattern and then propagates the activation through to the processing units (feedforward). In the second step the error at the output units is then back-propagated to the hidden processing units. In the last step the connections coming into the hidden units modify their connection strengths by adjusting the weights using the back-propagated error from the last step.

These steps are explained in detail as follows (Rumelhart et al, 1986; Hecht-Nielsen, 1989, Billings and Chen, 1995; Tarrasenko, 1998):

When an input pattern is shown to the untrained network, it will produce any random output. To prevent this an error function needs to be defined to represent the difference between the network's current output and the correct output which needs to be produced. This is achieved by adjusting the weights on the links between the neurons using the generalised delta rule, which will be explained later. The procedure is explained below for a typical multi layer Neural Network as shown in Figure 7.2. The diagram shows a Network with the layers I-J-K, where I is the input layer and has 5 inputs, J is the hidden layer and has 3 hidden units, and K is the output layer with 3 units.

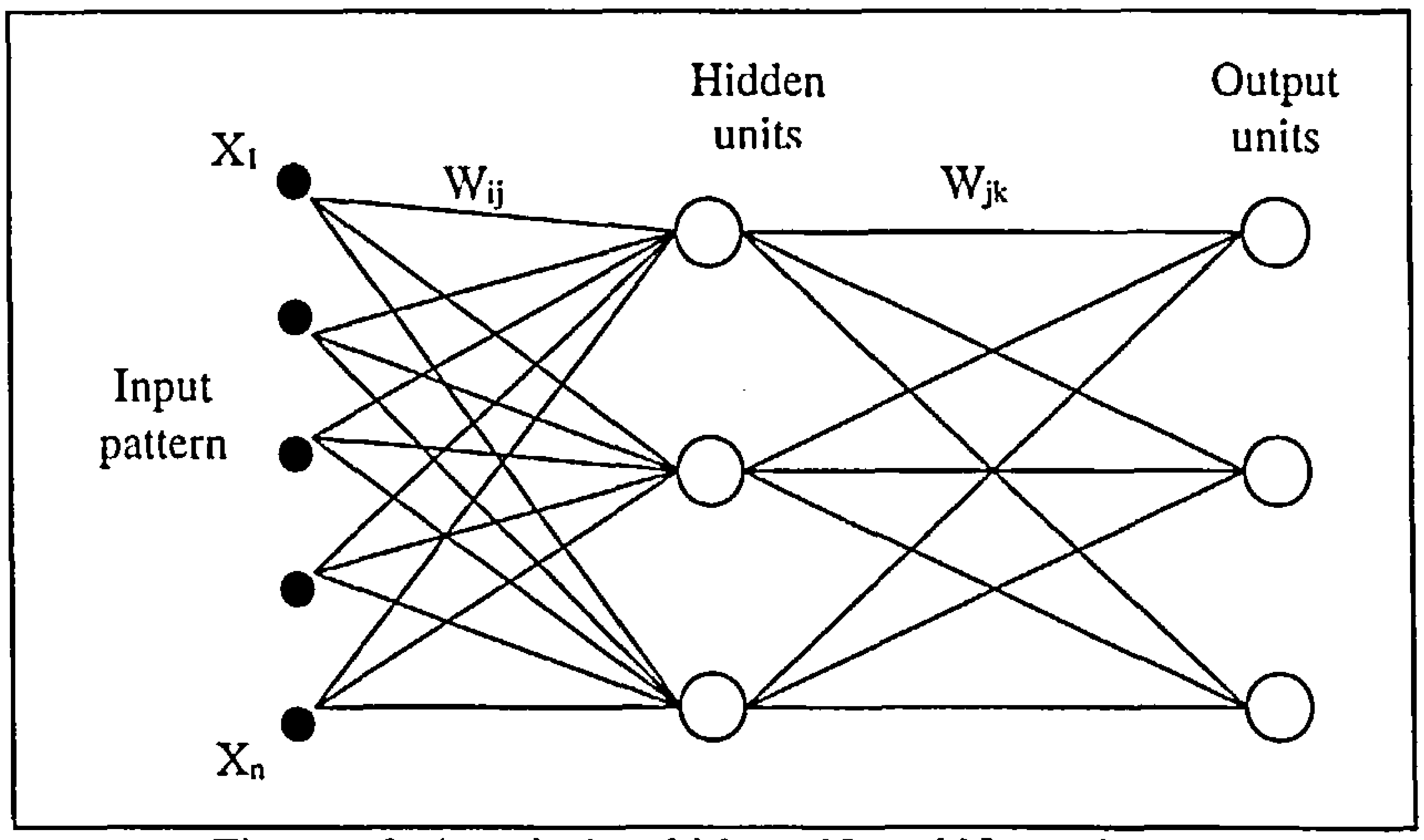


Figure 7.2: A typical multi-layer Neural Network

The first task of the algorithm is to assign a set of network weights as a starting point for the learning process. To accomplish this, the vector of weights (W_{ij}) starts with initial values randomly drawn from a uniform distribution. The goal is to start the error criterion minimisation with a solution as good as possible in order to save learning time and convergence conflicts. Its range is dependent on the program or user settings and is generally set between –0.5 to 0.5.

Given the randomly assigned weights, the input pattern is propagated forward through the network. Inputs are then multiplied by their associated weights and the results are passed to the neurons. The output from each hidden unit j is the assigned activation function f_j acting on the weighted sum (net_j). Some of these functions were shown in Figure 7.1. The results are used as inputs for the connected neurons in the next (hidden) layer in which they are reprocessed as described above until they reach the output layer where the final outputs (o_j) for this iteration are computed.

Equation 7.1 $$net_j = \sum_i w_{ij} o_i$$

Equation 7.2 $$o_j = f_j(net_j)$$

In order for the algorithm to minimises the total error, a set of errors are computed by comparing the target to the calculated output using the following equation:

Equation 7.3 $$E = \frac{1}{2}\sum_j (t_j - o_j)^2$$

Where E is the error function; t_j represents the target output on neuron j; o_j represents the actual output of that neuron; 1/2 is used for convenience in notation for taking the derivative later.

The aim of the training process is to minimise the above mentioned error over all training patterns. The procedure to do this uses a recursive algorithm that starts at the output neurons and working back to the first hidden layer. Adjusting the weights in proportion to the partial derivative of the error with respect to the weights achieves this result.

Equation 7.4 $$w_{ij}(n+1) = w_{ij}(n) + \Delta w_{ij}$$

Where $w_{ij}(n+1)$ is the value of the weight from neuron i to neuron j after adjustment; $W_{ij}(n)$ is the value of the weight before adjustment; and Δw_{ij} represents the amount of weight change

Because the networks are multi-layered, the weights consist of those connecting hidden and output layers and those connecting input or hidden layers with other hidden layers, so the calculations here are separately shown below. It should be noted that these equations result from the use of the sigmoid logistic function.

For the hidden to output layer the change of weights is calculated as follows:

Equation 7.5 $$\Delta w_{jk} = -\eta \frac{\partial E}{\partial w_{jk}} = -\eta \delta_k o_j$$

where

Equation 7.6 $$\delta_k = \frac{\partial E}{\partial net_k} = o_k (1 - o_k)(t_k - o_k)$$

For modifying the weights connecting input and hidden layers, the global error is derived with respect to the weights connecting input nodes to nodes in hidden layer.

Equation 7.7 $$\Delta w_{ij} = -\eta \frac{\partial E}{\partial w_{ij}} = -\eta \delta_j o_j$$

where

Equation 7.8 $$\delta_j = \frac{\partial E}{\partial net_j} = o_j (1 - o_j)(\sum_k \delta_k w_{jk})$$

The learning rate η is a user-defined parameter that controls the rate of weight modification in back-propagation process. It is a coefficient that regulates the speed of the learning process and is usually set to a small value to ensure that the network reaches a solution. The small value has the negative consequence of increasing the number of iterations necessary to obtain a solution, and a high possibility of getting trapped into a local minimum of the error surface, whereas a large rate can overstep the global minimum.

A method often used to alter the search direction and speed up convergence is to add some of the previous direction to the current gradient, which is called momentum shown as μ. It determines some degree of persistence in the modification of the weights, since the change depends on the previous change. The value of η can be kept higher in order to speed up convergence, since μ is able to provide some stability for the search process, so that it can avoid excessive oscillations of the weights (Tarassenko, 1998). The resulting weight change is:

Equation 7.9 $$\Delta W_{jk} = W_{jk}(\tau+1) - W_{jk}(\tau) = -\eta\delta_k y_j + \mu(W_{jk}(\tau) - W_{jk}(\tau-1))$$

Equation 7.10 $$\Delta W_{ij} = W_{ij}(\tau+1) - W_{ij}(\tau) = -\eta\delta_j y_i + \mu(W_{jk}(\tau) - W_{ij}(\tau-1))$$

where μ is a user-defined parameter between 0 and 1, and τ is the iteration number. It is suggested that momentum is highly dependent on the ordering of the examples presented to the network in which a series of examples from the same class can result in high momentum disturbing the progression of the learning process. This reinforces the need to present the training set in random order to minimise such undesirable effects.

There are two ways to use the back-propagation algorithm, the on-line mode (also known as stochastic or sequential mode) and the off-line mode (also known as batch or epoch-based mode). In the on-line mode the weights are updated after the presentation of each training set, whereas in the off-line mode the weights are updated after the presentation of all training known as an epoch (Haykin, 1999).

Randomising the order of the training sets is a good practice when training a network as this makes the search for a suitable synaptic weight stochastic over the learning cycle. As a result the possibility of limited cycles for finding the most suitable weight could be avoided. This makes the on-line mode more effective in escaping local-minima, but may also miss some good local minimum that was being explored which is not the case in the off-line method of training. One advantage of the off-line method over the on-line method would be that it is much faster since it does not need to compute the weight modification as often. Despite the fact that the on-line method has some disadvantages, it is highly popular particularly for solving pattern classification problems since it is simple to implement and provides effective solutions to problems (Haykin, 1999). One advantage of the on-line method, which could be of importance in this study, is that it is able to make use of redundant data because the examples are presented one at a time. Redundant data are datasets within the training set that contain exactly the same patterns which is the case in many or some of the datasets within NETDATA.

7.3 Designing a Network

The software used for the design of the Neural Network in this study is NeuroSolutions for Excel (NeuroDimensions, 2001) which is a Microsoft Excel add-in that simplifies and enhances the process of getting data into and out of a neural network. One of the advantages of NeuroSolution is that all tasks can be performed directly from Excel. The software provides Visual Data Selection, Neural Network design wizard and one-step training and testing. More advanced features such as data pre-processing, statistical data analysis, parameter optimisation are also available in the software.

NeuroSolution allows columns to be chosen and tagged as input and / or desired outputs. The software also allows selecting and tagging the rows which should be used for training, cross validation and testing data. Once this is done the available software wizard allows the user to select the type of network, activation function, number of hidden layers and number of hidden neurons in each layer to construct the network. The back-propagation algorithm, reviewed earlier in this chapter, is used for the design of the networks. The Sigmoid function and the Hyperbolic Tangential function were considered as the activation functions of the neurons. Since the results of the different networks using these activation functions did not show any major differences in the final outcome, only the results of networks using the sigmoid function will be presented.

Factors such as the quantity of training patterns, the number of input and output neurons and the relationships between the input and output data have to be taken into consideration to select an adequate hidden structure. The construction of a network with many hidden layers and processing units can easily result in a poorly performing model. When a hidden processing structure is too large and complex the network tends to memorise input and output sets rather than learn relationships between them. Such a network may train well but performs poorly in the testing phase when presented with inputs outside the training set. In addition, network training time will significantly increase when a network is unnecessarily large and complex. There is currently no method for determining the optimal numbers of neurons in the hidden layer other than by experiment. It is suggested that standard feedforward networks with only one single hidden layer are capable of solving any problem that larger networks can solve (Goh, 1995; Shi et al, 1998). It is also suggested to start with designing simple networks that use relatively few hidden layers and processing units. If the degree of learning is not sufficient or certain trends and relationships cannot be grasped, the network complexity can be increased in order to improve learning.

Once the input and output columns and the datasets are tagged and the network is constructed the training process can be started. The software allows the user to choose the number of epochs to be used for training. The training process follows the methods as explained in earlier section of this chapter. Once the training is completed the software will generate a report with the results of the training, cross validation and testing in a new worksheet in Microsoft Excel. The following sections will describe how data were prepared and will explain the results of the classification and data prediction process achieved from using Neural Networks.

7.4 Data Preparation

To use the Networks, data needed to be gathered for training purposes. The training data set includes a number of cases, each containing values for a range of input and output variables. There are currently no certain guidelines that relate the number of cases needed to the size of the network. In general it can be stated that the more examples available the more representative the data, which leads to a proportional decrease in noise effects. The initial choice of variables is guided by intuition. Knowledge of the problem domain will give some idea of which input variables are likely to be influential. In the first attempts, any variables that possibly could have an influence were included. A part of the design process is to cut down the number of variables. Generally with the increase in the number of variables used as input and output, the number of cases required for training will also increase.

Many practical problems suffer from unreliable data. Some variables may be corrupted by noise, for instance due to inaccurate measurement processes, or values may be missing altogether. This obviously is not ideal and should be avoided. The network can replace missing values or partial information by their mean value or by the last available value. This, however, will result in noise in the dataset and can lead to an accurate fit on the training data while resulting in a poor generalisation. Although Neural Networks are noise tolerant, there is a limit to this. For instance occasional outliers far outside the range of normal values for a variable will bias the training. The best approach is to identify and remove such outliers by discarding the case. It is also possible to convert the outlier into a missing value, but as mentioned earlier this outlier-tolerant training is less effective due to the increase of noise. The best approach is to select data that are complete and do not contain extreme values. Therefore, only complete sets of data were chosen from NETDATA for training and sets containing extreme values were omitted, as these would affect the performance of the network.

All the above stages rely on a key assumption that the training, verification and test data must be representative of the underlying model (and, further, the three sets must be independently representative). All eventualities must be covered since a Neural Network can only learn from cases that are present. It can not be expected from a network to make a correct decision when it encounters previously unseen cases with values outside the range of the training data. Often, the best approach is to ensure even representation of different cases, then to interpret the network's decisions accordingly.

Another problem, which needed to be considered in the preparation of the data, was overfitting. Overfitting means that the network models the noise present in the training set instead of the underlying function we want to extract. The more complex the network the higher the risk of overfitting. The best solution to this problem is to increase the number of examples in the database. The more examples available, the more representative the data, which also results in a proportional decrease in noise effects. In addition, several observations of the same example will direct the network to learn their average rather than fitting closely a single noisy observation. Another method is the use of cross verification. To do this some of the training cases are reserved and are not actually used for training in the back propagation algorithm. Instead, they are used to check the progress of the algorithm. It is normally the case that the initial performance of the network on the training and verification sets is the same, if it is not (approximately) the same the division of cases between the two sets was probably biased. As training progresses and the training error drops the verification error drops too. However, if at any time during the training process the verification error stops dropping, or starts to rise, this indicates that the network is starting to overfit the data, and training should be stopped. When over-fitting occurs during the training process like this it is called over-learning. This problem can be solved by decreasing the number of hidden units and /or hidden layers.

7.5 Classification of glacial tills using Neural Networks

Geotechnical engineering aims to describe the behaviour and performance of the ground as a construction material. The assessment of the engineering behaviour of the ground requires the evaluation of its properties. Geotechnical testing is the most common and reliable method for the evaluation of ground properties. Laboratory tests can be used to classify soils into groups with similar properties and to predict soil behaviour parameters under certain conditions. But this can be costly and time consuming and also limited to places where sampling was carried out. As it is evident from many site investigation reports available data sets are sometimes incomplete. This could be due to the large number of available samples in some locations where tests were carried out randomly on different samples, or due to the loss of some of the data while transporting or transferring. This part of the study aims to provide geotechnical engineers with a support tool for soil classification and evaluation of the soil properties.

As mentioned earlier tills are variable and complex materials and a wide range of factors influences their behaviour. Subdividing them into more specific types or classes can reduce the problems arising from the variability of the tills. This subdivision is based on certain characteristics that are common for the members of the same class of ground. The classification in the British Soil Classification system is based on the grain size (particle size distribution), liquid limit, plasticity index and the organic content. One model, which was followed in earlier parts of this study, put the different layers into units (Robertson et al, 1994). It was pointed out that relying only on the description of the soil is insufficient for classifying and evaluating the properties of glacial tills. As it was seen in chapter 5 many properties of the different glacial units overlap which can result in inaccurate classification and evaluation in the behaviour of these soils. In this part of the study Neural Networks are used to investigate their potential in classifying glacial tills according to their index parameters. Following the model introduced by Robertson et al (1994), as shown in Figure 2.8, three possible groups are available for the classification of tills namely Units 1, 2 and 3.

The system was trained with complete sets of data taken from the database. It takes various index parameters as input and attempts to classify them into one of the above units. For the training set the data were pre-classified based on their index properties and their description. As mentioned earlier the data need to be tagged as input, output, training, cross validation and testing in order for the software to recognise which datasets to use at each stage. The output for the classification is in the form of 1's and 0's. To provide the network with these classification, each sample that belongs to a certain unit will get the value 1 for the correct unit and the value 0 for the other units as shown in Table 7.1.

Table 7.1: Sample of input and output data used as part of the training set for classification of till units.

	INPUT								OUTPUT		
Description	Depth (m)	ρ (Mg/m^3)	ρ_D (Mg/m^3)	NMC (%)	PL (%)	LL (%)	PI	LI	*UNIT 1*	*UNIT 2*	*UNIT 3*
Firm orange brown mottled grey sandy gravelly CLAY.	1.5	1.92	1.5	26.8	19	46	27	0.289	*1*	*0*	*0*
Firm to stiff brown very sandy CLAY	2.55	2.04	1.67	19.6	18	38	20	0.080	*0*	*1*	*0*
Very stiff grey brown sandy gravelly CLAY with occasional cobbles and gravels	5.7	2.17	1.93	12.9	15	33	18	-0.117	*0*	*0*	*1*

A total number of 840 complete datasets from five sites in Northumberland, namely Steadsburn, Hathery Lane, Bebside, Acklington and Stobswood, were chosen from which 740 data sets were used for training the network, 40 for cross validation and 60 for testing. To avoid biasing the learning towards a series of patterns in which the data are ordered a process called Data Sequencing was used in which the data were presented in random order as the learning set.

In order to be able to compare the classification of the Neural Network with the classification based on their plasticity characteristics the selected data were plotted on a standard plasticity chart as shown in Figure 7.3.

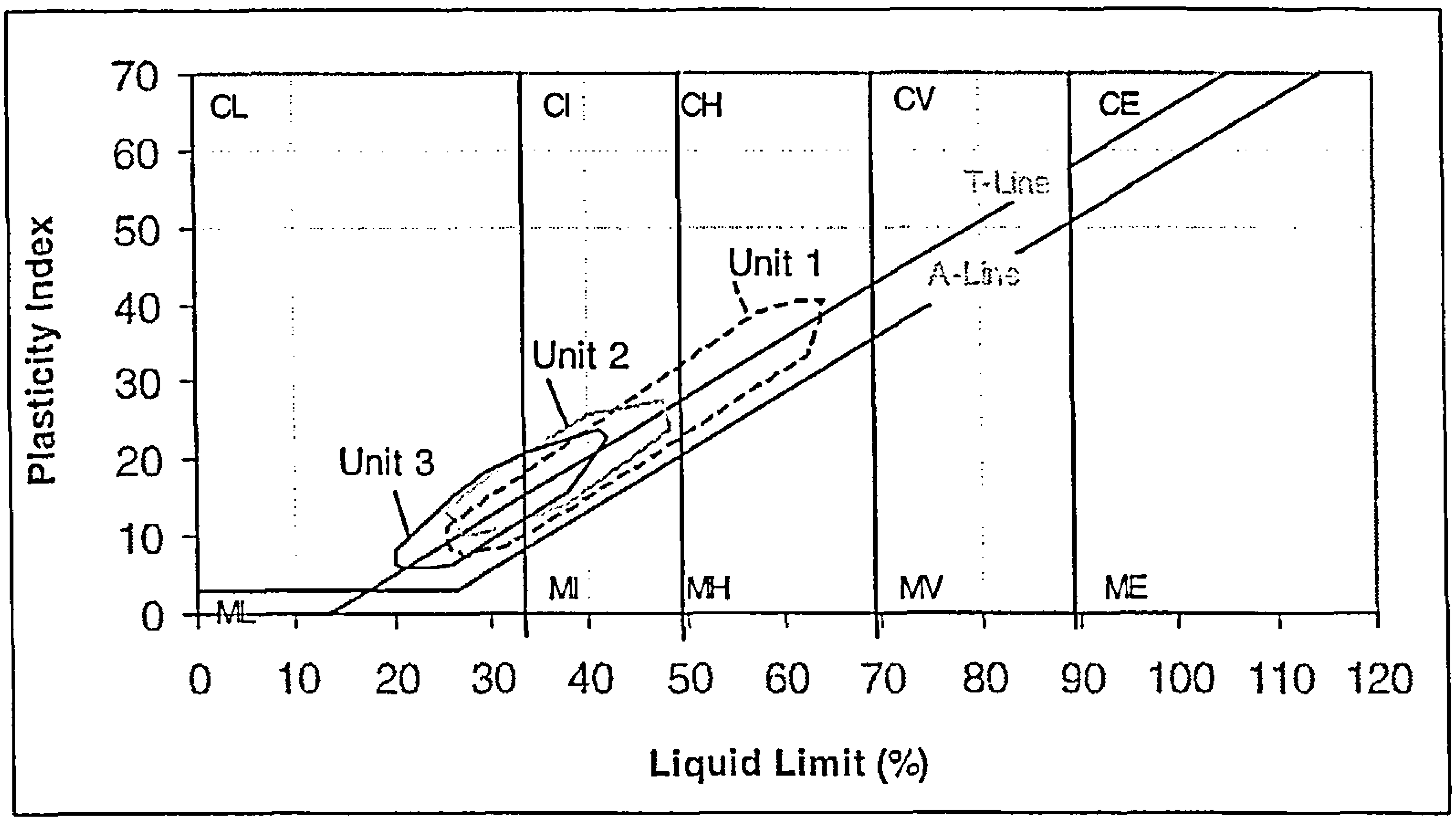


Figure 7.3: Data used for the training of the Neural Network for classification purposes on a plasticity chart.

It can clearly be seen from Figure 7.3 that many of the data from Units 1, 2, and 3 fall within the same range and overlap. Other parameters are required in order to distinguish between the Units and classify them more accurately. For this purpose several tests were carried out using Neural Networks in which Unit 1, 2 and 3 were used as the output for the classification, and the inputs were different index parameters which varied for each test. The learning process follows the process explained in earlier sections of this chapter.

In order to find the best network topology for the purpose of classification several tests were carried out with the same inputs but different numbers of hidden layers and hidden units. Networks with 1, 2, 3 and 4 hidden layers were constructed. The number of hidden units in each layer was then varied in order to find a suitable topology. It was found that networks with only one hidden layer were not able to perform well and resulted in high error rates. Networks with two hidden layers performed generally better. The addition of more hidden layers did not have a great effect on the results but would add unnecessarily to the complexity of the network, which would slow the training process down. Similarly the use of too many hidden neurons in the hidden layers would only affect the speed of the network whereas in networks with too few hidden neurons the network was unable to perform well. In general based on the experiments carried out during this study, a network with two hidden layers performed quite well both in terms of the final network output and the speed of training. The first hidden layer had twice as many hidden neurons as the number of inputs, and the second layer contained twice as many neurons as the number of output units. For instance for a network with 4 inputs 3 outputs, the first hidden layer would contain 8 neurons and the second hidden layer would contain 6 hidden neurons. This structure proved to have enough complexity for a good performance. It was also found that using different training algorithms, such as Sigmoid function or Tangential function, did not make a big difference in the final output of the network. It is suggested to try different algorithms in order to find the best performance for any specific case.

The results presented here are the final output and performance of Neural Networks with two hidden layers, where the neurons use the Sigmoid function. Table 7.2 shows the results of the best network performance in detail. This is followed by Table 7.3 with a summary of the performance of networks with different inputs.

Table 7.2: Best network performance for classification of till units.

Input	ρ (Mg/m3), W (%), LL (%)			
No. of hidden layers	2			
No. of hidden units	Layer 1: 6	Layer 2: 6		
Training function	Sigmoid			
No. of epochs	8000			
Training	**Output / Desired**	*Unit 1*	*Unit 2*	*Unit 3*
	Unit 1	238	8	0
	Unit 2	12	232	4
	Unit 3	0	10	236
	Performance	***Unit 1***	***Unit 2***	***Unit 3***
	MSE	0.02	0.05	0.05
	MAE	0.11	0.21	0.15
	Min Abs Error	0.00	0.00	0.00
	Max Abs Error	0.89	0.81	0.80
	r	0.94	0.89	0.94
	Percent Correct	95.20	92.80	92.60
Cross Validation	**Output / Desired**	*Unit 1*	*Unit 2*	*Unit 3*
	Unit 1	11	0	0
	Unit 2	0	16	0
	Unit 3	0	2	11
	Performance	***Unit 1***	***Unit 2***	***Unit 3***
	MSE	0.04	0.23	0.04
	MAE	0.18	0.28	0.09
	Min Abs Error	0.00	0.00	0.00
	Max Abs Error	0.99	1.00	0.45
	r	0.91	0.87	0.95
	Percent Correct	100.00	88.90	100.00
Testing	**Output / Desired**	*Unit 1*	*Unit 2*	*Unit 3*
	Unit 1	19	0	0
	Unit 2	0	23	1
	Unit 3	0	0	17
	Performance	***Unit 1***	***Unit 2***	***Unit 3***
	MSE	0.01	0.02	0.01
	MAE	0.05	0.08	0.05
	Min Abs Error	0.00	0.00	0.00
	Max Abs Error	0.50	0.66	0.64
	r	0.98	0.95	0.97
	Percent Correct	100.00	100.00	94.40

- Input parameters used for classification by the network and details of network topology are written at the top rows of the table
- Classification (for training, cross validation and testing):
  Output / Desired - eg. during training 241 sets of data out of 250 were correctly identified as samples from Unit1 and 9 out of 250 samples were incorrectly identified as Unit2
- Network performance:
  MSE = Mean Square Error , MAE = Mean Absolute Error , Min Abs Error = Minimum Absolute Error , Max Abs Error = Maximum Absolute Error , r = Linear Correlation Coefficient,
  Percent correct = Percentage of cases correctly identified by network

Table 7.3: Showing the results of training, cross validation and testing process for the network

Input							Process	Output		
ρ (Mg/m^3)	ρ$_D$ (Mg/m^3)	W (%)	PL (%)	LL (%)	PI	LI		Unit 1 (% Correct)	Unit 2 (% Correct)	Unit 3 (% Correct)
*		*	*	*			Training	94.4	91.2	93.8
*		*	*	*			Cross Validation	100.0	77.8	100.0
*		*	*	*			Testing	100.0	82.6	94.4
	*	*	*	*			Training	95.2	92.4	94.6
	*	*	*	*			Cross Validation	100.0	77.8	100.0
	*	*	*	*			Testing	100.0	91.3	94.4
*		*		*			Training	95.2	92.8	92.6
*		*		*			Cross Validation	100.0	88.9	100.0
*		*		*			Testing	100.0	100.0	94.4
	*	*		*			Training	94.8	92.4	92.6
	*	*		*			Cross Validation	100.0	84.8	100.0
	*	*		*			Testing	100.0	100.0	94.4
*		*	*				Training	95.6	91.6	94.2
*		*	*				Cross Validation	90.9	77.8	100.0
*		*	*				Testing	100.0	78.3	100.0
	*	*	*				Training	95.6	91.6	94.2
	*	*	*				Cross Validation	90.9	77.8	100.0
	*	*	*				Testing	100.0	78.3	100.0
*		*			*		Training	93.6	91.6	92.6
*		*			*		Cross Validation	100.0	72.2	92.3
*		*			*		Testing	100.0	91.3	94.4
	*	*			*		Training	93.6	92.0	92.6
	*	*			*		Cross Validation	100.0	77.8	100.0
	*	*			*		Testing	100.0	91.3	94.4
*			*	*			Training	86.8	80.0	84.6
*			*	*			Cross Validation	81.8	72.2	90.9
*			*	*			Testing	94.7	78.3	94.4
	*		*	*			Training	88.4	83.2	86.0
	*		*	*			Cross Validation	81.4	77.8	90.9
	*		*	*			Testing	94.7	82.6	94.4
*		*				*	Training	95.2	91.2	93.8
*		*				*	Cross Validation	90.9	72.2	100.0
*		*				*	Testing	100.0	78.3	94.4
	*	*				*	Training	95.2	91.2	94.2
	*	*				*	Cross Validation	90.9	77.8	100.0
	*	*				*	Testing	100.0	78.3	100.0
		*	*	*			Training	95.6	91.6	94.2
		*	*	*			Cross Validation	100.0	77.8	100.0
		*	*	*			Testing	100.0	87.0	94.4
*		*					Training	92.0	88.0	92.6
*		*					Cross Validation	90.9	72.2	90.9
*		*					Testing	100.0	87.0	88.9
*			*				Training	84.0	74.8	80.8
*			*				Cross Validation	81.8	55.6	100.0
*			*				Testing	89.5	56.5	94.4
*				*			Training	86.0	77.8	84.8
*				*			Cross Validation	81.8	61.1	90.9
*				*			Testing	94.7	87.0	94.4

Table 7.3 continued

Input							Process	Output		
ρ (Mg/m³)	ρD (Mg/m³)	W (%)	PL (%)	LL (%)	PI	LI		Unit 1 (% Correct)	Unit 2 (% Correct)	Unit 3 (% Correct)
*					*		Training	89.6	81.6	86.2
*					*		Cross Validation	72.7	66.7	90.9
*					*		Testing	94.7	69.6	94.4
*						*	Training	83.2	81.6	80.4
*						*	Cross Validation	81.8	66.7	72.7
*						*	Testing	84.2	69.6	72.2
		*	*				Training	95.2	90.4	93.0
		*	*				Cross Validation	100.0	77.8	100.0
		*	*				Testing	100.0	87.0	100.0
		*		*			Training	94.2	91.4	93.4
		*		*			Cross Validation	100.0	83.3	100.0
		*		*			Testing	100.0	87.0	94.4
			*	*			Training	81.6	70.8	76.0
			*	*			Cross Validation	81.8	83.3	72.7
			*	*			Testing	84.2	82.6	94.4
				*	*		Training	82.4	72.0	76.0
				*	*		Cross Validation	81.8	77.8	72.7
				*	*		Testing	84.2	87.0	83.3
		*					Training	88.4	93.2	90.2
		*					Cross Validation	90.9	88.9	90.9
		*					Testing	100.0	91.3	94.4
	*						Training	83.2	74.0	81.6
	*						Cross Validation	81.8	61.1	81.8
	*						Testing	94.7	60.9	72.2
						*	Training	70.0	37.2	80.0
						*	Cross Validation	72.7	36.4	63.6
						*	Testing	73.7	30.4	72.2

As it can be seen from Table 7.3 the best results were achieved from networks with the following inputs:

- Bulk Density, Natural moisture content, Liquid Limit
- Dry Density, Natural moisture content, Liquid Limit
- Natural moisture content, Plastic limit
- Natural moisture content, Liquid Limit

The networks with the above inputs performed well during any of the training, cross validation and testing stages compared to networks with other inputs. The results confirm that the natural moisture content, the plastic limit and the liquid limit are the most important parameters that need to be considered for the classification of glacial deposits. The presence of either bulk or dry density has also helped the performance of the network and the best performing network included the density as one of its input parameters. As shown in Figure 7.3 relying solely on one property such as the plasticity is not sufficient for an accurate classification. The results of the Neural Network classification also confirm that by considering several different properties of the soil along with each other will result in a much more reliable classification and that Neural technology has the potential to carry out this task with high accuracy.

The results shown in Tables 7.3 suggest that most errors in the classification of each unit are due to the similarities of the units that lie next to each other. This is especially recognisable when comparing the performance of the networks during training. Since most of the index parameters of Unit 2 are between or close to those of Units 1 and 3 the network has difficulty in identifying this unit and has the most error in classifying samples of this unit. However as the percentage of units correctly identified confirms, the networks still were able to classify most cases correctly.

7.6 Prediction of undrained shear strength

In attempting to design, analyse and control the behaviour of systems, one must first be able to model and predict their complex behaviours. It is possible to use regression methods to establish an empirical function from acquired data that relate some parameters to each other. However, the behaviour of many of these systems is controlled by non-linear interrelationships (Chao and Skibniewski, 1998). In geotechnical engineering, empirical relationships are often used to estimate certain engineering properties of soils. In the previous chapter it was tried to find the correlation between various geotechnical parameters of tills using traditional statistical methods or existing empirical correlations. For complex situations an alternative computing model is needed that can adopt itself to the relationships present in the data and provide a mapping function for such relationships.

In this part of the study Neural Networks are used to find a way of predicting the undrained shear strength of glacial soils. The system is trained with complete sets of data taken from the database. It takes various index parameters as input and attempts to predict the undrained shear strength of the soil. These index parameters are plotted against undrained shear strength in Figure 7.4. A total of 960 complete datasets from eight locations in Northumberland, namely Acklington, Bebside, Chester House, Colliersdean, Hathery Lane, Steadsburn, Stobswood and Widdrington were chosen for this purpose from which 850 sets were used as input, 60 for testing and 50 for cross validation. For the design of the networks the back-propagation method and the sigmoid function were used. The datasets include parameters from Units 1, 2, 3 and 4LC.

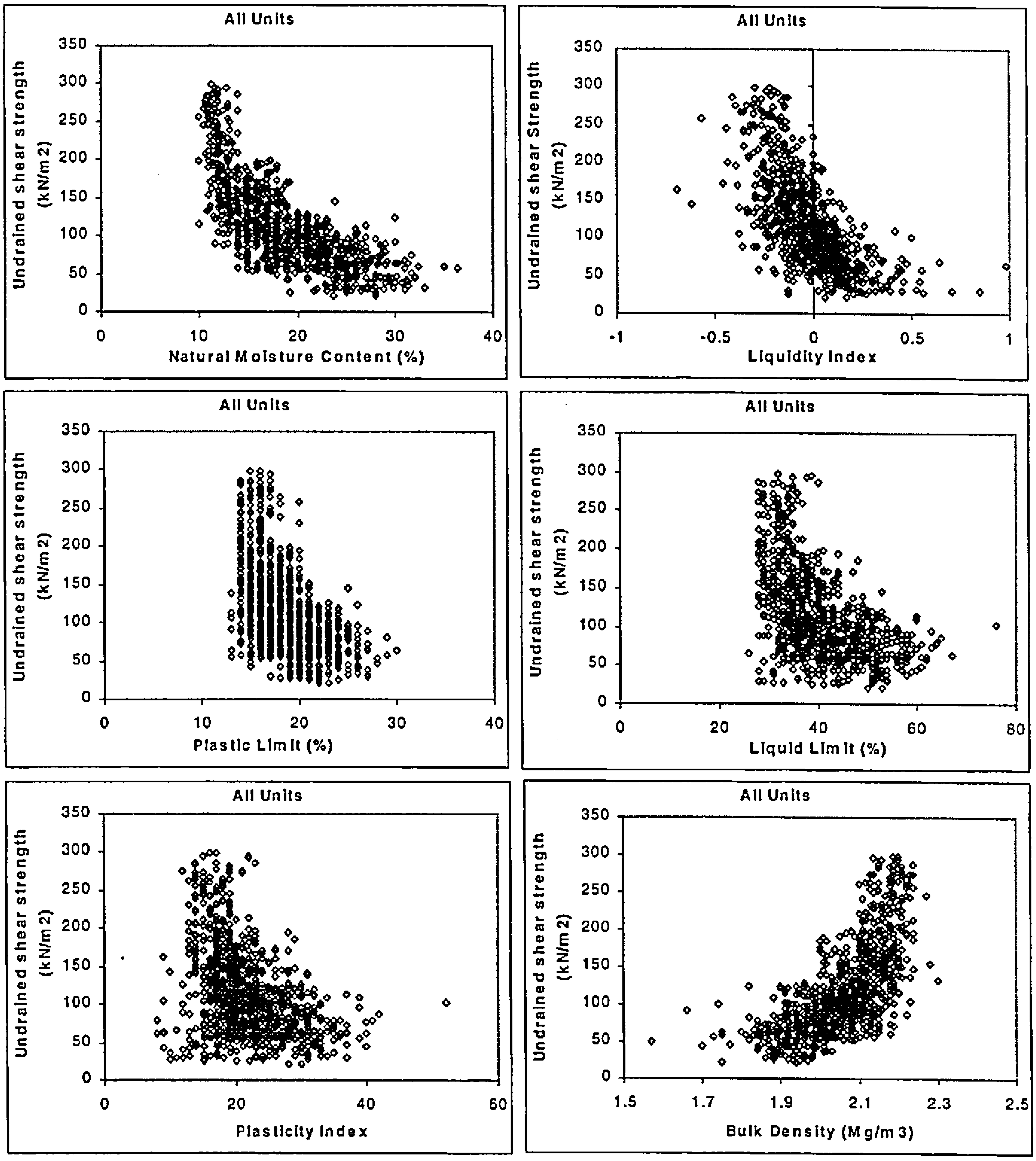


Figure 7.4: Plot of undrained shear strength against some index parameters used as inputs to train the Neural Network.

The topology of the networks used for predicting the undrained shear strength is similar to the networks used for classification as explained in the previous section. Networks with two hidden layers were found to be adequate for this purpose.

A number of tests were carried out and the results are shown in Figures 7.5 to 7.12. The training results are shown using the Mean Absolute Error (MAE) calculated for each set of input. The cross validation and testing results display the actual c_u value and the value predicted by the network. It can be seen that in most cases the predicted value follows the pattern of the actual shear strength values. Although extreme values were not included in the dataset used but it can be seen that the majority of errors occur where the actual values are higher or lower that the average. The error could be reduced by limiting the data to a certain range. Networks using the following inputs achieved the best results:

- Bulk density, Natural moisture content, Plastic Limit, Liquid Limit
- Bulk density, Natural moisture content, Plastic Index
- Bulk density, Natural moisture content, Liquidity Index
- Natural moisture content, Plastic Limit, Liquid Limit
- Natural moisture content, Liquidity Index

Histograms have been prepared of the percentage error of the predicted values of the undrained shear strength and can be seen in Figure 7.5 to Figure 7.12. The average percentage error during training is approximately 27.5% and for the cross validation and testing is approximately 25% and 28% respectively. The figures also show the plots of the actual target values and the values predicted by the network during cross validation and testing.

A similar approach was taken in order to investigate the potential of Neural Networks in predicting effective shear strength parameters c' and φ' using index parameters as input. However, due to insufficient data the Network was not able to train and make any predictions. This could be investigated in future studies where more data are available.

Input: BDEN, NMC, PI					
Training		Cross Validation		Testing	
Performance	*TRIG-CU*	*Performance*	*TRIG-CU*	*Performance*	*TRIG-CU*
MSE	1221.31	MSE	990.77	MSE	1181.41
MAE	26.95	MAE	26.10	MAE	27.80
Min Abs Error	0.04	Min Abs Error	6.12	Min Abs Error	0.24
Max Abs Error	119.30	Max Abs Error	83.65	Max Abs Error	75.40
r	0.80	r	0.89	r	0.73

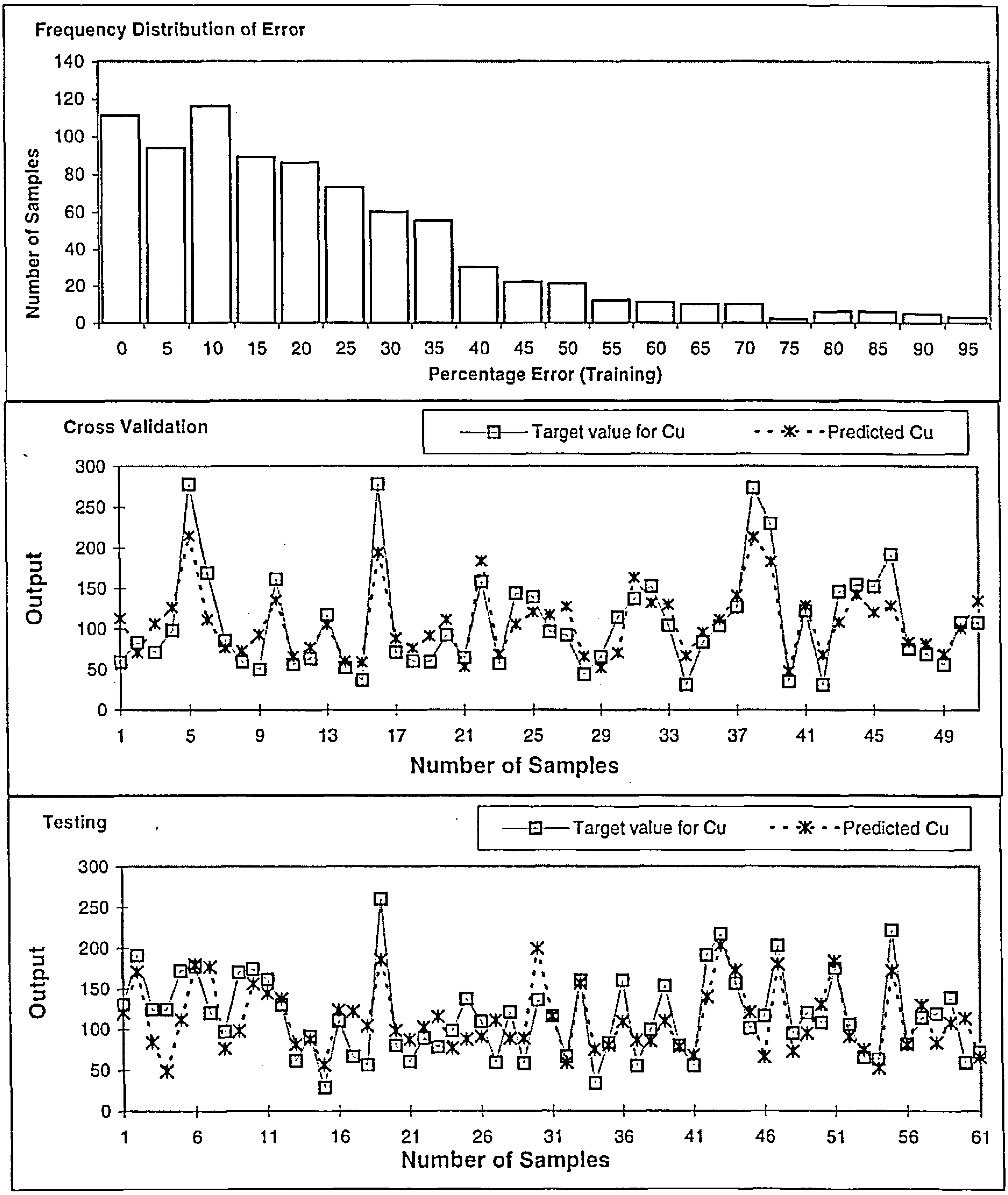


Figure 7.5: Neural Network performance using ρ, w, PI as input for prediction.

Input: W, PL, LL					
Training		Cross Validation		Testing	
Performance	*TRIG-CU*	*Performance*	*TRIG-CU*	*Performance*	*TRIG-CU*
MSE	1247.50	MSE	1057.22	MSE	1169.07
MAE	26.80	MAE	23.31	MAE	27.57
Min Abs Error	0.01	Min Abs Error	0.72	Min Abs Error	0.45
Max Abs Error	122.30	Max Abs Error	88.47	Max Abs Error	76.17
r	0.79	r	0.87	r	0.74

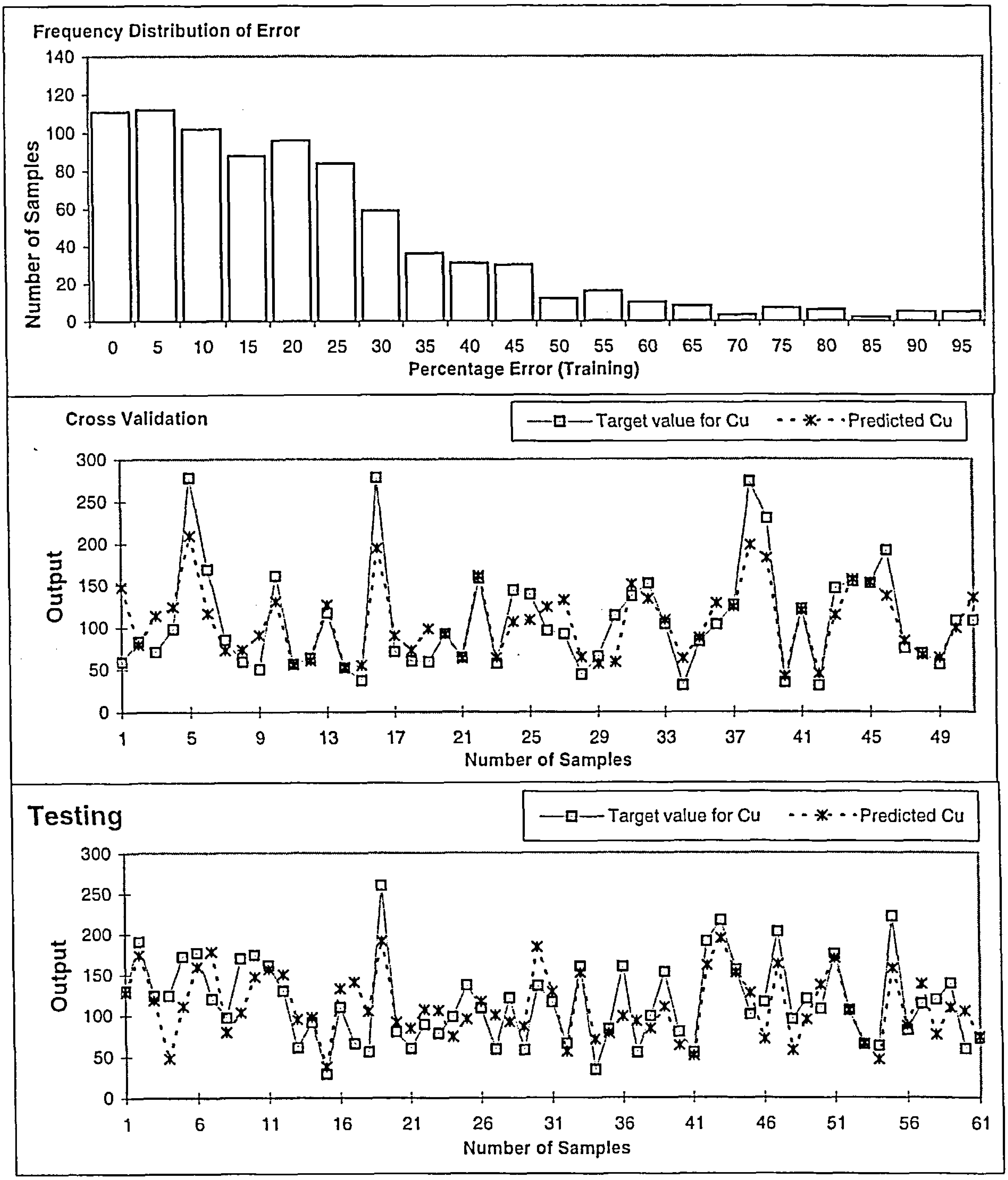


Figure 7.6: Neural Network performance using w, PL, LL as input for prediction.

Input: BDEN, NMC, LI					
Training		Cross Validation		Testing	
Performance	*TRIG-CU*	*Performance*	*TRIG-CU*	*Performance*	*TRIG-CU*
MSE	1218.36	MSE	912.83	MSE	1073.91
MAE	26.75	MAE	23.29	MAE	25.99
Min Abs Error	0.02	Min Abs Error	0.11	Min Abs Error	1.69
Max Abs Error	121.57	Max Abs Error	78.30	Max Abs Error	73.66
r	0.80	r	0.90	r	0.76

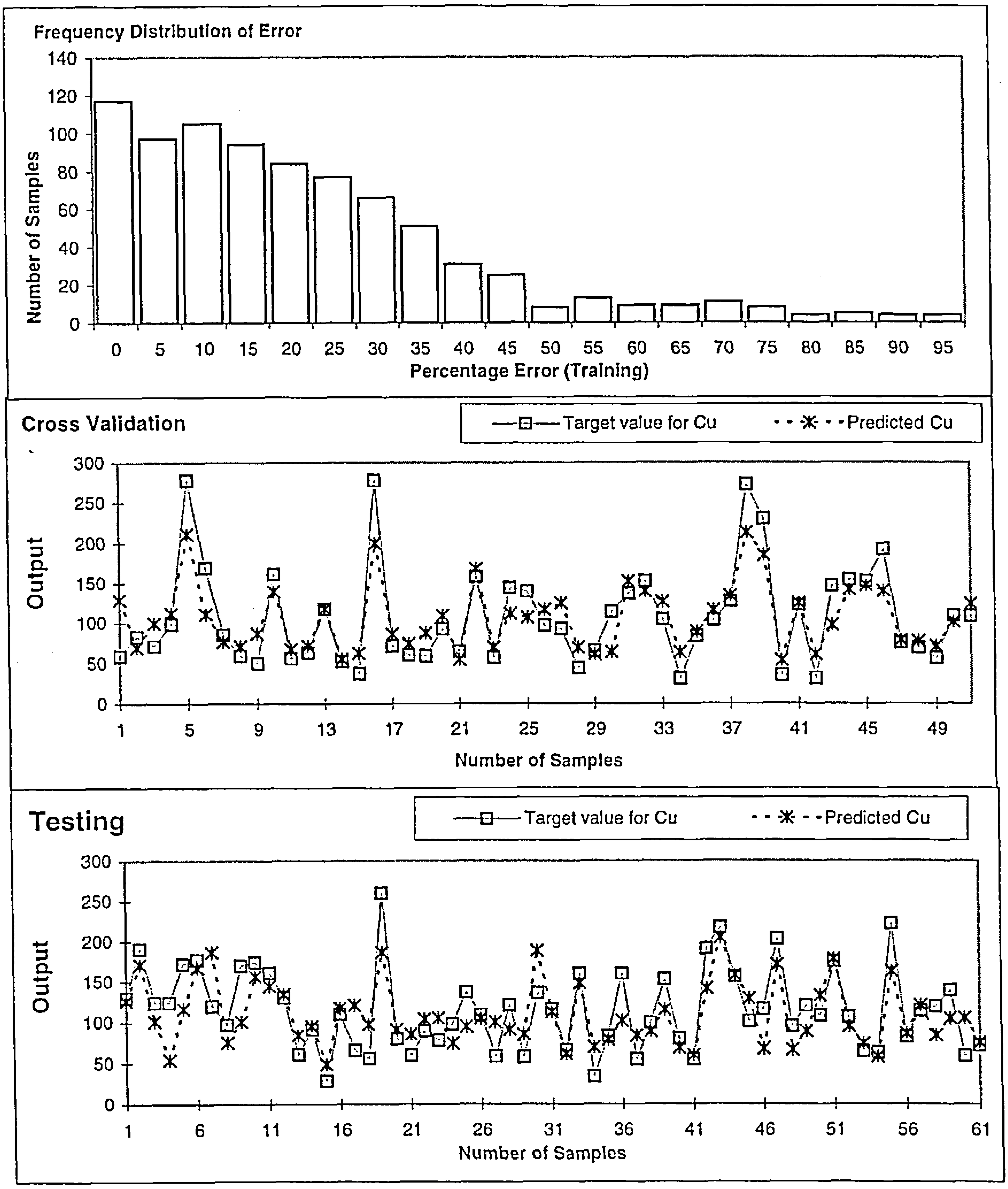


Figure 7.7: Neural Network performance using ρ, w, LI as input for prediction.

Input: Bulk density, Natural water content, Plastic Limit, Liquid limit					
Training		Cross Validation		Testing	
Performance	*TRIG-CU*	*Performance*	*TRIG-CU*	*Performance*	*TRIG-CU*
MSE	1146.15	MSE	877.47	MSE	1111.09
MAE	25.58	MAE	23.18	MAE	25.88
Min Abs Error	0.06	Min Abs Error	0.89	Min Abs Error	0.11
Max Abs Error	115.38	Max Abs Error	72.26	Max Abs Error	80.14
r	0.81	r	0.90	r	0.75

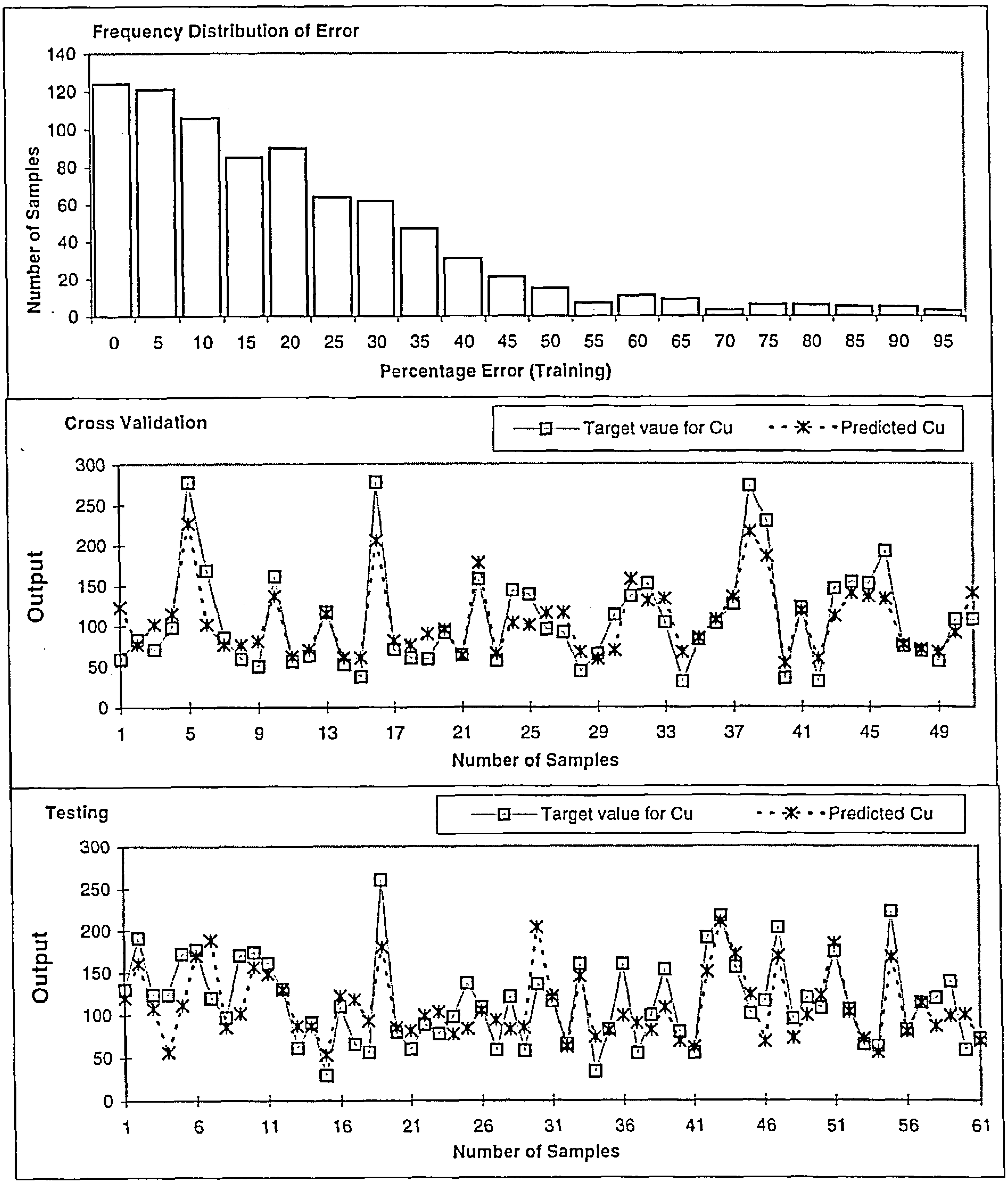


Figure 7.8: Neural Network performance using ρ, w, PL, LL as input for prediction.

Input: NMC, LI					
Training		Cross Validation		Testing	
Performance	*TRIG-CU*	*Performance*	*TRIG-CU*	*Performance*	*TRIG-CU*
MSE	1250.12	MSE	1022.35	MSE	1149.00
MAE	27.14	MAE	23.68	MAE	27.59
Min Abs Error	0.11	Min Abs Error	0.09	Min Abs Error	1.95
Max Abs Error	130.07	Max Abs Error	82.99	Max Abs Error	72.26
r	0.79	r	0.88	r	0.74

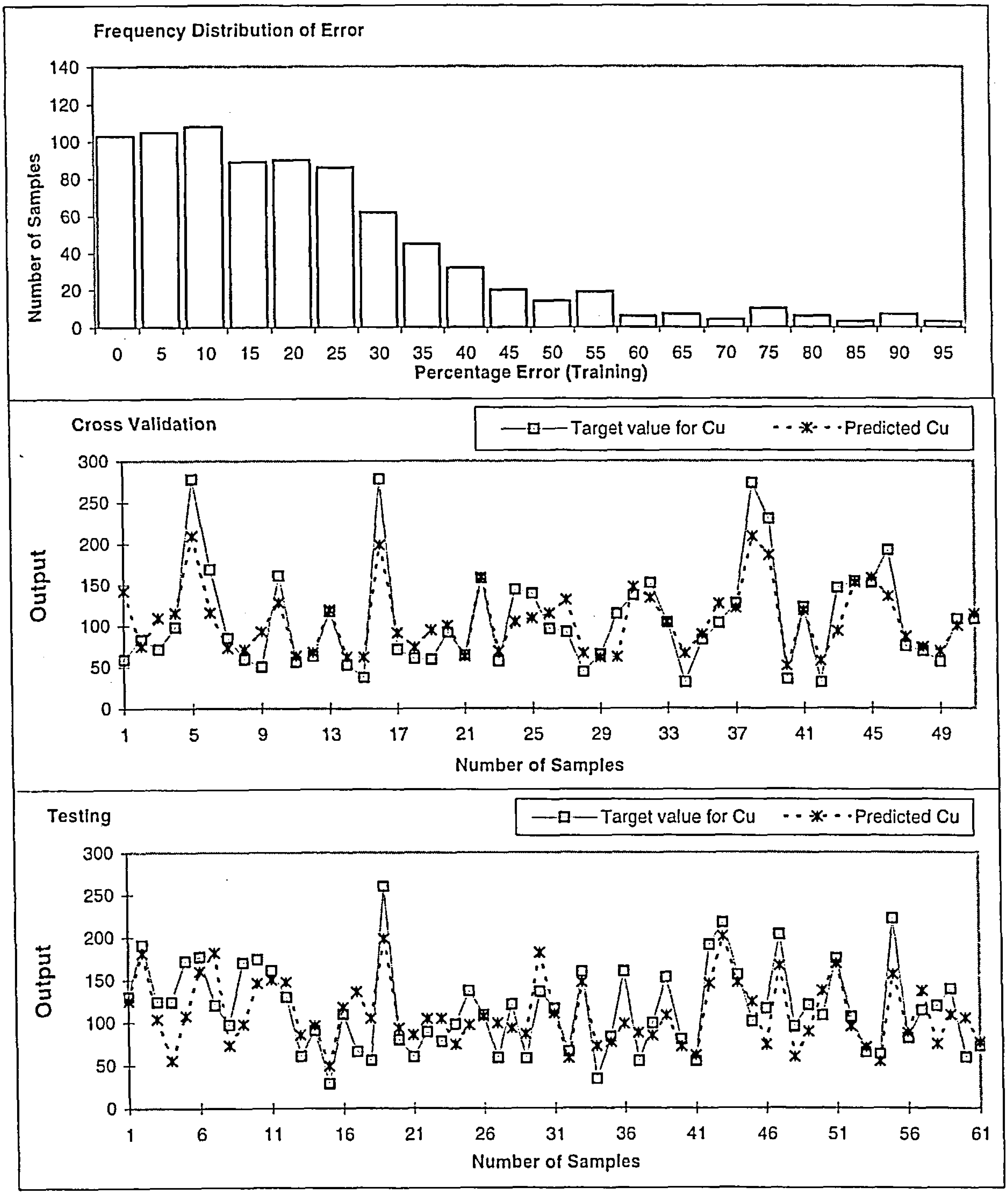


Figure 7.9: Neural Network performance using w, LI as input for prediction.

Input: NMC, PI					
Training		Cross Validation		Testing	
Performance	*TRIG-CU*	*Performance*	*TRIG-CU*	*Performance*	*TRIG-CU*
MSE	1319.27	MSE	1206.91	MSE	1305.60
MAE	28.05	MAE	26.64	MAE	29.59
Min Abs Error	0.01	Min Abs Error	2.43	Min Abs Error	0.30
Max Abs Error	127.12	Max Abs Error	93.05	Max Abs Error	78.36
r	0.78	r	0.85	r	0.70

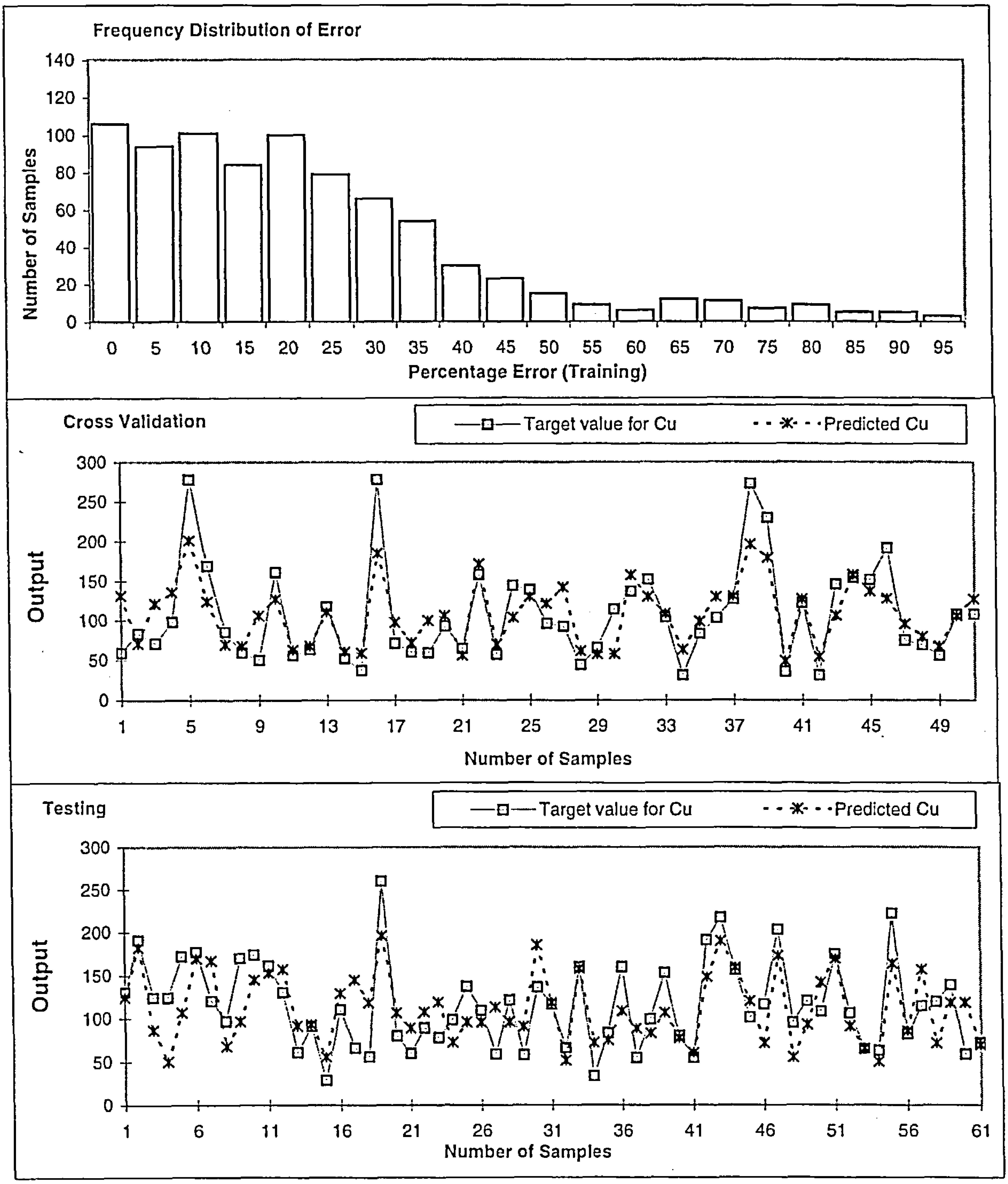


Figure 7.10: Neural Network performance using w, PI as input for prediction.

Input: NMC					
Training		Cross Validation		Testing	
Performance	*TRIG-CU*	*Performance*	*TRIG-CU*	*Performance*	*TRIG-CU*
MSE	1323.69	MSE	1203.62	MSE	1298.86
MAE	28.18	MAE	26.49	MAE	29.55
Min Abs Error	0.09	Min Abs Error	0.20	Min Abs Error	0.40
Max Abs Error	129.60	Max Abs Error	93.32	Max Abs Error	77.19
r	0.78	r	0.85	r	0.70

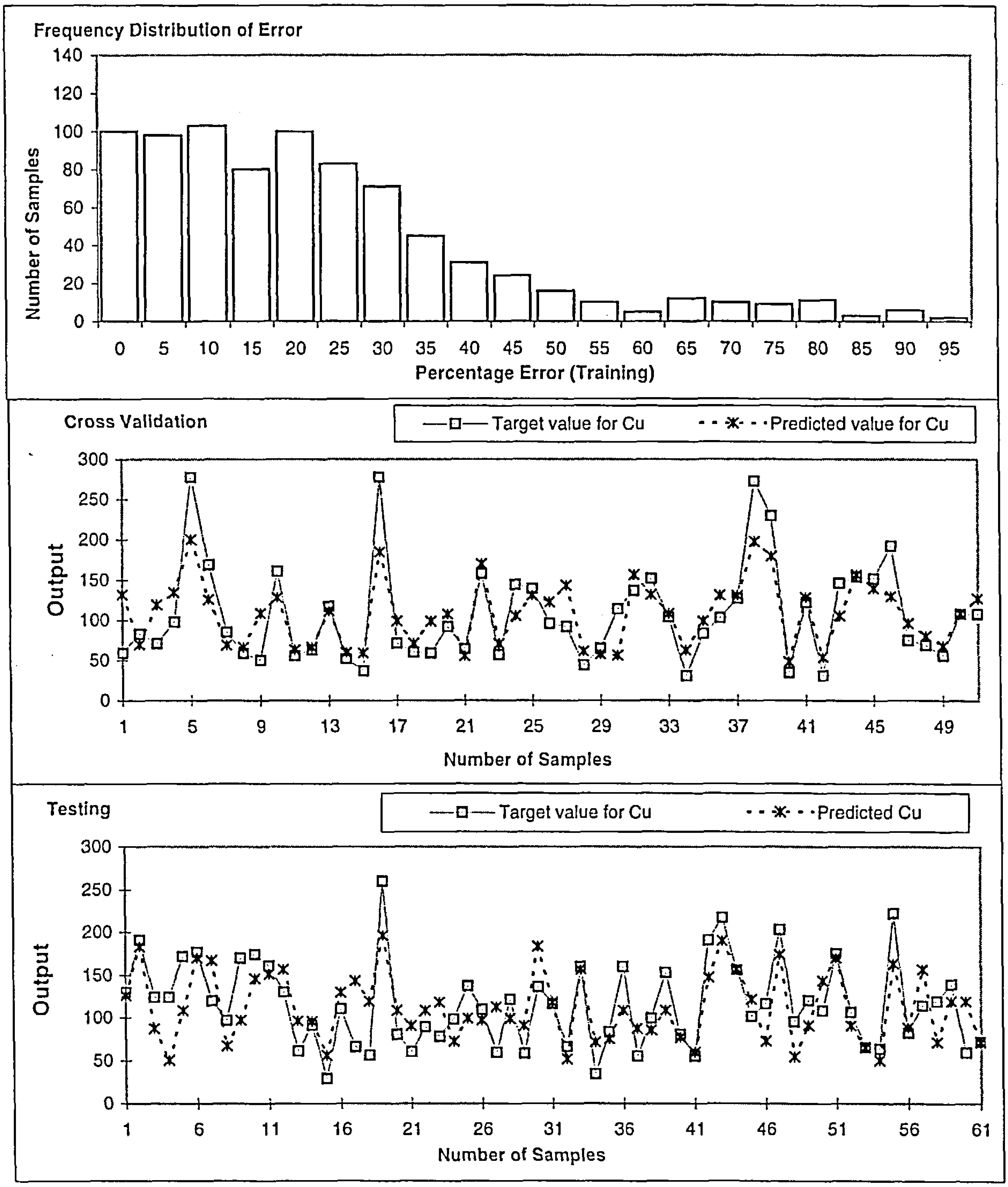


Figure 7.11: Neural Network performance using w as input for prediction.

Input: LI					
Training		Cross Validation		Testing	
Performance	*TRIG-CU*	*Performance*	*TRIG-CU*	*Performance*	*TRIG-CU*
MSE	1748.61	MSE	1485.14	MSE	1429.18
MAE	31.54	MAE	29.23	MAE	31.16
Min Abs Error	0.06	Min Abs Error	2.39	Min Abs Error	0.44
Max Abs Error	141.34	Max Abs Error	108.08	Max Abs Error	94.40
r	0.69	r	0.80	r	0.67

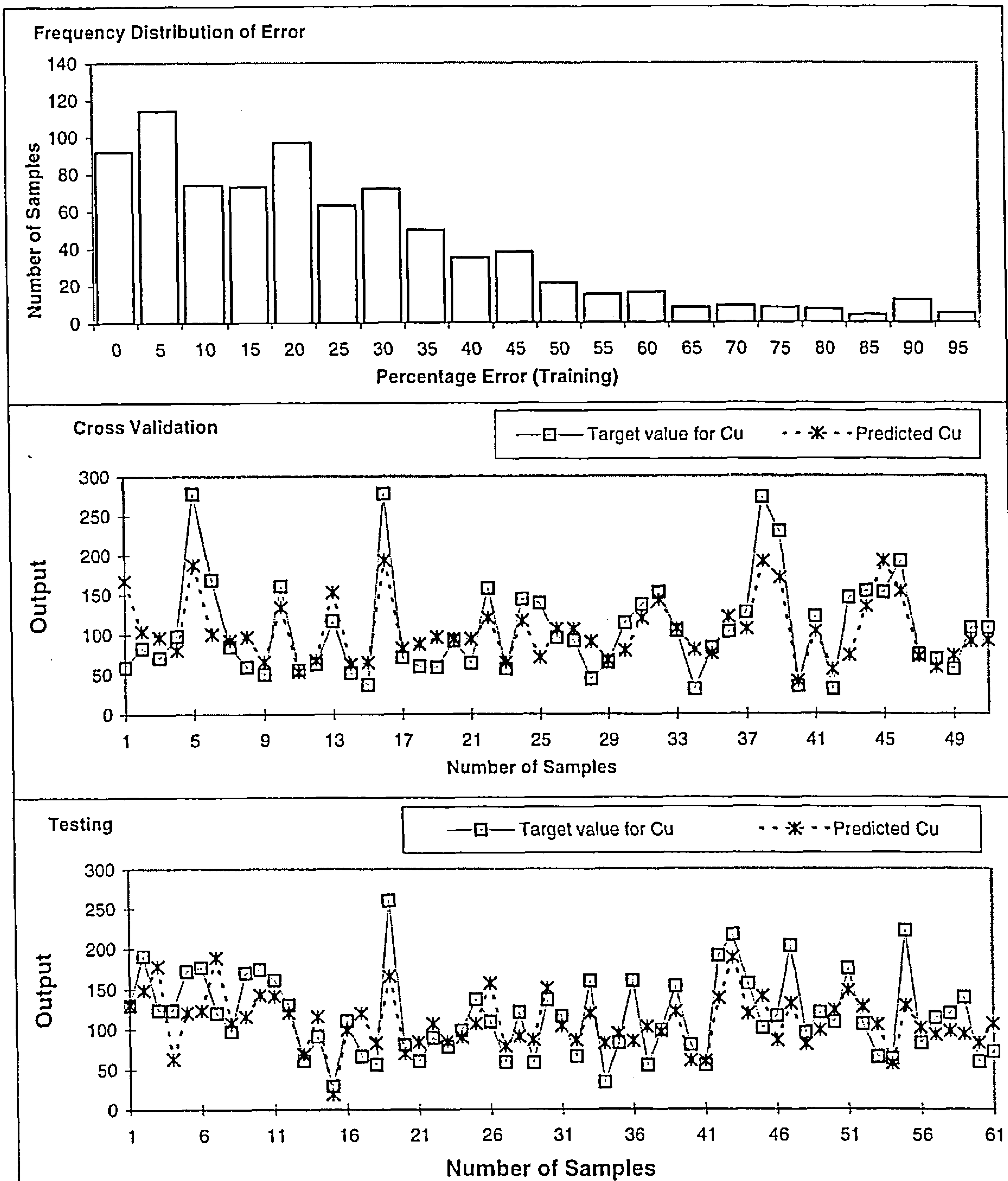


Figure 7.12: Neural Network performance using LI as input for prediction.

7.7 Conclusion

In this chapter the potential of Neural Networks for the purpose of classification of different glacial till units, and the prediction of undrained shear strength of glacial soil was investigated.

As already mentioned there are no rules for the design of network topologies for different applications. The performance of a network may be affected by the speed of the processing unit of the computer, and the code in which the software is written. Therefore a number of different network topologies were used in order to find a suitable network for both classification and prediction purposes. A suitable method for the design of network topologies was suggested and successfully implemented for this study.

The Neural Network was able to successfully identify various units and classify them according to their index parameters. Some of the errors during classification are due to the similarities of the various units, especially Units 1 and 2.

The network was also able to predict the undrained shear strength of glacial soils using various index parameters of the soil as input. This could be useful tool to predict values for incomplete datasets where strength test results are not available.

Chapter 8

Summary and conclusion

8.1 Introduction

Ground Investigations encompass information relating to various parameters and site conditions, which have been collected by different techniques and in different formats for different purposes. Although a large number of ground investigations have been carried out in glacial terrains in the UK only a fraction of the information they revealed is available to the geotechnical profession. The decision to develop NETDATA arose from a need to ensure that the information resulting from such ground investigations is stored, managed and distributed in an efficient and controlled manner. The requirement was also defined in the CIRIA report 1999 (Trenter, 1999).

In the past, data were being captured, processed and held in various formats, by different contractors at diverse locations. The high cost of identifying what data existed, the potential duplication of effort and the risk of data inconsistency all pointed to the need to develop a central, controlled database. The design of this database would mean that the interpretations and modelling essential to the safety assessment would be underpinned by a reliable data source. An aim of this study was therefore to create a useful source of information about the properties of glacial till.

In the following section a summary of the work carried out will be given. Results achieved from this study will also be discussed.

8.2 Summary of research

Glacial tills form nearly a continuous cover over most of northern England's landscape. It is considered to have been formed during the late Devensian age of the Quaternary period (Smith, 1994). As mentioned before tills are engineering soils, and the variable and often complex successions in which they occur have led to problems on civil and mining engineering projects. The geology, successions, and the different types of till in Northern England have been reviewed and some examples of the problems caused due to the presence of tills were given. The research activities carried out throughout this project are reviewed briefly in the following sections.

8.2.1 Designing a geotechnical database

NETDATA is a database that has been designed and developed in order to fulfil the need of a reliable source of data on the geotechnical parameters of glacial tills in Northern England. Microsoft Access version 97 was found to be a suitable Relational DataBase Management System (RDBMS) with an appropriate interface and software tools for the design of NETDATA. The AGS Format was followed as a data model in order to put the available data into a standard format and ensure consistency and coherency between the data. Extensive use was made of the software capabilities and tools to provide a user-friendly and secure interface for handling data, and for carrying out various tasks such as searching for certain data and presenting them in different formats. The functionality of the database and its uses are shown in figure 8.1.

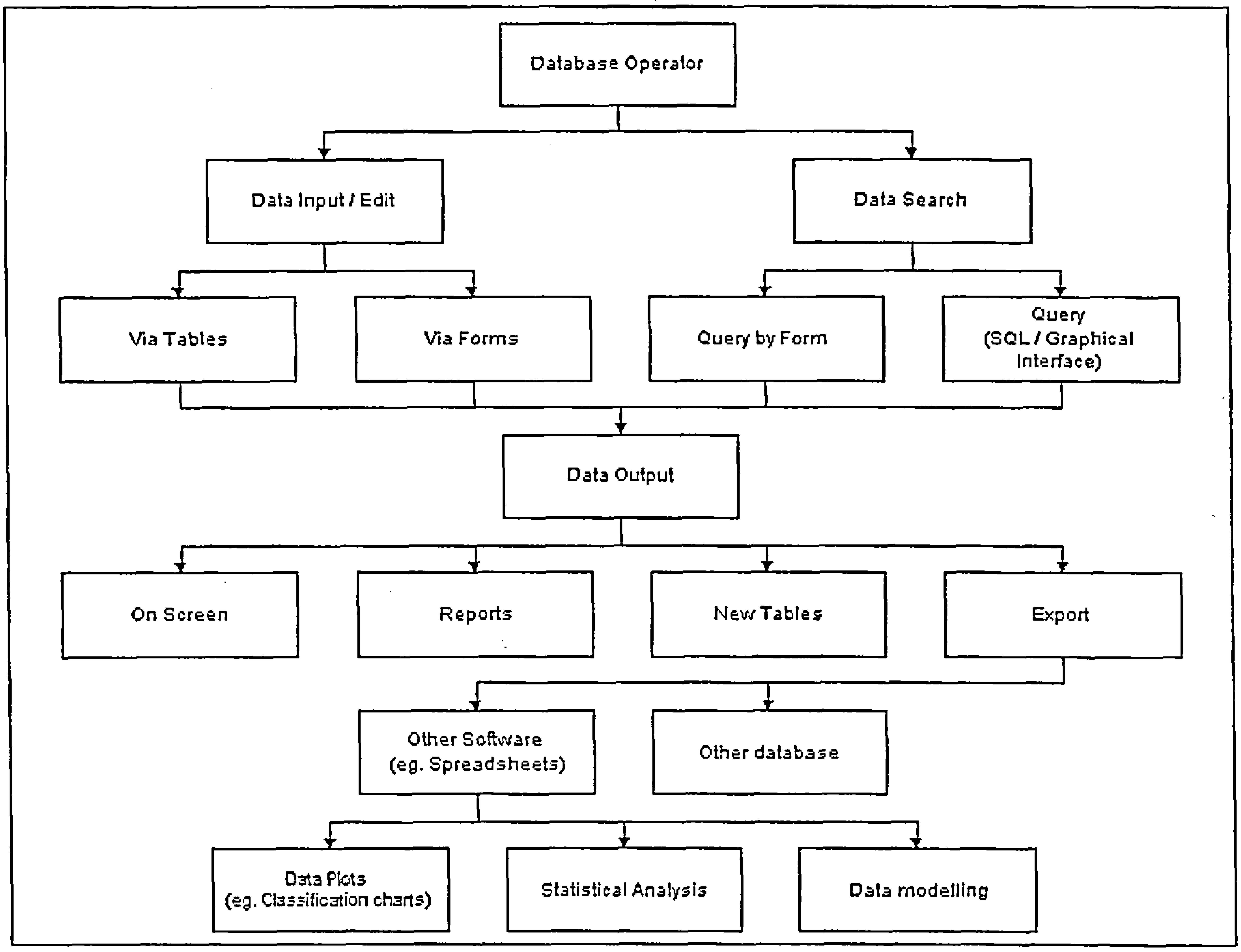


Figure 8.1: Flowchart showing the functionality of NETDATA.

The database stores and centralises available data for the tills from Northern England in a standard format that can easily be updated. At the end of this project, details of more than 1150 boreholes from 33 ground investigation projects in Northern England were recorded in the database. Results of soil mechanics laboratory tests on approximately 8300 samples are stored in NETDATA.

The database will be used as a single, central source of data, which imposes consistency by a standard data format and provides flexibility for further use. It is also an independent and cost-effective system in terms of data location and data management application. It aims to ensure that data are coherent and consistent, captured and processed to meet the needs of the industry, maintained in a secure and controlled environment, and to remain accessible as and when required.

8.2.2 Analysis of data

Tables with the summary of the data stored in the database were produced and presented in chapter 5. The data were studied and compared carefully. The study is based on the tripartite stratigraphy that has been introduced by previous researchers for the glacial sediments in Northern England. The properties of the glacial units were identified through a combination of geological and geotechnical properties. The analysis compared the properties of the different units from different locations to establish typical parameters and compare them with published data. An overview is given in table 8.1.

Table 8.1: Typical properties of Northern England glacial tills and glaciofluvial deposits

	Northumberland				Durham				Cumbria			
	Unit 1	Unit 2	Unit 3	Unit 4	Unit 1	Unit 2	Unit 3	Unit 4	Unit 1	Unit 2	Unit 3	Unit 4
ρ (Mg/m^3)	1.99	2.06	2.17	1.99	1.98	2.06	2.22	2.03	1.98	2.05	2.21	2.02
ρ_D (Mg/m^3)	1.63	1.73	1.93	1.61	1.63	1.73	1.96	1.62	1.64	1.72	1.96	1.68
e	0.63	0.54	0.39	0.66	0.66	0.55	0.36	0.66	0.65	0.57	0.36	0.60
NMC (%)	21.8	18.6	12.6	23.9	22.3	19.1	12.9	25.6	21.5	19.7	12.1	20.3
PL (%)	20.6	17.9	15.0	21.2	21.0	19.5	16.2	23.5	20.6	18.3	15.6	18.2
LL (%)	46.8	39.4	31.3	46.6	38.0	37.3	31.5	43.6	39.9	35.8	30.8	38.6
PI (%)	26.3	21.5	16.4	25.5	17.1	17.9	15.3	20.2	19.8	17.4	15.3	21.9
LI	0.038	0.019	-0.163	0.108	0.108	-0.012	-0.230	0.139	0.010	0.016	-0.237	0.128
<425 fraction	92.7	89.7	83.1	95.5	84.3	82.3	75.0	86.5	83.5	80.2	74.0	93.5
c_u (kN/m^2)	104.4	106.5	185.7	72.7	68.8	80.0	141.0	45.2	72.6	65.5	191.1	81.8

The index tests are a good quantitative indicator of the geotechnical properties of tills and are relied on to be definitive in respect to engineering classification, but since they are carried out on a specific fraction of a sample, the results can only reflect the behaviour of that fraction. Results of Atterberg limits lie about a straight line known as the T-line which is above and parallel to the A-line of Casagrande. The upper and lower tills fall mostly into the category of clays with low to high plasticity. PSD results indicate that the tills in Northumberland are mostly matrix dominant. Both the density and shear strength of glacial tills tend to increase with depth. It should be noted that the data seem to contain some extreme values, either being much higher or lower than expected for a certain glacial unit. These could be due to the variability of the material or due to errors in testing, or errors in reporting the results. Such results were included in the database and used throughout this project as provided in the ground investigation reports.

Empirical relationships between the different parameters were compared with relationships that have been suggested by other researchers. It was seen that many of the existing empirical equations do not fit the available data from the database. It was found that due to the variability of the glacial tills large scatters existed in the data which made the analysis difficult in many cases. It is suggested to carry out the analysis on a site-specific scale in order to be able to achieve better results.

8.2.3 Neural Network approach

Neural Networks have been used for classifying and predicting geotechnical design parameters of tills according to their index properties. Training a neural network consists of an iterative process in which the network is given the desired inputs along with the correct outputs. It then alters its weights to try and produce the correct output within a reasonable error margin. If it succeeds, it has learned the training set and is ready to perform upon previously unseen data (testing data). If it fails to produce the correct output it re-reads the input and again tries to produce the correct output. The weights are slightly adjusted during each iteration through the training set, known as a training cycle, until the appropriate weights have been established. Depending upon the complexity of the task to be learned, many thousands of training cycles may be needed for the network to correctly identify the training

set. Once the output is correct the weights can be used with the same network on unseen data to examine how well it performs. The whole idea of a neural network is to train the network on an input set and then to show the network a similar but different data set, which it has not seen before. The network should then be able to produce an appropriate output. Data stored within NETDATA were used for training and testing the networks.
Several tests were carried out using for both classification and prediction purposes. Since there are currently no guidelines available for the design of a suitable network topology, a number of designs were tested. It was found that networks with two hidden layers, where the first layer contains twice as many neurons as the number of inputs and the second layer contains twice as many neurons as the number of outputs, have a suitable topology and were able to reduce the error during training. Networks with less hidden layers or hidden neurons were too simple and could not perform well, whereas networks with more complexity would only affect the speed of the network and did not produce any better results.

Neural Networks proved to be reliable tools for the classification of glacial tills. Using index parameters of glacial till samples from a number of locations they were able to accurately identify them as part of a particular glacial unit. In the case of glacial tills, this classification method shows higher accuracy compared to the use of plasticity classification charts.

The Neural Networks were also able to predict the undrained shear strength of soil samples with relatively high accuracy using only the index parameters of the samples as input. It was intended to implement this method also for the prediction of effective shear strength parameters but due to the lack of sufficient data this part was omitted from this study and could be investigated in the future.

8.3 Some suggestions for further work

The creation of a database is commonly seen as an end in itself, a deliverable of a project. This view is unsatisfactory as data cost a lot to be acquired, managed, disseminated, stored and used. As mentioned in earlier chapters, the function of a database is to organise a volume of data and to make it accessible, so that it becomes useful information. The data stored in NETDATA were used for statistical analysis and also for training and testing Neural Networks. The following sections suggest some other uses of the database for further research.

8.3.1 Expansion of database and data analysis

NETDATA is a dynamic and evolving system and should expand both in terms of the variety and the volume of the data that it holds. For this study results of various laboratory tests were put into the database and analysed. Other parameters derived from in-situ tests such as values derived from Standard Penetration tests or in-situ strength tests could be added to the database and used for further studies.

The analysis carried out on the data stored in NETDATA in this project could be the first step of the use of this geotechnical database. Further analysis using the available data should also lead to better ground investigation practice, allowing the different tills to be recognised and the most appropriate sampling and testing methods to be chosen. More detailed studies of the physical characters of the glacial tills, including petrological examinations should be carried out in order to obtain a better understanding of the extent to which their engineering properties are governed by the depositional processes. This should be done by investigating face exposures rather than by using borehole samples.

8.3.2 A glacial model

In this study the different till units were distinguished based on their geotechnical properties rather than their physical descriptions. It was found that similar Units at different locations follow the same patterns. However, the origin of the differences and similarities between the units is not clear. As mentioned earlier some researchers described the differences due to the weathering of the soils whilst others suggest that the differences are due to the variation of the source material. It is felt that there is a growing need for further research to understand the regional geology in order to solve the contradictions between the theoretical models that have been brought forward related to the glacial history of North of England.

One approach could be the design of a graphical model of the ground layers, based on the available data, using Geographic Information System (GIS). A GIS is a computer system capable of assembling, storing, manipulating, and displaying geographically referenced information, in other words data identified according to their locations. Software such as Arc/Info or Arc/View have widely been used as a tool for modelling of engineering data (Miles and Ho, 1999). GIS technology integrates the capabilities of a database with the visual perspective of a map (Holdstock, 1998). A critical component of a GIS is its ability to produce graphics on the screen or on paper allowing the viewer to visualise and thereby understand the results of analyses or simulations of potential events. With a GIS it is possible to point at a location, object, or area on the screen and retrieve recorded information about it from off-screen files such as a database. Similar to other projects (Nirex, 1996; Bowie, 1995; Camp and Brown, 1993) NETDATA could be linked to a GIS system and used for modelling the ground conditions of glaciated terrain in Northern England and for creating geological maps in various scales using the data stored in the database.

8.3.3 The design of an intelligent Geo-system

The use of artificial intelligence in many scientific areas is growing day by day. Regarding to the use of artificial intelligence in geotechnical engineering it has been argued that computers may be developed with supporting programs that can learn and thereby facilitate soil classification and soil interpretations (McCracken and Cate, 1986). The design of a hybrid system, which combines such technologies, could be the way forward to develop a powerful and more efficient decision support system by taking advantage of the combined capabilities of each system.

In an Expert system, rules must be learned from expert input or by interpreting rules from experience and a logical analysis of that experience. They are useful tools where the knowledge needed to solve the problem is already understood but they have the lack of learning by themselves. Neural Networks, however, solve problems by pattern matching instead of applying rules and also allow input information to be incomplete and vague. By combining the two systems there is no need for lengthy and costly knowledge extraction since the system can learn from real examples. The idea of integrating Neural Networks and expert systems was also investigated by other researchers (Caudill, 1990; Moslehi et al; 1991, Sterling and Lee, 1992; Kim et al, 1999). Other attempts have combined Neural Networks and GIS systems together (Gangopadhyay et al, 1999). In the combined system the knowledge-base implements the knowledge regarding the classification or design parameters using the information provided by the Neural Network. This system can then be combined with GIS as a tool for the three dimensional characterisation of the subsurface.

References

Abdellatif, A., Le Bihan, J., Limame, M. 1990. *Oracle: A user's guide*, First Edition, Macmillan Education Ltd, London.

Adeli, H. 1988. AI Techniques and the Development of Expert Systems. *Expert Systems in Construction and Structural Engineering*, Edited by H. Adeli, USA, Chapman and Hall Ltd.

Aflaki, E. 1996. *Intrinsic properties of glacial till: An aid to site investigation interpretation.* Unpublished PhD thesis, University of Newcastle.

AGS 1999. *Electronic Transfer of Geotechnical and Geoenvironmental Data*, 3rd Edition, published by: The Association of Geotechnical and Geoenvironmental Specialists, Kent.

Alderman, J.K. 1959. *The Geotechnical properties of glacial deposits in north-west England*, Unpublished PhD thesis, University of Manchester.

Anon 1982. *The Siting and Construction of Temporary Spoil Mounds at Opencast Coal Sites.* Code of Practice, Federation of Civil Engineering Contractors, London.

Anon 1989. *The stability of Excavated Slopes at Opencast Coal Sites.* Code of Practice, Federation of Civil Engineering Contractors, London.

Arrowsmith, E.J. 1985. Case histories of slope stability: Failure and remedial measures in NW England. In: Forde, M.C. (ed.) *Glacial Tills 85 - Proceedings of the International Conference on Construction in Glacial Tills and Boulder Clays*, Edinburgh, pp. 113 - 120.

Ashley, G.M., Shaw, J. And Smith, N.D. 1985. *Glacial Sedimentary Environments, SEPM Short Course*, No. 16, Published by the Society of Economic Paleontologists and Mineralogists, Tusla, Oklahoma.

Bamford, C. and Curran P. 1991. *Data Structures and Databases.*, Second edition, Macmillan Education Ltd, London.

Baird, H.G. 1988. Earthworks control - assessment of suitability. *Ground Engineering*, Vol. 22, No. 4, May.

Barnes, G.E. and Staples, S.G. 1988. The acceptability of clay fill as affected by stone content. *Ground Engineering*, January, pp. 22 - 30.

Batchelor, A.J., Forde, M.C., and Topping, B.H.V. 1985. Slope stability design in glacial tills. In: Forde, M.C. (ed.) *Glacial Tills 85 - Proceedings of the International Conference on Construction in Glacial Tills and Boulder Clays*, Edinburgh, pp. 219 - 226.

Beale, R. and Jackson, T. 1990. *Neural Computing: an introduction.* Institute of physics publishing, Bristol and Philadelphia.

Benn, D.I. and Evans, D.J.A. 1998. *Glaciers and Glaciation*, Arnold, London.

Bennet, M.R. and Glasser, N.F. 1996. *Glacial Geology: Ice Sheets and Landforms*. John Willey and sons, Chichester.

Bishop, A.W., Green, G.E., Garga, V.K., Andersen, A. and Brown, J.D. 1971. A new ring shear apparatus and its application to the measurement of residual strength. *Geotechnique*, Vol. 21, pp. 273-328.

Bishop, A.W. and Henkel, D.J. 1976. *The measurement of soil properties in the triaxial test.* Second Edition, Edward Arnold, London.

Bjerrum, L. 1954. Geotechnical Properties of Norwegian Marine Clays. *Geotechnique*, Vol. 4, pp. 49-69.

Bjerrum, L. and Simons, N.E. 1960. Comparison of shear strength characteristics of normally consolidated clays. *Proceedings of the ASCE Research Conference on the Shear Strength of Cohesive Soils*, Boulder, pp 711-726.

Billings, S.A. and Chen, S. 1995. Neural networks and system identification. In: Irwin, G.W., Warwick, K. and Hunt, K.J. (eds.): *Neural Network Application in Control*. Ch. 11, pp 229-251, The Institution of Electrical Engineers, London.

Boulton, G.S. 1975. Processes and patterns of subglacial sedimentation, a theoretical approach. In: Wright, A.E. and Moseley, F. (eds.): *Ice Ages: Ancient and Modern*, Geological Journal Special Issue, No. 6, pp 7-42. Seel House Press, Liverpool.

Boulton, G.S. 1976. *The development of geotechnical properties in glacial tills. Glacial Till*, (Legget, R.F. ed.), The Royal Society of Canada, Special Publications, No.12, pp. 292-303.

Boulton, G.S., Jones, A.S., Clayton, K.M., and Kenning, M.J. 1977. A British ice-sheet model and patterns of glacial erosion and deposition in Britain. In: Shotton, F.W. (ed.), *British Quaternary studies, recent advances*. Clarenden Press, Oxford, pp. 232-245.

Boulton, G.S. and Paul, M.A. 1976. The influence of genetic processes on some geotechnical properties of glacial tills. *Quarterly Journal of Engieneering Geology*, Vol. 9 No. 3, pp. 159-194.

Boulton, G.S., Peacock, J.D. and Sutheland, D.G. 1991. Quaternary. In: Craig, G.Y. (ed.), *Geology of Scotland*, 3rd edition, Geologcal Society, London, pp. 503-543.

Bowie, R.C. 1995. Data management in the National Geological Records Centre. In: Giles, J.R.A. (ed.) *Geological Data Management*, Geological Special Publication No. 97, pp 117-125.

Bowen, D.Q. 1978. *Quaternary Geology: A stratigraphic framework for multidisciplinary work.*, Pergamon Press, Oxford.

BS 1377. 1990. *Methods for testing soils for civil engineering purposes*. British Standards Institution, London.

BS 5930. 1981. *Code of Practice for Site Investigations*, British Standards Institution, London.

Burland, J.B. 1990. On the compressibility and shear strength of natural clays." *Geotechnique*, Vol. 40, No. 3, pp. 329-378.

Cal, Y. 1995. Soil Classification by Neural Network. *Advances in Engineering Software*, Elsevier Science Limited, Vol. 22, pp. 95-97.

Camp, C.V., and Brown, M.C. 1993. GIS procedures for developing three-dimensional subsurface profile. *Journal of Computing in Civil Engineering*., ASCE, Vol.7 No. 3, pp. 296 - 309.

Carter, M. 1983. *Geotechnical Engineering Handbook.* Pentech Press, London.

Carruthers, R.G. 1953. *Glacial Drifts and the Undermelt Theory*, Newcastle upon Tyne, Harold Hill.

Casagrande, A. 1936. The determination of the pre-consolidation load and its practical significance. *Proceedings of the first International Conference of Soil Mechanics*, Vol. 3.

Catt, J.A. 1991a. Late Devensian glacial deposits and glaciations in eastern England and the adjoining offshore region. In: Ehlers, J., Gibbard, P.L. and Rose, J. (eds.), *Glacial deposits of Great Britain and Ireland*, Balkema Press, Rotterdam, pp. 61-68.

Catt, J.A. 1991b. The Quaternary history and glacial deposits of East Yorkshire. In: Ehlers, J., Gibbard, P.L. and Rose, J. (eds.), *Glacial deposits of Great Britain and Ireland*, Balkema Press, Rotterdam, pp. 185-191.

Caudill, M. 1990. Expert Networks. In: Eberhart, R.C. and Dobbins, R.W. (eds.): *Neural Network PC Tools, A practical Guide*, Academic Press Limited, London, Ch. 9, pp. 189-214.

Caulcutt, R. 1991. *Statistics in research and development*, Chapman and Hall, London, second edition.

Chao, L.C. and Skibniewski, M.J. 1998. Neural Networks for Evaluating Construction Technology. In: Flood, I. And Kartam, N. (eds.): *Artificial Neural Networks for Civil Engineers: Advanced Features and Application.* ASCE, Ch. 1, pp.1-34.

Clayton, C.R.I., Matthews, M.C. and Simons, N.E. 1995. *Site Investigation*, Second Edition, Blackwell Science Ltd, Oxford.

Cocksedge, J.E. 1983. Road construction in glaciated terrain. In: Eyles, N. (eds): *Glacial Geology - An introduction for engineers and earth scientists*, Pergamon Press, Oxford, Ch. 13, pp.302-317.

CP 2001. 1957. *British Standard Code of Practice: Site Investigations*. British Standard Institution, London.

Craig, R.F. 1997. *Soil mechanics* ,6th edition, E & FN Spon, an imprint of Chapman and Hall, London.

Davey-Wilson, I.E.G. and Mistry, K. 1995. An intelligence database to predict geotechnical parameters. *Developments in Artificial Intelligence for Civil and Structural Engineering*, Civil-Comp Press, Edinburgh, pp.105-111.

Davidson, D.T. and Sheeler, J.B. 1952. Clay fraction in engineering soils,III : Influence of amount of properties. *Proceedings of the Highway Research Board*, Washington, pp. 558-563.

Day, R.B., Tucker, E.V., and Wood, L.A. 1983. The computer as an interactive geotechnical data bank and analytical tool. *Proceedings of the Geotechnical Association*. Vol. 94, pp. 123-132.

Derbyshire, E. 1975. Distribution of glacial soils in Great Britain. *The engineering behaviour of glacial materials*, Midland Soil Mechanics and Foundation Engineering Society, Birmingham, pp.6-17.

Derbyshire, E. and Love, M.A. 1986. Glacial Environments. In: Fookes, P.G., and Vaughan, P.R., (eds.) *A Handbook of Engineering Geomorphology*, Surrey University Press, pp. 66-81.

Dickins, D.R.E. 1995. The Geology of the English Solway Coast area of outstanding natural beauty (AONB). *Report to Allerdale Borough Council. Cumbria Environmental and Geological Services*, Therapland Moss, Bothel, Cumbria.

Douglas, T. 1991. Glacial deposits of Northumbria. In: Ehlers, J., Gibbard, P. L. and Rose, J. (eds.) *Glacial Deposists in Great Britain and Ireland*. pp.169-174, A.A.Balkema / Rotterdam.

Dreimanis, A. 1989. Tills, their genetic terminology and classification. In: Goldthwait, R.P. and Matsch, C.L. (eds.). *Genetic Classification of Glacigenic Deposits*, Balkema, Rotterdam, pp. 17-84.

Eastwood, T., Dixon, E.E.L., Hollingworth, S.E., and Smith, B. 1931. The geology of the Whitehaven and Workington District. *Memoir of the British Geological Survey*, Sheet 28, HMSO, London.

Eastwood, T., Hollingworth, S.E., Rose, W.C.C. and Trotter, F.M. 1968. Geology of the Country around Cockermouth and Caldbeck. *Memoir of the British Geological Survey*, Sheet 23. HMSO, London.

Ellis, G.W., Yao, C., Zhao, R., and Penumadu, D. 1995 Stress-strain modelling of sand using artificial neural networks. *Journal of Geotechnical Engineering*, Vol. 121, No. 5, pp. 429-435.

Elmasri, R. and Navathe, S.B. 2000. *Fundamentals of Database Systems.* Third Edition, World Student Series. Addison-Wesley

Eyles, N. 1983. Glacial geology: A landsystems approach. In: Eyles, N. (ed.), *Glacial Geology - An introduction for engineers and earth scientists*, Pergamon Press, Oxford, Ch. 1, pp.1-18.

Eyles, N. and Dearman, W. 1981. A glacial terrain map of Britain for engineering purposes. *Bulletin of the International Association of Engineering Geology*, Vol. 24, pp. 173-184.

Eyles, N. and McCabe, A.M. 1989. The late Devensian (<22,000 BP) Irish Sea basin: the sedimentary record of a collapsed ice sheet margin. *Quaterbary Science Reviews*, Vol.8, Pergamon Press, Oxford, pp. 307-351.

Eyles and Sladen, J.A. 1981. Stratigraphy and geotechnical properties of weathered lodgement till in Northumberland, England. *Quarterly Journal of Engineering Geology*, Vol. 14, No. 2, pp. 129-141.

Fausette, L.V. 1994. *Fundamentals of neural networks: architecture, algorithms, and applications.* Englewood Cliffs, NJ :Prentice-Hall.

Fenves, S.J. 1996. The Penetration of Information Technologies into Civil and Structural Engineering Design: State-of-the-art and Directions towards the Future. In: Kumar,B. and Retik, A. (eds.) *Information Representation and Delivery in Civil and Structural Engineering Design,* Civil-Comp Press, Galashiels, Scotland, pp 1-5.

Finn, P.S., and Eldred, P.J.L. 1987. Data management with microcomputers in geotechnical engineering practice. *Quarterly Journal of Engineering Geology*, London, Vol 20, pp 131-137.

Flint, R.F. 1957. *Glacial and Pleistocene Geology.* John Wiley and sons, New York.

Flint, R.F. 1971. *Glacial and Quaternary Geology.* John Wiley, New York.

Flint, R.F., Sanders, J.E., and Rodgers, J. 1960. Diamictite: A subtitude term for symmictite. *Geological Society of America Bulletin*, Vol. 71, pp. 1809-1810.

Fookes, P.G., Hinch, L.W., Huxley, M.A. and Simons, N.E. 1975. Some soil properties in glacial terrain - the Taff Valley, South Wales. *The engineering behaviour of glacial materials*, 93-116.

Fookes, P.G., Gordon, D.L. and Higginbottom, I.E. 1978. Glacial Landforms, their deposits and engineering characteristics. *The engineering behaviour of glacial materails*, second edition, Geo Abstracts Limited, Norwich, pp,18-51.

Fookes, P.G. 1991. Quaternary Engineering Geology. In: Forster, A., Culshaw, M.G., Cripps, J.C., Little, J.A., and Moon, C.P. (eds.), *Quaternary Engineering Geology*, Geological Society, Engineering Geology Special Publication No. 7, pp. 73-98.

Funahashi, K. 1989. On the approximate realization of continuous mapping by neural networks. *Neural Networks* Vol. 2 pp 183-192.

Gallant, S.I. 1993. *Neural Networks learning and expert systems*, Cambridge, Mass., MIT Press.

Gangopadhyay, S., Gautam, T.R., Gupta, A.D. 1999. Subsurface characterization using Artificial Neural Networks and GIS. *Journal of Computing in Civil Engineering*, pp.153-161.

Geodasy. 2002. Publisher: A.F.Howland Associates. Norfolk, England, http://www.howland.co.uk/, (25/06/2002)

Getz, K. Litwin, P. and Reddick, G. 1994. *Microsoft Access 2 Developer's Handbook.* Sybex Inc. California, USA.

Ghaboussi, J, Garret, J.H. and Wu, X. 1991. Knowledge-based modeling of material behaviour with neural networks. *Journal of engineering mechanics*, ASCE, Vol. 117, No. 1, pp 132-153.

Gibson, R.E. 1953. Experimental determination of the true cohesion and true angle of internal friction in clays. *Proceedings of the third International Conference on soil mechanics and foundation engineering*, Zurich, pp. 126-130.

Giles, J.R.A., Lowe, D.J. and Bain, K.A. 1997. Geological Dictionaries - Critical Elements of every geological database. *Computers and Geosciences.* Vol 23, pp 621-626

gINT. 2002. Publisher: Geotechnical Computer Applications. Santa Rosa, USA, http://www.gcagint.com/, (25/06/2002)

Goh, A.T.C. 1995a. Modeling soil correlations using neural networks. *Journal of computing in civil engineering*, ASCE, Vol. 9, No. 4, pp 275-278.

Goh, A.T.C. 1995b. Empirical design in geotechnics using neural networks. *Geotechniques,* Vol. 45, No. 4, pp709-714.

Goldthwait, R.P. 1971. Introduction to till, today. In: Goldthwait, R.P. (ed.) *Till: A Symposium*, pp. 3-26.

Groff, J.R. and Weinberg, P.N. 1990. *Using SQL*, McGraw-Hill, USA.

Hambrey, M.J. 1994. *Glacial Environments,* UCL Press, London.

Hamilton, A.B. 1966. Freezing shrinkage in compacted clays. *Canadian Geotechnical Journal*, Vol.3, No. 1, pp. 1-17.

Haykin, S. 1999. *Neural Networks - A comprehensive foundation*, Prentice Hall, London.

Head, K.H., 1986, 1992 and 1994. *Manual of Soil Laboratory testing*. Vols. 1, 2 and 3, Pentech Press, London.

Health and Safety Commission. 1999. *Health and Safety of quarries-quarries regulations 1999- approved code of practice*. HSE Books, Sudburry, Suffolk, UK.

Hecht-Nielsen, R. 1989. Theory of the Backpropagation Neural Network. *International Joint Conference on Neural Networks*, Vol. 1, pp. 593-605.

Henkel, D.J. 1959. The relationships between the shear strength, pore-water pressure, and volume-change characteristics of saturated clays. *Geotechnique*, Vol. 9, No. 1, pp. 119-135.

Hoeksema, R.N. and Hart, C. 1990. Stanford Rock Physics Database. *Stanford Rock and Borehole Project*, V.40. pp. Z1-Z28.

Holdstock, D.A. 1998. Basics of geographic information systems (GIS). *Journal of Computing in Civil Engineering.*, ASCE, Vol. 12, No. 1, pp. 1 - 4.

HoleBASE II. 2002. Publisher: Key Systems. Worcestershire, England, http://www.keygeotech.co.uk/, (25/06/2002).

Houlsby, G.T. and Ruck, B.M. 1998. Interpretation of signals from an accoustic cone penetrometer. In Robertson and Mayne (eds.): *Geotechnical site characterization* , A.A.Balkema, Rotterdam, pp 1075-1080.

Huddart, D. 1971. A relative glacial chronology from the tills of the Cumberland lowland. *Proceedings of the Cumberland Geological Society*, Vol. 3, pp 21-32.

Huddart, D., Tooley, M.J., and Carter, P. 1977. The coasts of North West England. In: Kidson, C. and Tooley, M.J. (eds) *The Quaternary History of the Irish Sea. Geological Journal Special Issue*, No. 7, Wiley, Chichester, pp. 119 - 154.

Huddart, D. 1991. The glacial history and glacial deposits of the North and West Cumbria lowlands. In: Ehlers, J., Gibbard, P. L. and Rose, J. (eds.) *Glacial Deposists in Great Britain and Ireland*, pp.151-167, A.A.Balkema, Rotterdam

Hughes, D.B. and Clarke, B.G. 1997. The glacial tills of Northern England in relation to the stability of screening and spoil mounds at opencast coal mines. In: Marinos, P.G., Koukis, G.C., Tsiambaos, G.C., and Stournaras, G.C. (eds.) *Engineering Geology and the Environment* Balkema, Rotterdam, pp 2419-2424.

Hughes, D.B. and Clarke, B.G. and Money, M.S. 1998. The glacial succesion in lowland Northern England. *The Quarterly Journal of Engineering Geology.* Vol.31, Part3, pp.211-234.

Jain, A.K., Mao, J., and Mohiuddin, K.M. 1996. Artificial Neural Networks: A tutorial. *Computer*, Vol. 29, No. 3, pp. 31-44.

Kaetzel, L.J. and Clifton J.R. 1995. Expert / knowledge based systems for materials in the construction industry: State-of-the-art report. *Materials and Structures*: *TC-93: Expert Systems for building materials and structures*, Rilem technical committees commissions techniques de la Rilem, Vol.28, pp. 160-174

Kazi, A. and Knill, J.L. 1969. The sedimentation and geotechnical properties of the Cormer Till between Happisburgh and Cormer, Norfolk. *The Quarterly Journal of Engineering Geology* . Vol.2, Part1, pp. 63-87.

Kenny, T.C., 1967, "The influence of mineral composition on the residual strength of natural soils." In: *Proceedings of the Geotechnical Conference*, Oslo, pp. 123-131.

Kim, C.Y., Bae, G.J., Hong, S.W., Moon, H.K., Oh, M.K. 1999. Neural network expert system developed for predicting the ground settlement and the damage assessment of adjacent structures due to tunnel excavation. *Proceedings of the International Offshore and Polar Engineering Conference*, Vol. 1, pp 514-520.

Koch, G. and Loney, K. 1997. *Oracle 8 : The complete reference*, Osborne / McGraw - Hill, Berkley, U.S.A.

Kroenke, D.M. and Dolan, K.A. 1988. *Database Processing - Fundamentals, Design, Implementation.*, Macmillan Publishing Company, New York.

Lambe, T.W. and Whitman, R.V. 1979. *Soil Mechanics, SI Version*. Wiley, New York.

Logar, J. and Turk, G. 1997. Neural Network as a constitutive model of soil. In: *Zeitschrift fuer angewandte Mathematik und Mechanik*, Vol. 77, No. S1, pp. 195-196

Lowe, D.J. 1995. The geological data manager. In: Giles, J.R.A. (ed.), *Geological Data Management*, Geological Society Special Publication No. 97, pp. 81-90.

Lunn, A.G. 1995. Chapter 7 – Quaternary. In: Johnson G.L.A. (ed.) *Robson's Geology of North England, Transactions of the Natural History Society of Northumbria*, Vol. 56, Part 5, pp 297-311.

Lupini, J.F., Skinner, A.E., and Vaughan, P.A. 1981. The drained residual strength of cohesive soils. *Geotechnique*, Vol. 31, pp. 181-213.

Malasri, S. 1988. Soil Classification: An ESIA approach. *Computers in Education Division of ASEE (COED)*, Vol. 8, pp 43-47.

McCracken, R.J., and Cate R.B. 1986. Artificial intelligence, cognitive science, and measurement theory applied in soil classification. *Soil Science Society of America Journal*, Vol. 50, pp 557-561.

McCulloch, W.S. and Pitts, W. 1943. A logical calculus of the ideas immanent in nervous activity. *Bulletin of mathematical biophysics*, Vol. 5, pp. 115-133.

McGown, A. 1975. *Genetic Influences on the nature and properties of basalt melt out tills*, Unpublished PhD thesis, University of Strathclyde.

McGown, A. and Derbyshire, E. 1977. Genetic influences on the properties of tills. *Quaterly Journal of Engineering Geology*, Vol.10, pp. 389-410.

Melhem, H.G., Roddis, W.M.K., Nagaraja, S., Hess, M.R. 1996. Knowledge acquisition and engineering for steel bridge fabrication. *Journal of Computing in Civil Engineering*. Vol. 10, No.3, pp. 248 - 256.

Michie, D., Spiegelhalter, D.J., and Taylor, C.C. 1994. *Machine Learning, Neural and Statistical Classification*. Ellis Horwood, London.

Microsoft Corporation. 1994. *Microsoft Access User's Guide*

Miles, S.B. and Ho, C.L. 1999. Applications and issues of GIS as tool for civil engineering modeling. *Journal of Computing in Civil Engineering*, 144-152.

Millmore, J.P., and McNicol, R. 1983. Geotechnical aspects of the Kielder Dam. *Proceedings of the Institution of Civil Engineers*, Vol. 74, Part 1, pp. 805-836.

Moslehi, O., Hegazy, T.,Fazio, P. 1991. Neural Networks as tools in construction. *Journal of Construction Engineering and Management*. Vol. 117, No. 4, pp 606-625, ASCE.

Morgenstern, N.R. 1967. Shear strength of stiff clay. *Proceedings of geotechnical Conference*, Oslo, Vol. 2, pp. 59 - 69.

Muller, R.J. 1997. *Oracle: Developer / 2000 Handbook*, Second edition, McGraw - Hill, Berkley, U.S.A.

NeuroDimensions. 2002. Publisher: Neuro Dimensions Inc., Florida, U.S.A., http://www.nd.com, (25/06/2002)

Nirex. 1996. *Sellafield Geological and Hydrogeological Investigations: The Nirex Digital Geoscience Database (NDGD) - An Overview*. Nirex Science Report No. S/96/001.

Norbury, D.R., Child, G.H. and Spink, T.W. 1986. Acritical Review of Section 8 (BS5930) - Soil and Rock Description. In: Hawkins, A.B. (ed.), *Site Investigation Practice: Assessing BS 5930*, Geological Society, Engineering Geology Special Publication, No. 2, pp. 331-342

Paul, M. A. and Little, J. A. 1991. Geotecnical properties of glacial deposits in lowland Britain. In: Ehlers, J., Gibbard, P. L. and Rose, J. (eds.) *Glacial Deposists in Great Britain and Ireland*, pp.389-404, A.A.Balkema, Rotterdam

Penumadu, D., Jin-Nan, L., Chameau, J-L., and Arumugam, S. 1994. Rate Dependant Behavior of Clays Using Neural Networks. *Proceedings of the. 13th Conference of International Society of Soil Mechanics and Foundation Engineering*, New Delhi: New Delhi, Oxford & IBH Publication Company, Vol. 4, pp 1445-1448.

Peters, J., and McKewon, J. 1976. Glacial till and the development of the Nelson River. In: Legget, R.F. (ed.), *Glacial Till.*, Royal Society of Canadian Special Publications 12, pp. 364-380.

Raper, J.F. and Wainwright, D.E. 1987. The use of the geotechnical database 'Geoshare' for site investigation data management. *Quarterly Journal of Engineering Geology*, Vol 20, pp. 221-230.

Rasmussen, K. 1995. An overview of database analysis and design for geological systems. In: Giles, J. R. A. (ed.), *Geological Data Management*, Geological Society Special Publication No 97, pp. 5-11.

Robertson,T.L. Clarke, B.G. and Hughes, D.B. 1994. Classification and strength of Northumberland Till. *Ground Engineering*. December 1994, Thomas Telford, London, pp 29-34.

Rosenblatt, F. 1961. *Principles of Neurodynamics: Perceptrons and the theory of brain mechanism*, Washington DC., Spartan Books.

Rumelhart, D.E., Hinton, G.E. and Williams, R.J. 1986. Learning internal representations by error propagation. In: Rumelhart, D.E. and McClelland, J.L. (eds.), *Parallel distributed processing: explorations in the microstructure of cognition.* Vol.1: Foundations, Cambridge, Massachusetts: The MIT Press.

Seed, H.B., Woodward, R.J. and Lundgren, R. 1964 a. Clay mineralogical aspects of the Atterberg limits. *ASCE Journal of the Soil Mechanics and Foundations Division*, Vol. 90, SM4, pp. 107-131.

Seed, H.B., Woodward, R.J. and Lundgren, R. 1964 b. Fundamental aspects of the Atterberg limits. In: *ASCE Journal of the Soil Mechanics and Foundations Devision*, Vol. 90, SM6, pp. 75-105.

Shi, J., Origato, J.A.R. and Bai, J. 1998. Modular Neural Network for predicting settlements during tunnelling. *Journal of geotechnical and geoenvironmental Engineering*, pp. 389-395.

SID. 2002. Software Publisher: M Z Associates. Cambridge, England, http://www.mzassociates.co.uk/, (25/06/2002)

Skempton, A.W. 1943. Notes on the compressibility of clays. *Quarterly Journal of Geological Society of London*, Vol. 100, pp. 119-135.

Skempton, A.W. 1948. Vane tests in the alluvial plain of the River Forth, near Grangemouth. *Geotchnique*, Vol.1 pp. 111-124.

Skempton, A.W. 1953. The colloidal activity of clays. *Proceedings, 3rd International Conference on Soil Mechanics and Foundation Engineering*, London, Vol. 1, pp. 57-61.

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Toll, D.G. and Oliver, A.J. 1995. Structuring soil and rock descriptions for storage in geotechnical databases. In: Giles, J. R. A. (ed.), *Geological Data Management*, Geological Society Special Publication N0 97, pp.65-71.

Toll, D.G. 1996. Artificial Intelligence Applications in Geotechnical Engineering. *Electronic Journal of Geotechnical Engineering*, Premiere Issue, (19/07/2001) at: http://www.ejge.com

Trenter, N.A. 1999. *Engineering in Glacial Tills.* CIRIA, London, Report No. C504.

Tsushida, T. 1994. A unified concept of e-log. P relationship of clays. *Proceedings of the 13th International Conference on Soil Mechanics and Foundation Engineering*, New Delhi, India, pp. 71-74.

Vaughan, P.R. and Walbancke, H.J. 1975. The stability of cut and fill slopes in boulder clay. *Proceedings of the symposium on the engineering behaviour of glacial materials.* Pp. 185-195.

Voight, B. 1973. Correlation between Atterberg plasticity limits and residual shear strength of natural soils. *Geotechnique.* Vol. 23, pp. 265-267.

Wasserman, P.D. 1989. *Neural Computing-Theory and Practice.* Van Nostrand Reinhold. New York.

Weltman, A.J. and Healy, P.R. 1978. *Piling in 'Boulder Clay' and other glacial tills*, DOE and CIRIA piling development group, Report PG5. Reprinted 1990, London.

Wroth, C.P. and Wood, D.M. 1978. The correlation of index properties with some basic engineering properties of soils. *Canadian Geotechnical Journal*, Vol. 15, No. 2, pp. 137-154.

Whyte, I.L. 1985. The angle of shearing resistance for granular tills and its relevance to slope stability. In: Forde, M.C. (ed.), *Glacial Tills 85 - Proceedings of the International Conference on Construction in Glacial Tills and Boulder Clays*, Edinburgh, pp. 25-30.

Youssef, M.S., El-Ramli, A.H. and El-Demery, M. 1965. Relationships between shear strength, consolidation, liquid limit and plastic limit for remoulded clays. *Proceedings of the 6th International Conference on Soil Mechanics and Foundation Engineering*, Montreal, Vol. 1, pp. 126-129.

Zeidenberg, M. 1990. *Neural Networks in Artificial Intelligence.* Ellis Horwood limited. England.

Zhou, Y., and Wu, X. 1994. Use of Neural Networks in the analysis and interpretation of site investigation data. *Computers and Geotechnics*, Vol. 16, pp. 105-122.

Appendix A

AGS File Format Rules

A.1 Introduction

The Rules have been the subject of much discussion and these notes seek to explain the overall framework within which they are formulated (AGS, 1999).

A fundamental consideration has been that potential users of the Format should be able to use standard software tools to produce the data files. The spreadsheet is the most basic tool for the task, allowing data "tables" to be created and ASCII data files to be produced. Likewise, data files produced according to the Rules can be read directly by spreadsheet software. Although the Rules make it possible for users to manipulate AGS data files using spreadsheets alone, it is to be expected that more specific software will be used to automate the reading and writing of the data files. These software systems may range from simple data entry and editing programs through to complete database systems with data translation modules for AGS files.

Another fundamental point to bear in mind when assessing these Rules is that the resulting data file has been designed to be easy for the computer to read. The data files do not replace the printed reports which they accompany. However, the layout does allow data items to be readily identified should the need arise.

A.2 The Rules

The following rules must be used when creating an AGS Format file.

Rule 1 The data file shall be entirely composed of ASCII characters. The extended ASCII character set must not be used.

Rule 2 Each data file shall contain one or more data GROUPs. Each data GROUP contains related data.

Rule 3 Within each GROUP, data items are contained in data FIELDs. Each data FIELD contains a single data VARIABLE. Each line of the AGS Format file can contain several data FIELDs.

Rule 4 The order of data FIELDs on each line within a GROUP is defined at the head of each GROUP by a set of data HEADINGs.

Rule 5 Data HEADINGs and GROUP names must be taken from the approved Data Dictionary for data covered by these. In cases where there is no suitable entry, a user-defined HEADING may be used in accordance with Rules 21,22 and 23.

Rule 6 The data HEADINGs fall into one of 2 categories: KEY or COMMON

KEY fields must appear in each GROUP, but may contain null data (see Rule 15).

KEY fields are necessary to uniquely define the data.

The following sub-rules apply to KEY fields and are required to ensure Data Integrity. (See also Note 3)

Rule 6a *HOLE_ID should always be the first field except in the **PROJ GROUP, where *PROJ_ID should be the first field.

*HOLE_ID is also omitted from the **ABBR,**DICT, **CODE , **UNIT and **FILE GROUPs.

Rule 6b There must not be more than one line of data in each GROUP with the same combination of KEY field entries.

Rule 6c Within each project every data entry made in the KEY fields in any GROUP must have an equivalent entry in it's PARENT GROUP.

e.g. All HOLES referenced in any GROUP must be defined in the **HOLE GROUP.

Rule 7 All data VARIABLEs can contain any alphanumeric data (i.e. both text and numbers). Numerical data should be in numerals. e.g. 10 not TEN. (See also Note 2).

Note that all numerals must be presented as a text field.

Rule 8 Data GROUP names, data field HEADINGs and data VARIABLEs must be enclosed in double quotes ("...").

e.g. for inches or seconds, (") must not appear as part of the data variable.

Rule 9 The data field HEADINGs and data VARIABLEs on each line of the data file should be separated by a comma (,).

Rule 10 Each GROUP name shall be preceded by 2 asterisks (**).

e.g. "**HOLE"

Rule 11 HEADINGs shall be preceded by 1 asterisk (*).

e.g. "*HOLE_ID"

Rule 12 No line of data HEADINGs or data VARIABLEs shall exceed 240 characters. The character count should include delimiting quotes and commas.

e.g. "*HOLE_ID","*HOLE_NATE" = 23 characters

Rule 13 A line of data HEADINGs exceeding 240 characters can be continued on immediately following lines. A data HEADING must not itself be split between lines. A comma must be placed at the end of a HEADINGs line that is to be continued.

e.g. "*HOLE_ID","*SAMP_TOP","*SAMP_REF","*SPEC_REF",

"*CLSS_LL","*CLSS_PL","*CLSS_BDEN"

Rule 14 A line of data VARIABLEs exceeding 240 characters must be continued on immediately following lines. Data VARIABLEs can be split between lines. A VARIABLE continuation line shall begin with the special name <CONT> in place of the first data VARIABLE (PROJ_ID or HOLE_ID). The continued data is then placed in the correct field order by inserting the appropriate number of Null data VARIABLEs before it. Note that each line of data in a GROUP should contain the same number of VARIABLEs.

(See also Note 4).

e.g. "**GEOL"

"*HOLE_ID","*GEOL_TOP","*GEOL_BASE","*GEOL_DESC","*GEOL_LEG"

"<UNITS>","m","m","",""

"501","1.2","2.4","Very stiff brown CLAY with",""

"<CONT>","","","extremely closely spaced fissures","CLAY"

Rule 15 Null data VARIABLEs must be included as 2 consecutive double quotes ("").

(See also Note 2)

e.g. ,"",

Rule 16 Data GROUPs can be repeated within a file with different HEADINGs.

Rule 17 The number of data HEADINGs per GROUP shall not exceed 60.

Rule 18 A UNITS line must be placed immediately after the HEADINGS line in all GROUPs except **ABBR, **CODE,**DICT and **UNIT. An entry must be made for each data VARIABLE. Null entries ("") must be used for data VARIABLES that are unitless, e.g. text. The line must begin with the special name <UNITS> in place of the first data variable (PROJ_ID or HOLE_ID).

(See also Note 5)

e.g. "**GEOL"

"*HOLE_ID","*GEOL_TOP","*GEOL_BASE","*GEOL_DESC"

"<UNITS>","m","m",""

Rule 18a A line of UNITS exceeding 240 characters can be continued on immediately following lines. A UNIT must not itself be split between lines. A comma must be placed at the end of a UNITS line that is to be continued.

e.g. "**GEOL"

"*HOLE_ID","*GEOL_TOP","*GEOL_BASE","*GEOL_DESC"

"<UNITS>","m","m",""

Rule 18b Each data file shall contain the **UNIT GROUP. This GROUP uses defined units and contains all the standard SI units used in all other AGS GROUPs, as well as some common non-SI equivalents. Every UNIT entered in a <UNITS> line of a GROUP and the CNMT_UNIT field of the **CNMT GROUP must be defined in the **UNIT GROUP. Both standard and non-standard UNITS must be defined in the **UNIT GROUP.

Rule 19 Each data file shall contain the **PROJ GROUP.

Rule 20 Each data file shall contain the **ABBR GROUP to define any data abbreviations where these have been used as data entries in the data GROUPs.

Rule 21 Each file shall contain the **DICT GROUP to define non-standard GROUP and HEADING names where these have been used in the data GROUPs.

Rule 22 Each non-standard GROUP name shall contain the prefix **?.

A GROUP name shall not be more than 4 characters long excluding the **? prefix and shall consist of uppercase letters only.

e.g. "**?TESX"

Rule 23 Each non-standard HEADING shall contain the prefix *?.

A HEADING name shall not be more than 9 characters long excluding the *? prefix and shall consist of uppercase letters, numbers or the underscore character only. HEADING names shall start with the GROUP name followed by an underscore character, except for HEADINGs which duplicate a HEADING in another GROUP, in which case this HEADING shall be used instead.

e.g. "*?ISPT_CALN"

Rule 24 Miscellaneous computer files (e.g. digital images) may be included with a data file. Each such file should be defined in a **FILE GROUP. File names shall not contain more than 8 characters in the main body and not more than 3 characters in the extension.

Correct example: FNAME.XLS

Incorrect example: A LONG NAME.XYZ

Rule 25 Every data file that contains a **CNMT GROUP for chemical test results must also contain a **CODE GROUP that defines the codes used for each determinand given in the CNMT_TYPE field of the **CNMT GROUP. This applies to standard codes selected from the 'pick' lists in Appendix 1 and user defined codes.

A.3 Notes on the Rules

The following notes explain some points of detail in the Rules.

Note 1 - ASCII 'CSV' Files

The Rules define ASCII data files of a type commonly referred to as CSV (Comma Separated Value). This type of file is produced and read by some spreadsheet (and other) systems. The data items are separated by commas and are surrounded by quotes (").

Note 2 - Numeric and Character Data - Delimiters

The Rules permit any Data Field to contain text, since this allows characters in numeric fields and caters for those countries which use the comma in place of the decimal point. For these reasons ALL Data Fields must be surrounded by quotes.

Note that most spreadsheet and database systems provide a VALUE( ) function (or similar) to convert text data to numeric data. This function can be used where calculations need to be carried out on data imported from AGS files.

Note 3 - Key and Common Fields

The Data Fields defined by the Format fall into one of two categories:

KEY Fields must be included every time a Data Group appears in a data file.

COMMON Fields are all other fields.

KEY Fields are important for maintaining data integrity. Without this the receiving software may not be able to use the data in a meaningful way.

For the purpose of creating AGS files this means that data entered into KEY Fields must be unique in each GROUP and that the corresponding entries are made in the PARENT GROUP.

Note 4 - Continuation Lines

It should be noted that some spreadsheets impose a finite limit (e.g. 240) on the number of characters within a single Data Field. The Rules define a scheme for producing continuation lines where there are long Data Fields. Although the scheme may seem complex at first sight, it is the system automatically produced by spreadsheets if the long data items are continued on additional rows IN THE SAME DATA COLUMN. Similarly, these Data Files will read into spreadsheets and preserve the long data items in their correct column order, for any length of data. The special <CONT> symbol must appear in the HOLE_ID Field, and thus <CONT> should never be used as a HOLE_ID.

Note 5 - Units

Note that a UNITS line must be included in every GROUP (except ABBR, CODE, DICT and UNIT) even where the default units are used.

The units of measurement shall be those given in the UNITS line. The preferred units are defined. The unit of measurement shall not be included in the ASCII Data Field.

The defined units are the preferred units for each of the data dictionary definitions and should be used wherever possible. They will either be the appropriate SI units or the unit defined by the particular British Standard relating to that specific item of data. It is recognised that situations will occur where neither the SI unit nor the British Standard unit are being used. All entries in the <UNITS> line must be defined in the **UNIT GROUP.

Appendix B

NETDATA GUIDE

NETDATA GUIDE

CONTENT PAGE

Introduction

Abstract

NETDATA (Northern England Till DATA) is a relational database that has been designed and developed to give a better understanding of the engineering behaviour of glacial tills. It stores and centralises available data of the tills from Northern of England in an easy to use format and can be used to analyse the geotechnical parameters of Northern England's glacial tills. This guide has been prepared to make the users of this database familiar with the structure and some of the features of NETDATA.

Aims of NETDATA

The initial reason for the development of the database was to centralise all available data in a common format. This immediately simplifies any comparative studies undertaken, assists in the identification of any problems with existing data, and highlights gaps in the data.

The main purposes of NETDATA is to increase the speed and ease of access to available geotechnical data of Northern England glacial Till, in a standard format. The following options are available within the database:

1. Updating data, which includes entering, deleting and editing or changing data.
2. Displaying the stored data in various forms such as:

- *Queries* make it possible to ask questions about the data stored in the tables of the database. This one of the most important facilities within the software and makes it possible to ask for specific information about the required data.
- *Reports* may be printed on paper or displayed on the computer screen. The report facility in the software can be used to organise and present data in groups, produce graphs and present the data in required formats.
- *Forms* provide an easy way to view data. Forms can be designed to present information in an user-friendlier format. They can be used to display data for review, editing or entering data into the database and for printing them for distribution.
- *Exporting data* from the database to a word processing package or into a spreadsheet is another way of presenting the data in a different format.

The Software

The software used to develop NETDATA is Microsoft Access version 97, which is a Relational DataBase Management System (RDBMS) for Microsoft Windows. This software is based on Personal Computers and is designed to give unparalleled access to data. A complete set of User's Guides (Microsoft Corporation, 1994) books and publications are available in the market for learning about Microsoft Access and how to work with the software. In order to achieve better results and improve performance it is recommended that users familiarise themselves with the software before using the database. Microsoft Access has also a powerful on-line help facility that provides step-by-step instructions to help and guide the user through the design of a relational database and also for the use of the available options.

Other Microsoft Office 97 programs such as Excel and Power Point are also required to run some of the links within NETDATA. These programs have been used for linking charts, graphics and documents to the database.

Installation

To install NETDATA you just need to copy the NETDATA folder to the c:\ drive of your computer. Please note that all addresses and links within the database are set for this drive only and will use the following address: "c:\netdata\filename". The NETDATA folder contains the Netdata.mdb file that needs to be run to open the database in Microsoft Access. Other file or folders s within the NETDATA folder are linked to the database and will run from inside the database. Therefore, <u>it is important that files, objects and links, related to this database, should not be renamed or changed.</u>

The NETDATA folder contains the following files:

Netdata.mde - this file needs to be run to open the database in Microsoft Access.

Netfiles - this subfolder contains files that are linked to the database. All of these files will be activated automatically from inside the database and therefore do not need to be activated or run individually by the users. A list of the files within the Netfiles folder is written below:

Netdata.hlp - is the help file prepared for the database.

Netdata.ico - is the application icon of NETDATA database.

Index.xls - is a Microsoft Excel file for producing plasticity charts. This file is linked to QRY-INDEX.xls.

PSD.xls - is a Microsoft Excel file for producing particle size triangle chart. This file is linked to QRY-INDEX.xls.

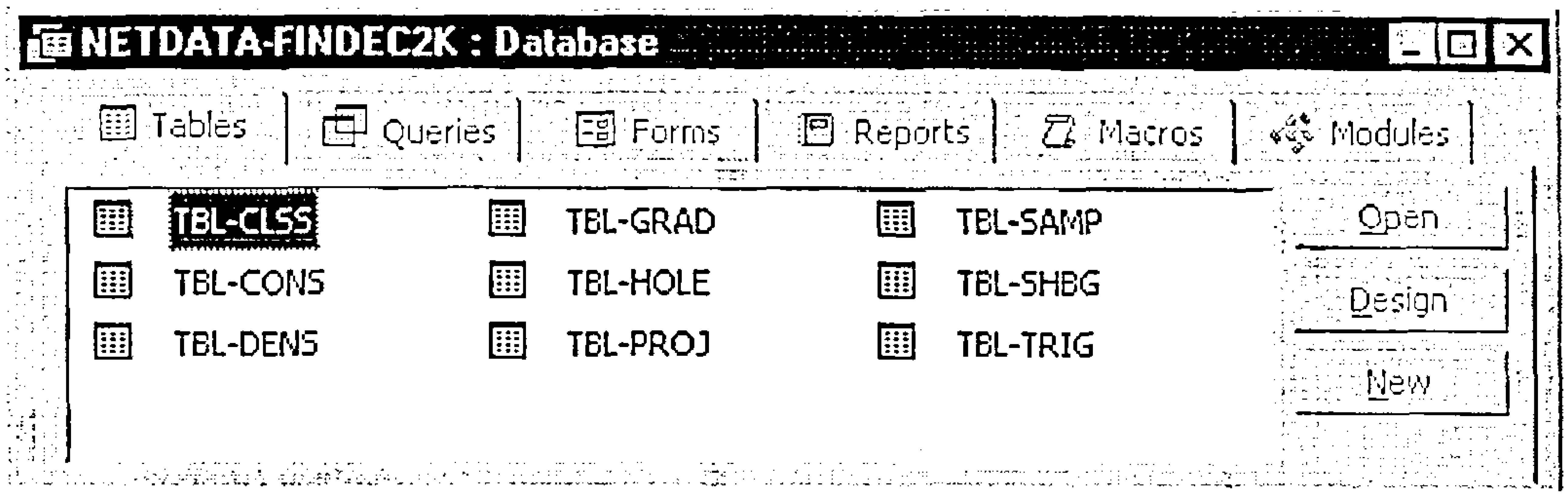
Other.xls - is a Microsoft Excel file containing the data of the QRY-ALL. The user can use this file to plot any required chart. This file is linked to QRY-ALL.xls.

QRY-INDEX.xls - is a Microsoft Excel file that contains data that are exported from the database. These data are the result of the QRY-INDEX query and are used for producing the plots in Index.xls and PSD.xls.

Intro.pps - is a Microsoft PowerPoint presentation that contains information about the background of the database and also some pictures from relevant sites.

Database Objects

The objects of the database are presented in the database window shown in the figure below:



The database window can be accessed from the menu.

NETDATA - Tables

Tables store the data of the database and organise them into columns (called fields) and rows (called records). They are the most important part of the database.

The tables available within NETDATA are listed in the database window. By clicking on any of the names, the tables can be opened. The tables can also be accessed through the database menu or the Switchboard that has been prepared for the database. The user is able to switch between datasheet view (for viewing the data in the tables) and design view (to see the design properties of individual tables) by using the View option in the main menu. The relation between the tables can be seen using the "Relationships" option in the database menu.

The field names within the tables are based on the AGS format. A data dictionary has been published by AGS (Association of Geotechnical and Geoenvironmental Specialists) that defines the data fields for each data group (AGS, 1999). The description and units of each field within tables, forms and queries will be displayed at the bottom of the screen.

In order to structure the data they have been put into individual groups (tables) and the fields within the groups have a standard name and use a standard unit of measurement. Codes of abbreviations are used in a number of AGS Format Groups in order to insure consistency in terminology and for brevity.

The following is the list of the tables within the database:

TBL-CLSS	Contains Plasticity test results
TBL-CONS	Contains consolidation test results
TBL-DENS	Contains values of density and moisture contents of samples
TBL-GRAD	Contains grading results (Particle size)
TBL-HOLE	Contains information about the boreholes
TBL-PROJ	Contains details about the project
TBL-SAMP	Contains sample details
TBL-SHBG	Contains results of shear box tests
TBL-TRIG	Contains triaxial test results
TBL-TRIX	Contains details of triaxial testing procedure

Relationships

In the AGS format the files that are used should contain basic data such as exploratory hole records and the test data required to be reported by the relevant British Standards and other recognised documents and which would normally be contained in a Factual Report. The file format is intended to provide a wide level of acceptance and, in view of this, it is considered that the data should be transmissible using American Standard Code for Information Interchange (ASCII) files.

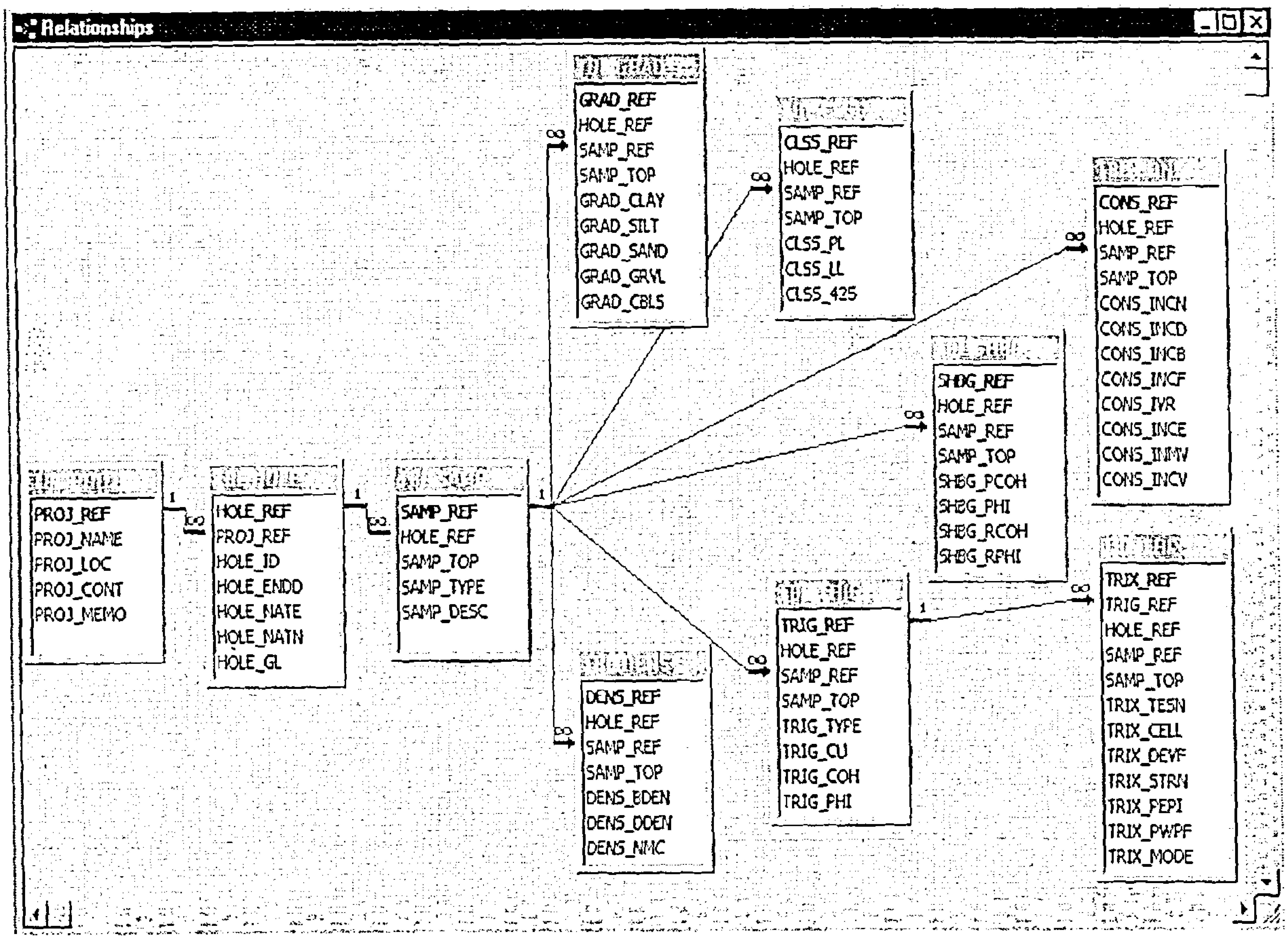
Data Groups (tables) have been chosen to relate to specific elements of data, which are obtained, such as project information and exploratory hole details.

Fields within each Data Group identify other items such as test details and test results. Two types of Data Fields defined by the AGS format are the KEY Field and the COMMON Fields. The KEY Fields must be included in every Data Group within a file. They are important for maintaining data integrity. Data entered into KEY Fields must be unique in each GROUP and the corresponding entries must be made in the PARENT GROUP. All other fields within a Group are called COMMON Fields. The letters "_REF" that follows the name of the fields, identify the KEY Fields within NETDATA.

The AGS Format Data Groups are organised in a hierarchy with an inverted tree like structure. At the top of the tree is the HOLE Group, and all other Groups lie below this. One of the Groups immediately below HOLE is SAMP, all the laboratory testing Groups lie below SAMP. The HOLE Group is termed the "parent" Group of SAMP. The PROJ Group sits above the tree, and has a general purpose. It must always be included in an AGS Format submission as it defines the project.

Each Group has only one parent, but there can be many Groups below each parent. Key Fields link each Group to its parent (the Group above it in the hierarchy). They also link one Group to the Group(s) below it. For this structure to work, and the link to be made correctly between related Groups, the data in the Key Fields must be consistent and unique.

The relation between the tables is shown below and can also be found using the "Relationships" option under the TOOLS menu in the database.



Units

While working in the datasheet view the description of the fields and the related units will be displayed at the bottom left corner of the NETDATA database window.

The units used for various fields within the database are based on the AGS Format

Measured Quantity	*Symbol of Unit*	*Description of Unit*
Length	m	metre
Length	mm	millimetre
Time	dd/mm/yy	Day month year
Concentration	%	percentage
Density	Mg/m3	megagrams per cubic metre
Pressure	kN/m2	kiloNewtons per square metre
Miscellaneous	m2/MN	square metre per megaNewton
Miscellaneous	m2/yr	square meters per year
Miscellaneous	deg	degree (angle)

Abbreviations

Abbreviations used for various fields within the database are based on the AGS Format

Field Name	*Abbreviation Code*	*Description*
SAMP_TYPE	U	Undisturbed sample
SAMP_TYPE	D	Small disturbed sample
SAMP_TYPE	B	Bulk disturbed sample
TRIX_TYPE	CD	Consolidated drained (single stage)
TRIX_TYPE	CDM	Consolidated drained (multi-stage)
TRIX_TYPE	CU	Consolidated undrained (single stage)
TRIX_TYPE	CUM	Consolidated undrained (multi-stage)
TRIX_TYPE	UU	Unconsolidated quick undrained (single stage)
TRIX_TYPE	UUM	Unconsolidated quick undrained (multi-stage)

NETDATA - Queries

The real power of a database is the ability to retrieve data in an order that the user needs to see. There are two main reasons for wanting to be able to get data out of a database:

- To analyse data using a different type of technique, in which case the data can be exported. Access is not intended for statistical analysis, so if some numerical data have been collected and formal statistical tests should be applied, it is probably best to export the data and use it in a statistics package. Some packages, such as Excel, will read Access table files so it is possible to export a table or query to these packages directly.
- To print some or all of the data; this is done through using a 'report'.

A Query gathers requested data from one or more tables. The results of a query can be viewed or edited in a form, or printed it in a report. Since retrieving data and running a query is the main aim for the user of the database, it is recommended that users familiarise themselves with different techniques of creating queries and retrieving data. After the query is designed it is possible to set specific criteria to search for certain data stored in the database.

The following queries are already prepared and can be used within NETDATA:

- QRY-CONS: this query will search the database for the results of the consolidation test.

- QRY-INDEX: This query can be used to search the database for index and classification test results. The results of this query are used to prepare reports and produce graphs.
- QRY-SHEAR: this query will search the database for the results of shear strength tests carried out either by triaxial method or shear box testing.
- FRM-QUERY_QBF: is a form that works similar to a query. It combines Visual Basic and SQL commands for filtering data (adapted from Getz et al, 1994). Users who are not familiar with the query design options may use most criteria expressions for filtering data in this form without the use of queries. This is done by inputting the search criteria in the available boxes in the form. Although this form is not as powerful as a query and has some limitations in setting combined expressions for the criteria, it is a useful tool for filtering data. The results are displayed in a format that can easily be printed out. It is also possible to view the results in datasheet format using the option provided in the menu.

Creating Queries

One easy way to create a query is to use the query wizard by taking the following steps:

1. Click on the Query button
2. Click on the New button
3. Select Simple Query Wizard
4. Select the Table or Query to be used
5. Select the fields

It is also possible to create a query without a wizard by taking the following steps (Microsoft Corporation, 1994):

1- In the Database window, click the Queries tab, and then click New.

2- In the New Query dialog box, click Design View, and then click OK.

3- In the Show Table dialog box, click the tab that lists the objects whose data you want to work with.

4- Double-click the name of each object you want to add to the query, and then click Close.

5- If you have multiple tables or queries in the query, make sure they are connected to each other with a join line so that Microsoft Access knows how the information is related. If they aren't connected, create the join line yourself. If the tables or queries are joined, you can change the type of join to affect which records the query selects.

6- Add fields to the query by dragging the field names from the field list to the design grid. For more information on how to add fields, click.

7- Refine your query by entering criteria, adding a sort order, creating calculated fields, computing the sum, average, count, or another type of total on the data it retrieves, or otherwise modifying the query's design.

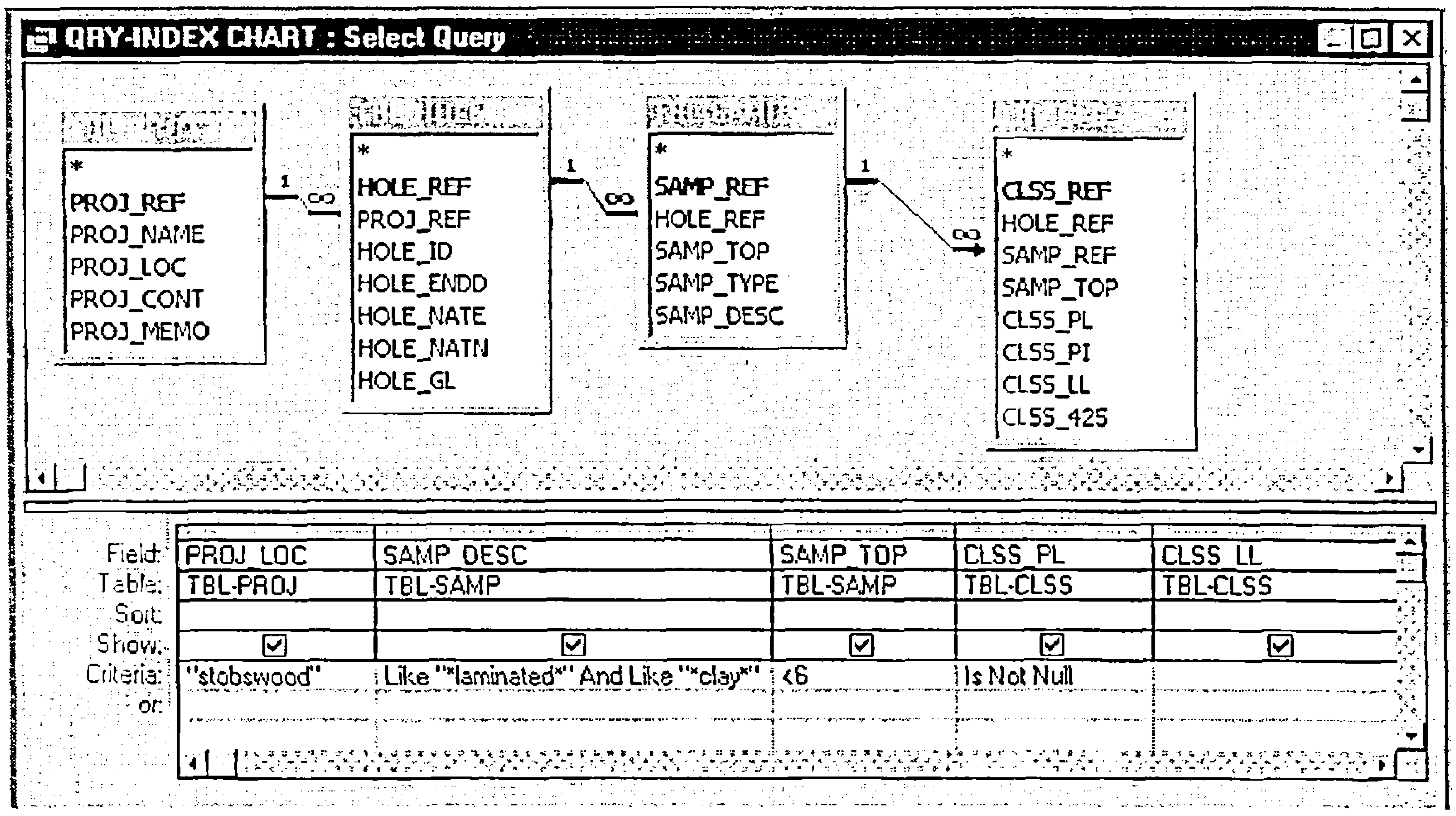
8- To save the query, click Save on the toolbar. Enter a name that follows Microsoft Access object-naming rules, and then click OK.

9- To see the results of the query, click View on the toolbar.

Setting search criteria in queries

Criteria can be used in queries to retrieve certain records. Criteria are restrictions that can be placed on a query to identify the specific records the user wants to work with.

The following figure shows an example of a query in design view. The upper part of the window shows the tables used in this particular query and the lower window contains the fields used and the criteria set for a search.



Using the "Sort" option in the query it is possible to sort the results of a query in ascending or descending order. By ticking on or off the boxes in the "Show" field it is possible to control the display of the results of one or more fields. Some examples for setting search criteria for a query are shown in the table below. As it can be seen expressions can be combined with "And", "Or", "Not" or comparison operators such as <, >, <>, <=, and >= can also be used.. For more details about queries the MS Access help option within the database can be used.

Field	*Expression*	*Displays*
PROJ_LOC	"Linefoot"	Projects from the location "Linefoot" only.
PROJ_LOC	Like "B*"	Projects whose location name start with the letter "B"
SAMP_DESC	Like "*gravel"	Samples whose description end with the word "gravel".
SAMP_DESC	Like "*SAND*"	Samples whose descriptions include the word "SAND".
SAMP_DESC	Like "Grey*" And Like "*CLAY*"	Samples whose descriptions start with the word "Grey" and also include the word "CLAY".
SAMP_DESC	Not Like "boulder"	Samples whose description does not include the word "boulder"
CLSS_PL	>15	Samples whose plastic limit is greater than 15.
CLSS_PL	=<20	Samples whose Plastic Limit is equal or smaller than 20.
GRAD_CLAY	<>10	Samples whose clay content is not equal to 10.
GRAD_SILT	=>15 And <20	Samples whose silt content is equal or bigger than 15 and smaller than 20
GRAD_SAND	Between 15 And 20	Samples whose sand content is between 15 and 20
GRAD_GRVL	Not 25	Samples whose gravel content is not 25
GRAD_CBLS	Is Not Null	Samples whose cobble content is not null

The following queries are already prepared and can be used within NETDATA:

- QRY-CONS: this query will search the database for the results of the consolidation test.
- QRY-INDEX: This query can be used to search the database for index and classification parameters. The results of this query are used to prepare reports and produce graphs.
- QRY-SHEAR: this query will search the database for the results of shear strength tests carried out either by triaxial method or shear box testing.
- FRM-QUERY_QBF: is a form that works similar to a query. It combines Visual Basic and SQL commands for filtering data (adapted from Getz et al, 1994). Users who are not familiar with the query design options may use most criteria expressions for filtering data in this form without the use of queries. This is done by inputting the search criteria in the available boxes in the form. Although this form is not as powerful as a query and has some limitations in setting combined expressions for the criteria, it is a useful tool for filtering data. The results are displayed in a format that can easily be printed out. It is also possible to view the results in datasheet format using the option provided in the menu.

NETDATA - Forms

Forms display data from tables or queries so they can be viewed, edited, or data can be entered. They are used to view and edit information in the database record by record and use familiar controls such as textboxes and check boxes that are used in windows. This makes viewing and entering data easy. Instructions of use are given and shown in all the database forms..

Macros have been used in NETDATA database for viewing some of the results of the QRY-INDEX in the form of Microsoft Excel graphs. The macros will be run automatically from inside the forms. In addition to the relevant test results and information about the sample other parameters were also calculated and included in these forms (see the form list below).

According to the AGS rules, data that can be calculated from other available data in the database should not be included in any of the tables. Therefore, the calculated parameters are restricted to the relevant forms only. Similar to other fields the description of these parameters, their units and method of calculating them can be viewed at the bottom left corner of the database screen.

For viewing the charts, the button VIEW CHART in the forms should be used. When changing the query parameters the form should be closed and re-opened so that the changes take effect. Notices will be displayed in the forms about how to use this option. The results of the last query that has been run will be exported to a Microsoft Excel worksheet that is linked to a second worksheet that does the required calculations and presents the related graphs. This process uses a few automatic links and the calculation may take sometime (depending on the speed of the computer and the number of results displayed). Microsoft Excel has been used for producing these graphs because it makes it easier for the user to follow the steps and understand the calculations. It also makes it possible for the user to make changes to the graphs or in the way the results are presented.

The following forms have been prepared for NETDATA:

- SWITCHBOARD: is the from displayed when starting NETDATA and shows different options for working with the database. This form contains links to other objects within the database.
- FRM-EVI_PROJ: for viewing, editing or inputting data to fields from TBL-PROJ. To change the mode from Edit/View data to Add data or vice versa the switchboard options can be used.

- FRM-EVI_HOLE: for viewing, editing or inputting data to fields from TBL-HOLE. To change the mode from Edit/View data to Add data or vice versa the switchboard options can be used.
- FRM-EVI_SAMP: for viewing, editing or adding data to fields from TBL-SAMP. To change the mode from Edit/View data to Add data or vice versa the switchboard options can be used.
- FRM-EVI_TESTS: for viewing, editing or adding data to fields from test result tables. To change the mode from Edit/View data to Add data or vice versa the switchboard options can be used.
- FRM-CHRT_INDX: is used to plot the plasticity chart using Microsoft Excel and based on the results of QRY-INDEX query. This form also calculates parameters such as the Plastic Index and the Liquid Index from the query results. These parameters are not included in any table.
- FRM-CHRT_PSD: is used to plot the grading classification triangle using Microsoft Excel and based on the results of QRY-INDEX query.
- FRM-CHRT_OTHER: is designed as flexible tool so that the user of the database can transfer the results of QRY-ALL to an Microsoft Excel sheet and plot any required chart. The charts will not be overwritten when the data are updated after changing the query parameters.

NETDATA - Reports

A Report summarises and presents data from tables and queries so that it is possible to print and analyse them. Besides of viewing and printing information from the database, a Report can display the information in various formats.

The report can be saved and printed later. Several reports have already been prepared for NETDATA and are listed below:

- RPT-HOLE: Displays borehole summary using the results of QRY-INDEX
- RPT-INDX: Displays results of classification tests using QRY-INDEX
- RPT-CONS: Displays results of consolidation tests using QRY-CONS
- RPT-SHBG: Displays results of shear box tests using QRY-SHEAR
- RPT-TRIX: Displays triaxial test results using QRY-SHEAR

Data shown in all the above mentioned reports are results of relevant queries. When using the switchboard to access any of the reports the user will be prompted with an information window that directs to the correct query. The user may set the criteria in the design view of the query and open any of the reports after saving the query with the new criteria. It should be noted that similar to forms the reports must be closed and re-opened so that changes to the queries take effect if the query parameters have changed.

Fields used in any of the reports are defined in the first page of the output. The reports can be previewed using the options from the database menu before printing.

An easy way to design a new report is to use the report wizard by taking the following steps:

1- Click on the report button

2- Click on the New button

3- Select Report Wizard

4- Select table or query to be used

5- Select required fields

6- Select required sort order

7- Choose format and style

NETDATA - Macros

A macro is an action or set of actions that can be used to automate tasks. For creating a macro the macro object on the database must be chosen and a new macro opened. The actions that should be carried out must be entered. It is also possible to specify arguments for each action. These arguments provide additional information on how to carry out the action. Details on how to create and how to use macros are available on the Microsoft Access online help menu. Macros have been used in the design of the database and for different actions within NETDATA. All macros within the database are set for automatic action or can be activated by clicking on a button on the switchboard or in forms. Users do not need to run any of the macros individually and therefore they are made invisible.

NETDATA - Modules

Modules store Access Basic code that can be written to customise, enhance, and extend the database. Modules are units of code that are written in Access Basic language. To use modules a good knowledge of programming in Visual Basic is needed. They are more powerful than macros but more complex to write.

Modules have been used to automate some of the functions within NETDATA and also to use the "Query By Form" option. Similar to Macros, the modules used within NETDATA are set for automatic action within the database and the user does not need to activate them individually. It should be noted that these are not made visible to the user.

Adding data to database

It is possible to add data directly into the database by typing them into the related tables, or by using the provided forms.

Because the structure of the database represents a kind of parent/child relationship, similar to a hierarchy, the data input must follow a certain order. Adding data should begin by putting data into "TBL-PROJ" followed by putting borehole data into "TBL-HOLE". After that details of the sample must be put into the "TBL-SAMP".

If this order is not followed the database will display an error message. For instance if the user attempts to put sample data into TBL-SAMP before the relevant borehole information are added to the TBL-HOLE the database will not save the new entries.

Data and text can also be copied and pasted into the database from other applications such as MS-Word or MS-Excel. You can use Paste to put the copied data into provided cells or Paste Append to add new sets of data at the end of a table. Data can also be imported using the option from the menu. For more details on how to add data into a database Microsoft Access User Guide or the Online Access Help option could be used.

Exporting data from database

The Access File/Export option allows the transfer of data between Access and Excel, databases and delimited or fixed length text. The exact shape of the file depends on the requirements of the package to which the exporting will be carried out. The exported files can be printed or used with any other package. For instance after running AND saving a query the data can be exported by taking the following steps:

1. Select Save As/Export from the File menu
2. Select Save To an External File or Database and choose the file type (eg. mdb, xls, csv, txt, rtf, html, etc.)

The exported file is given a default name that can be changed and the Export to File window allows the selection of any drive or directory for the file.

Printing data from NETDATA

- At some point there is a need to print data from a table.

1. Open the table in Datasheet View
2. Select File/Print
3. Press the OK button

The printout will be of the standard table, containing all the data.

- A selection of the data from one or more tables can be printed as follows:

1. Run a query to select the data required
2. Select File/Print
3. In the Print Range group, select Selection

- Reports have already been designed and are available within NETDATA. By running the QRY-REPORTS query, the results will automatically be put into the format of the reports and can be printed out.

1. Run the QRY-REPORTS query to select the data required
2. Open the required report
3. Select File/Print
4. In the Print Range group, select Selection

- Some of the forms available in NETDATA contain fields that calculate variables that are not included in any of the table. These data can also be printed by following the steps below:

1- Run the relevant query for the form (instructions are given within the forms)

2- From the database menu change to datasheet view

3- Select File/Print

4- In the Print Range group, select Selection

Important Notes

- Do not delete, rename or change any files, objects and links, related to NETDATA.
- Adding data to the tables, creating and running queries may result in a sudden increase of the file size of the database. It is recommended to use the "Compact Database" utility to compress the database after finishing work. The option to do this can be found under TOOL from the database menu.

References

AGS; 1999; "Electronic Transfer of Geotechnical and Geoenvironmental Data", 3rd Edition; published by: The Association of Geotechnical and Geoenvironmental Specialists, ISBN: 0 9519271 8 3

Getz, K. Litwin, P. and Reddick, G. 1994. *Microsoft Access 2 Developer's Handbook.* Sybex Inc. California, USA.

Microsoft Corporation. 1994. *Microsoft Access, Relational Database Management System for Windows Version 2.0, User's Guide*; 1st Edition, Microsoft Corporation, Ireland.

Appendix C

Sample of borehole log and laboratory test results

Norwest Holst Soil Engineering Ltd.

BOREHOLE LOG

Borehole No. **S47**

Contract No. E8615
Location Blenmeller
Client British Coal Opencast Executive
Method of Boring Cable Percussion
Diameter of Borehole 250mm

Sheet 1 of 3
Co.Ords E375334 N560580
Ground Level 288.12 m.A.O.D.
Date 14/11/89-23/11/89

Description of Strata	Legend	Depth Below G.L. (m)	O.D. Level (m)	Casing Depth at Sampling	Sampling and Coring	"N"/ R.Q.D.%	Daily Progress
PEAT		0.45	287.67		0.00-0.45		14/11
Soft light grey, brown silty sandy CLAY		1.10	287.02		0.50-0.95 (11) 1.15-1.30		
Firm, blue grey, brown mottled silty CLAY with some fine to coarse subangular to subrounded gravel and some cobbles		1.35	286.77		1.15-1.30 (150) 1.30-1.75 1.75-2.20 (110) 2.25		
Stiff dark grey brown, slightly sandy silty CLAY with some fine rounded gravel and some cobbles and boulders					2.75-2.83 (100) 2.75-3.50 3.50-3.95 (125) 4.00 4.50-4.80 (150) 4.80-5.50 5.50 5.50-6.50		14/11
					5.60-6.05	"40"	15/11
					c 6.50-7.60		
6.80m-7.50m Band of brown medium to coarse gravel with some cobbles					6.60-6.90 c 6.50-7.60	"71" for 150mm	
					7.65-7.95 (150) 8.20-8.65 (139) 8.70		
Becoming reddish brown at 9.70m					9.20-9.65 8150) 9.90-10.65		15/11

Type of Sample

Is	S.P.T.	▮	Undisturbed
Ic	C.P.T.	X	Vane
0	Jar	△	Water
●	Bulk	▯	Piezometer

Remarks (Observations of Ground Water etc.) (-) U100 blows

Water struck 5.50m rising to 4.10m after 20 minutes, sealed at 7.80m Water level pm 14/11/89 4.10m.
Water level am 15/11/89 3.65m
Chiselling 1.30m-1.75m - 1.30 hours
2.75m-3.50m - 2.30 hours
4.80m-5.50m - 1.30 hours
6.80m-7.50m - 1.30 hours
7.95m-8.20m - 1.00 hour
9.90m-10.65m - 2.00 hours

Water levels are subject to seasonal or tidal variations and should not be taken as constant

Figure C.1: Sample of a borehole log (Sheet 1 of 3).

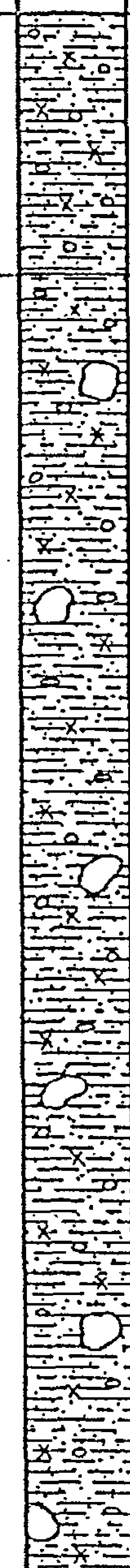
Norwest Holst Soil Engineering Ltd.

BOREHOLE LOG

Borehole No. **S47**

Contract No. F8615
Location Plenmeller
Client British Coal Opencast Executive
Method of Boring Cable Percussion
Diameter of Borehole 250mm-200mm-15.00mm

Sheet 2 of 3
Co.Ords. E375334 N560580
Ground Level 288.12 m.A.O.D.
Date 14/11/89-23/11/89

Description of Strata	Legend	Depth Below G.L.(m)	O.D. Level (m)	Casing Depth at Sampling	Sampling and Coring	"N"/ R.Q.D.%	Daily Progress
Stiff reddish brown slightly sandy silty CLAY with some fine to coarse subangular to subrounded gravel		11.65	276.47		10.75–11.15 (170) 11.15 11.65		15/11 15/11
Stiff reddish brown slightly sandy silty CLAY with some fine to coarse subangular to subrounded gravel with some cobbles and boulders Becoming dark grey brown by 19.30m					12.15–12.60 (170) 13.10 13.60–13.95 (170) 14.40 14.90–15.35 (175) 15.90 16.40–16.85 (160) 17.40 17.90–18.35 (168) 18.90 19.30–19.75 (175) 19.80		16/11 16/11 17/11 17/11

Type of Sample

Is	S.P.T.	▯	Undisturbed
Ic	C.P.T.	x	Vane
0	Jar	△	Water
●	Bulk		Piezometer

Remarks (Observations of Ground Water etc.) (-) U100 blows

Water not encountered

Chiselling	9.90m–10.65m	-	2.00 hours
	11.15m–11.30m	-	1.00 hour
	13.40m–13.60m	-	1.30 hours
	13.95m–14.40m	-	2.00 hours
	17.45m–17.65m	-	1.00 hour
	19.90m–20.35m	-	8.00 hours

Water levels are subject to seasonal or tidal variations and should not be taken as constant

Figure C.2: Sample of a borehole log (Sheet 2 of 3).

Norwest Holst Soil Engineering Ltd.

Borehole No. **S47**

BOREHOLE LOG

Contract No. F8615

Location Plenmeller

Client British Coal Opencast Executive

Method of Boring Cable Percussion

Diameter of Borehole 200mm-150mm

Sheet 3 of 3

Co. Ords E375334 N560580

Ground Level 288.12 m.A.O.D.

Date 14/11/89-23/11/89

Description of Strata	Legend	Depth Below G.L.(m)	O.D. Level (m)	Casing Depth at Sampling	Sampling and Coring	"N"/ R.Q.D.%	Daily Progress
Stiff greyish brown, occasionally reddish brown slightly sandy silty CLAY with some fine to coarse subangular gravel and some cobbles and boulders		27.30	260.82	250mm to 20.35m; 200mm to 20.60m; 150mm to 25.40m	20.80-21.25 (160); 21.30; 21.80; 22.30-22.45 (150); 22.70-23.15 (175); 23.70; 24.20-24.65 (150); 24.70; 25.20; 25.70-26.15 (155); 26.20; 26.70; 27.20-27.50 (150)		17/11; 20/11; 20/11; 21/11
Loose grey brown fine to medium slightly silty SAND		27.80	260.32		27.30; 27.30-27.80; 27.30-27.75 S	"16"	21/11

Type of Sample

Is	S.P.T.	▪	Undisturbed
Ic	C.P.T.	X	Vane
O	Jar	△	Water
●	Bulk		Piezometer

Remarks (Observations of Ground Water etc.) (-) U100 blows

Water struck 27.30m rising to 18.00m after 20 minutes

Water level pm 21/11/89, 18.00m Water level am 22/11/89, 5.30m

22/11/89 - sand blown up to 18.00m.

Piezometer inserted with tip at 24.30m

Grouting borehole to G.L.- 9 hrs.

Borehole complete at 27.80m

Chiselling 19.90m-20.35 - 8.00 hrs

20.35m-20.70m - 6.30 hrs

22.45m-22.70m - 0.30 hrs

23.30m-23.55m - 1.30 hrs

Water levels are subject to seasonal or tidal variations and should not be taken as constant

Figure C.3: Sample of a borehole log (Sheet 3 of 3).

Norwest Holst Soil Engineering Ltd.

Contract No. F8615 Client British Coal Location Plenmeller

SAMPLE DETAILS			CLASSIFICATION										CHEMICAL			DENSITY		COMPACTION			CBR	STRENGTH			CONSOLIDATION $p_c \to p_o + 100 kN/m^2$	
No. & Type	Depth m	Description	w %	LL %	PL %	PI %	<425μ %	SG	Particle size distribution: Clay %	Silt %	Sand %	Grvl %	SO_3 %	pH	Org %	Bulk ρ Mg/m^3	Dry ρd Mg/m^3	Ram kg	Max ρd Mg/m^3	O.M.C %	Mean %	Type	c kN/m^2	Ø degree	m_v m^2/MN	c_v m^2/yr
		S47																								
U	0.50	Light grey brown silty sandy CLAY	22	35	18	17	100									1.46	1.20					TU 102	7	0		
U	1.75	Dark grey brown mottled CLAY with some fine to coarse gravel	13	30	13	17	70									2.14	1.89					EUT	13	29		
U	3.50	Dark grey brown mottled CLAY with some fine to coarse gravel.	12	31	14	17	64									2.15	1.92					EUT	7	27		
W	4.10	Water Sample											* 1.00	7.8												
U	4.50	Dark grey brown mottled CLAY with some fine to coarse gravel	12	30	12	18	75									2.17	1.94					TU 102	64	7	0.15	2.9
B	5.50	Dark grey brown mottled CLAY with some fine to coarse gravel							11	19	20	50														
B	6.50	Dark grey brown mottled CLAY with some fine to coarse gravel							not representative 7		3	3														
U	9.20	Dark grey brown mottled CLAY with some fine to coarse gravel	13	32	13	19	71									2.12	1.88					EUT	5	27	0.16	3.7
U	11.60	Reddish brown slightly sandy silty CLAY with some fine to coarse gravel.	10	29	12	17	76									2.19	1.99					TU 102	150	7	0.12	3.0
U	17.90	Reddish brown slightly sandy silty CLAY with some fine to coarse gravel.	9.8	30	13	17	65									2.08	1.89					TU 102	96	0		
U	19.30	Reddish brown slightly sandy silty CLAY with some fine to coarse gravel.	11	31	15	16	81									2.06	1.86					TU 102	82	0		
U	20.80	Greyish brown slightly sandy silty CLAY with fine to coarse gravel	11	29	13	16	77									2.07	1.86					TU 102	46	0		

NOTES: U — Undisturbed; B — Bulk; D — Disturbed. NP — Non Plastic. * parts per 100,000. T — Triaxial compression; E — Effective stress; R — Remoulded. U — Undrained; W — Unconfined; S — Shear Box.

Summary of Laboratory Test Results **Borehole No. S47**

Figure C.4: Laboratory test results Summary Sheet (Page 1 of 2).

Norwest Holst Soil Engineering Ltd.

Contract No. F8615 Client British Coal Location Plenmeller

SAMPLE DETAILS			CLASSIFICATION										CHEMICAL			DENSITY		COMPACTION			C B R	STRENGTH			CONSOLIDATION	
No & Type	Depth m	Description	w %	L L %	P L %	P I %	<425µ %	S G	Particle size distribution Clay %	Silt %	Sand %	Grvl %	SO_3 %	pH	Org %	Bulk ρ Mg/m³	Dry ρd Mg/m³	Ram kg	Max ρd Mg/m³	O.M.C %	Mean %	Type	c kN/m²	Ø degree	$P_o \rightarrow P_o + 100kN/m^2$ m_v m²/MN	c_v m²/yr
		S47 (cont.)																								
U	22.30	Greyish brown slightly sandy silty CLAY with fine to coarse gravel.	5	34	15	19	76																			
U	22.70	Greyish brown slightly sandy silty CLAY with fine to coarse gravel.	14	32	14	18	80									2.12	1.80					TU 102	79	6		
U	24.20	Greyish brown slightly sandy silty CLAY with fine to coarse gravel	14	34	14	20	79									2.08	1.82					TU 102	93	6		
U	25.70	Greyish brown slightly sandy silty CLAY with fine to coarse gravel.	16	38	18	20	77									2.09	1.80					TU 102	140	0		

NOTES: U — Undisturbed; B — Bulk; D — Disturbed. N P — Non Plastic. T — Triaxial compression; E — Effective stress; R — Remoulded. U — Undrained; W — Unconfined; S — Shear Box.

Summary of Laboratory Test Results

Borehole No. S47

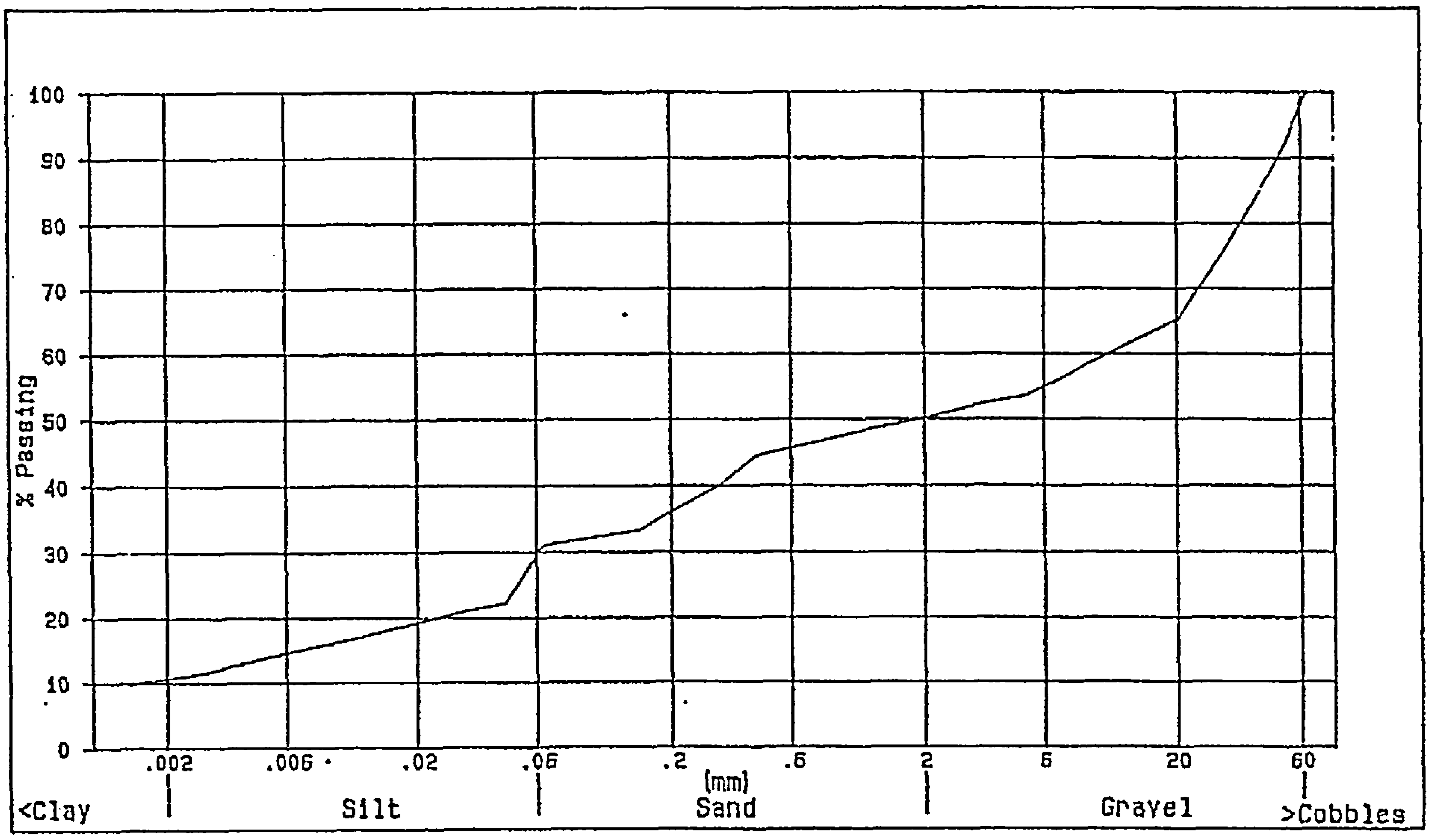
Figure C.5: Laboratory test results Summary Sheet (Page 2 of 2).

NORWEST HOLST SOIL ENGINEERING LTD.

PARTICLE SIZE DISTRIBUTION

LOCATION PLENMELLER CONTRACT No. F8615

Borehole No.S47 Depth 5.50m



Borehole No. S47 Depth 6.5m

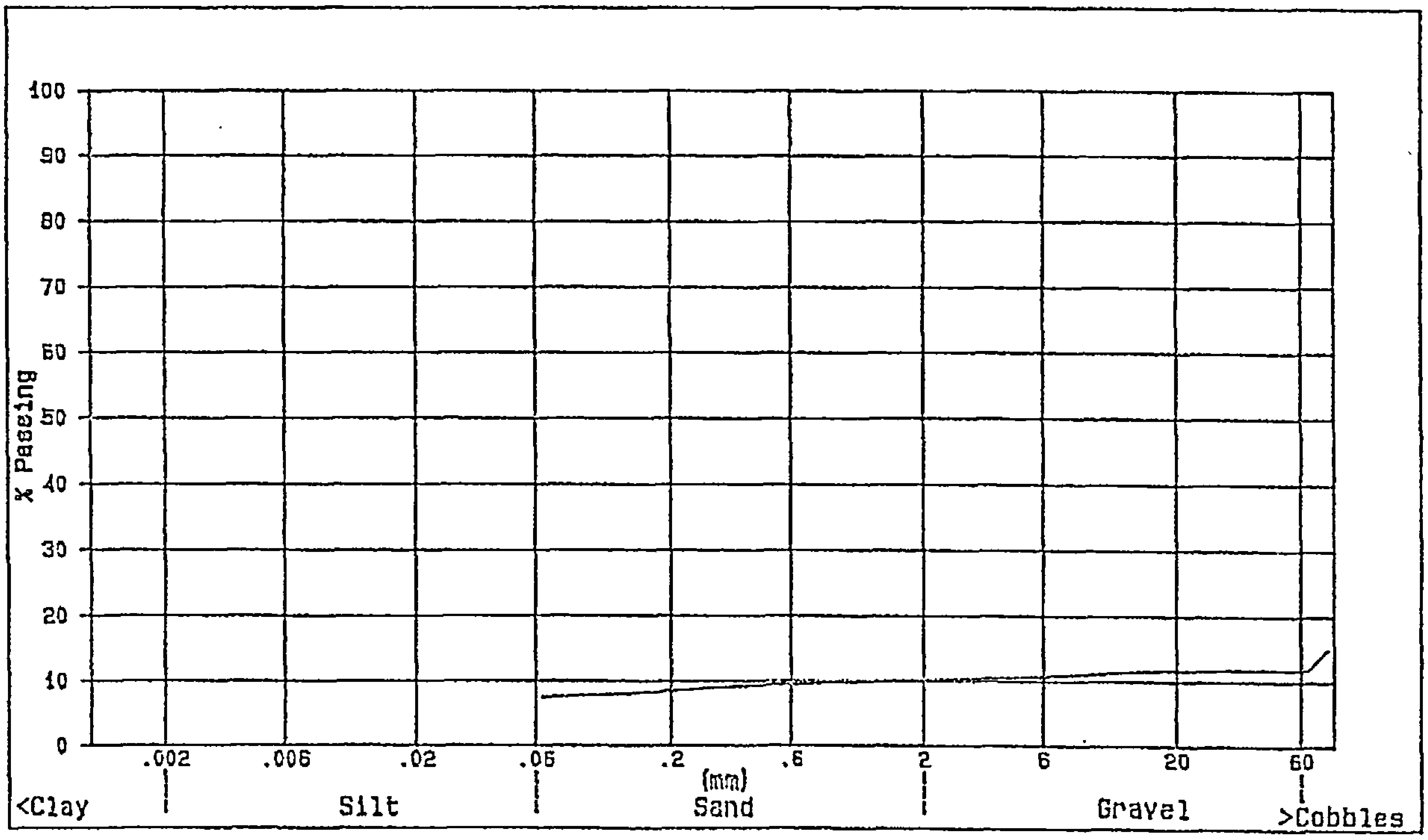


Figure C.6: Example of laboratory testing data sheet for Particle Size Distribution.

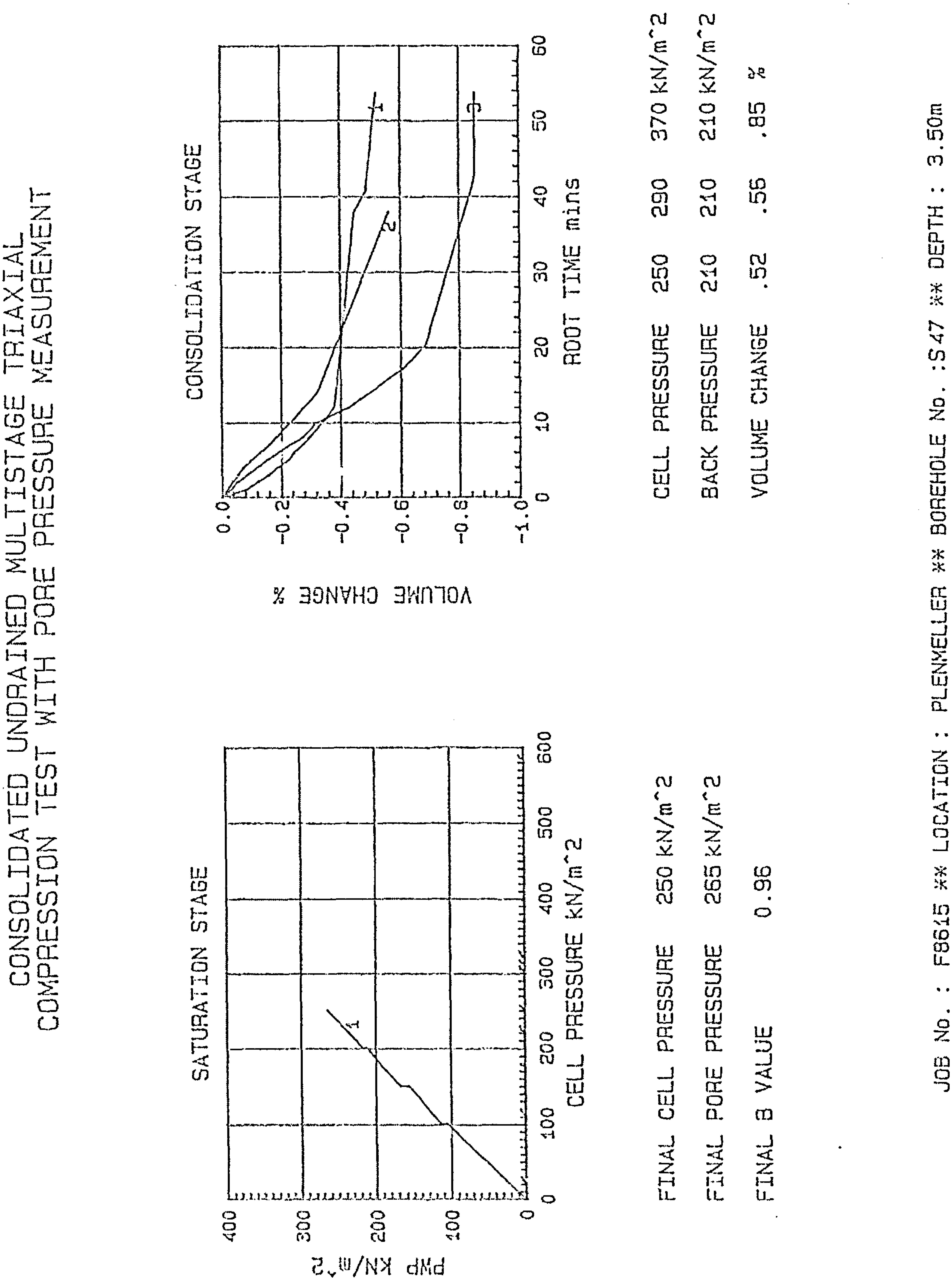
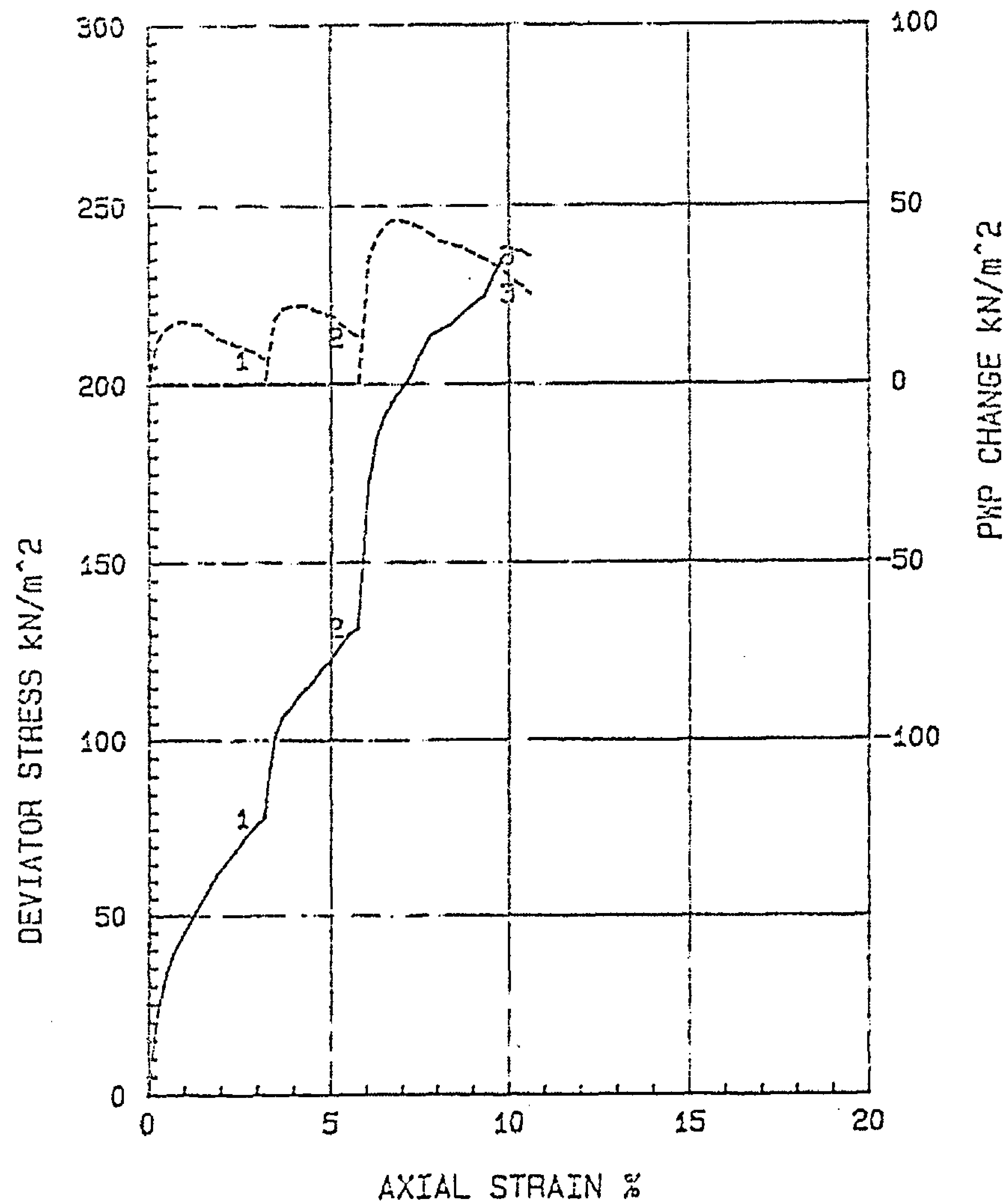


Figure C.7: Example of laboratory testing data sheet for consolidated undrained triaxial test (Page 1 of 4).

CONSOLIDATED UNDRAINED MULTISTAGE TRIAXIAL COMPRESSION TEST WITH PORE PRESSURE MEASUREMENT



	1	2	3	
INITIAL CONDITIONS				
SAMPLE UNDISTURBED				
SAMPLE HEIGHT	203.20			mm
SAMPLE DIAMETER	104.80			mm
WET DENSITY	2.15	2.14	2.15	Mg/m^3
WATER CONTENT	12	12	12	%
SATURATION STAGE				
FINAL CELL PRESSURE	250			kN/m^2
FINAL PORE PRESSURE	265			kN/m^2
CONSOLIDATION STAGE				
CELL PRESSURE	250	290	370	kN/m^2
BACK PRESSURE	210	210	210	kN/m^2
COMPRESSION STAGE				
STRAIN RATE	0.2	0.2	0.2	%/hr
FAILURE CONDITIONS				
AT MAX DEVIATOR STRESS				
AXIAL STRAIN	3.2	5.8	10.3	%
A VALUE	0.09	0.10	0.11	
SHEAR STRESS	39.2	65.9	118.8	kN/m^2
Q VALUE	72.2	132.9	251.8	kN/m^2
STRESS RATIO	3.38	2.97	2.79	
AT MAX STRESS RATIO				
AXIAL STRAIN	2.9	5.0	9.8	%
A VALUE	0.12	0.15	0.14	
SHEAR STRESS	37.6	61.4	117.4	kN/m^2
Q VALUE	68.6	122.4	245.4	kN/m^2
STRESS RATIO	3.43	3.01	2.83	
FINAL CONDITIONS (COMPUTED)				
WET DENSITY	2.14	2.15	2.16	Mg/m^3
WATER CONTENT	12	12	11	%

JOB No. : F8615 ** LOCATION : PLENMELLER ** BOREHOLE No. :S47 ** DEPTH : 3.50m

Figure C.8: Example of laboratory testing data sheet for consolidated undrained triaxial test (Page 2 of 4).

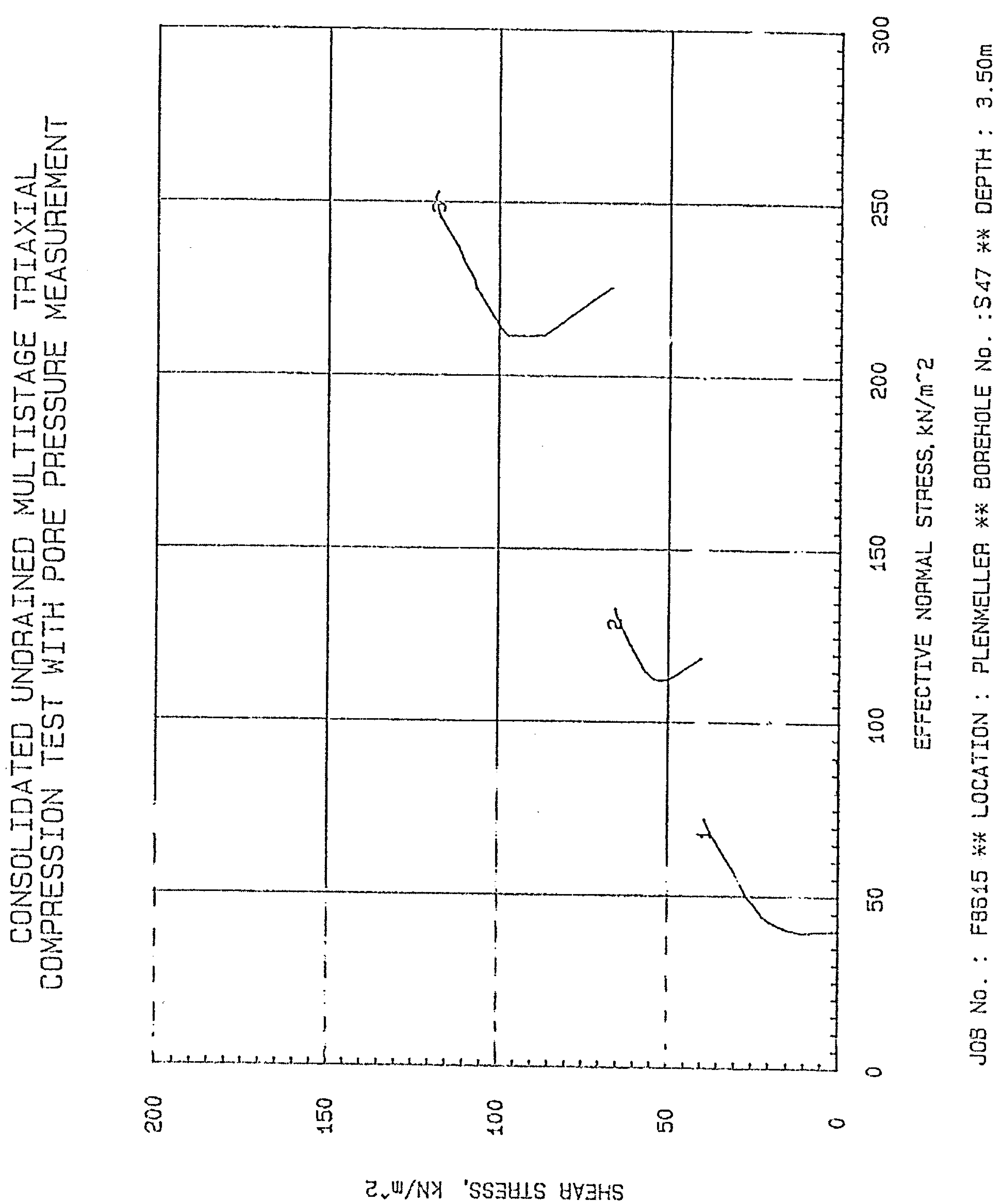


Figure C.9: Example of laboratory testing data sheet for consolidated undrained triaxial test (Page 3 of 4).

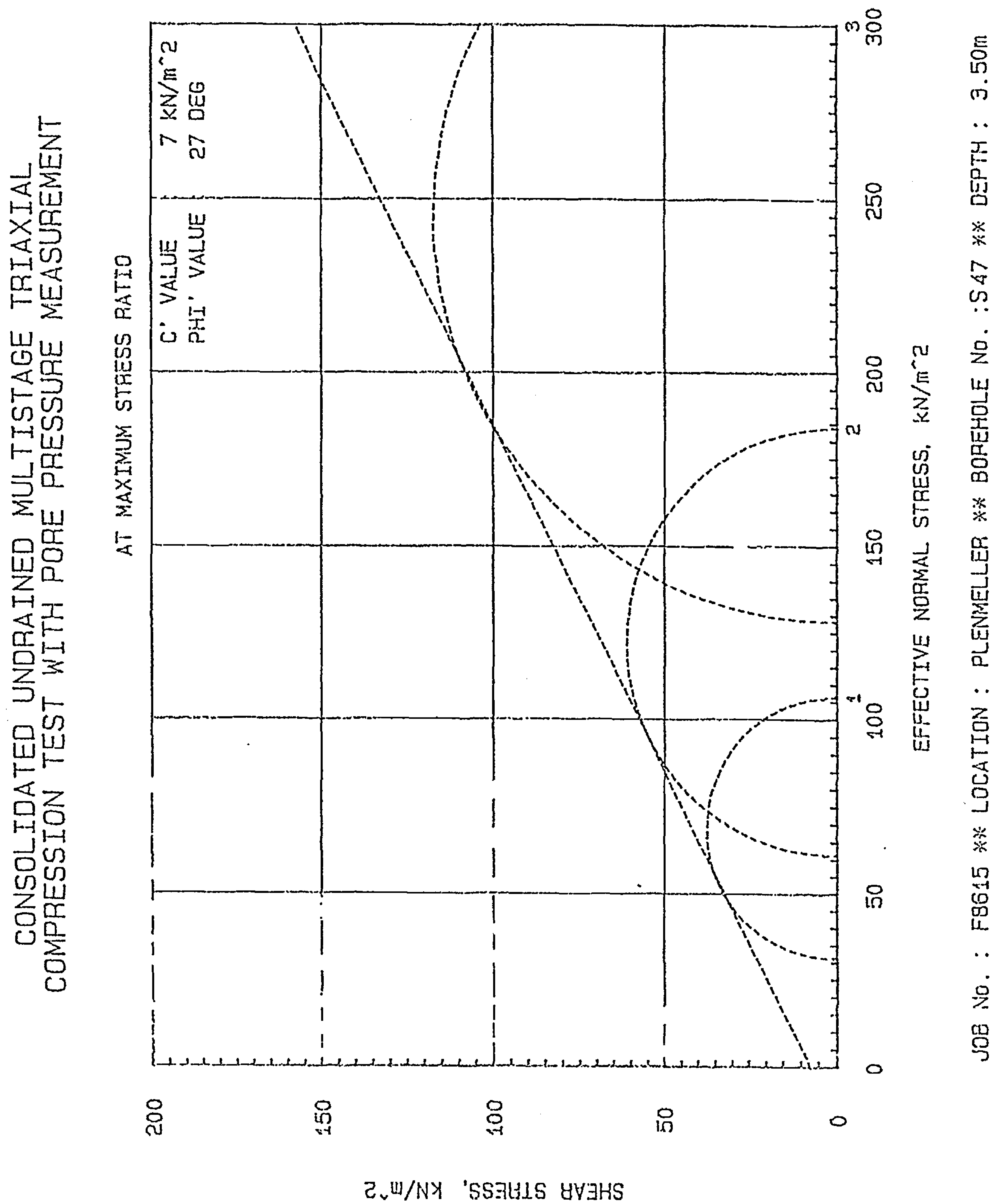


Figure C.10: Example of laboratory testing data sheet for consolidated undrained triaxial test (Page 4 of 4).

Norwest Holst Soil Engineering Ltd.

UNDRAINED TRIAXIAL COMPRESSION TESTS

Borehole Nos. S47

Contract No. ....F8615..

Location .....Plenmeller.. Client ....British Coal................

Borehole / Sample No. & Type	Depth (m)	Description of Material	Moisture content (%)	Density Bulk (Mg/m³)	Density Dry (Mg/m³)	Diameter (mm)	Cell Pressure (kN/m²)	Deviator Stress (kN/m²)	Cohesion Intercept (kN/m²)	Angle of Shearing Resistance (degrees)	Failure Strain % / Failure Mode
S47 / U	0.50	Light grey brown silty sandy CLAY	22	1.46	1.20	102	25 50 100	10 14 16	7	0	3 / P
S47 / U	4.50	Dark grey brown slightly sandy silty CLAY with gravel	12	2.17	1.94	102	50 100 200	154 177 195	64 (88)	7	17 / P
S47 / U	13.60	Reddish brown slightly sandy silty CLAY with some gravel	10	2.19	1.99	102	140 280 560	368 433 481	150 (214)	7	17 / C
S47 / U	17.90	Reddish brown slightly sandy silty CLAY with some gravel	9.8	2.08	1.89	102	180 360 720	178 190 210	96	0	17 / C
S47 / U	19.30	Reddish brown slightly sandy silty CLAY with some gravel	11	2.06	1.86	102	200 400 800	129 167 195	82	0	8 / C
S47 / U	20.80	Greyish brown slightly sandy silty CLAY with some gravel	11	2.07	1.86	102	200 400 800	75 88 113	46	0	5 / C
S47 / U	22.70	Greyish brown slightly sandy silty CLAY with some gravel	14	2.12	1.86	102	200 400 800	193 323 350	79 (144)	6	15 / C
S47 / U	24.20	Greyish brown slightly sandy silty CLAY with some gravel	14	2.08	1.82	102	200 400 800	242 304 376	93 (154)	6	17 / P
S47 / U	25.70	Greyish brown slightly sandy silty CLAY with some gravel	16	2.09	1.80	102	200 400 800	243 297 326	140	0	16 / C

Notes

P - Plastic B - Brittle C - Compound

Figure C.11: Example of laboratory testing data sheet for undrained triaxial compression test (Page 1 of 2).

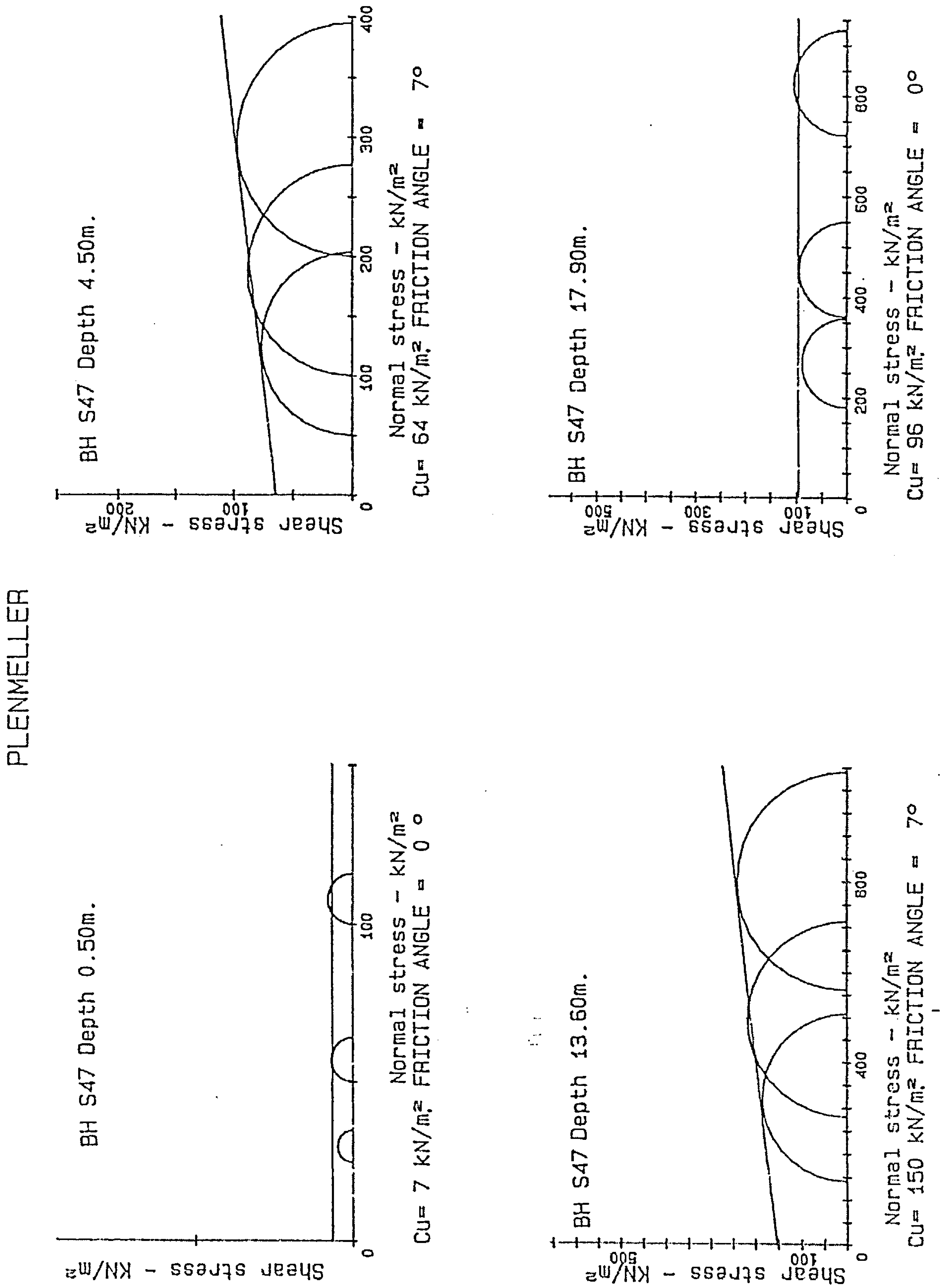
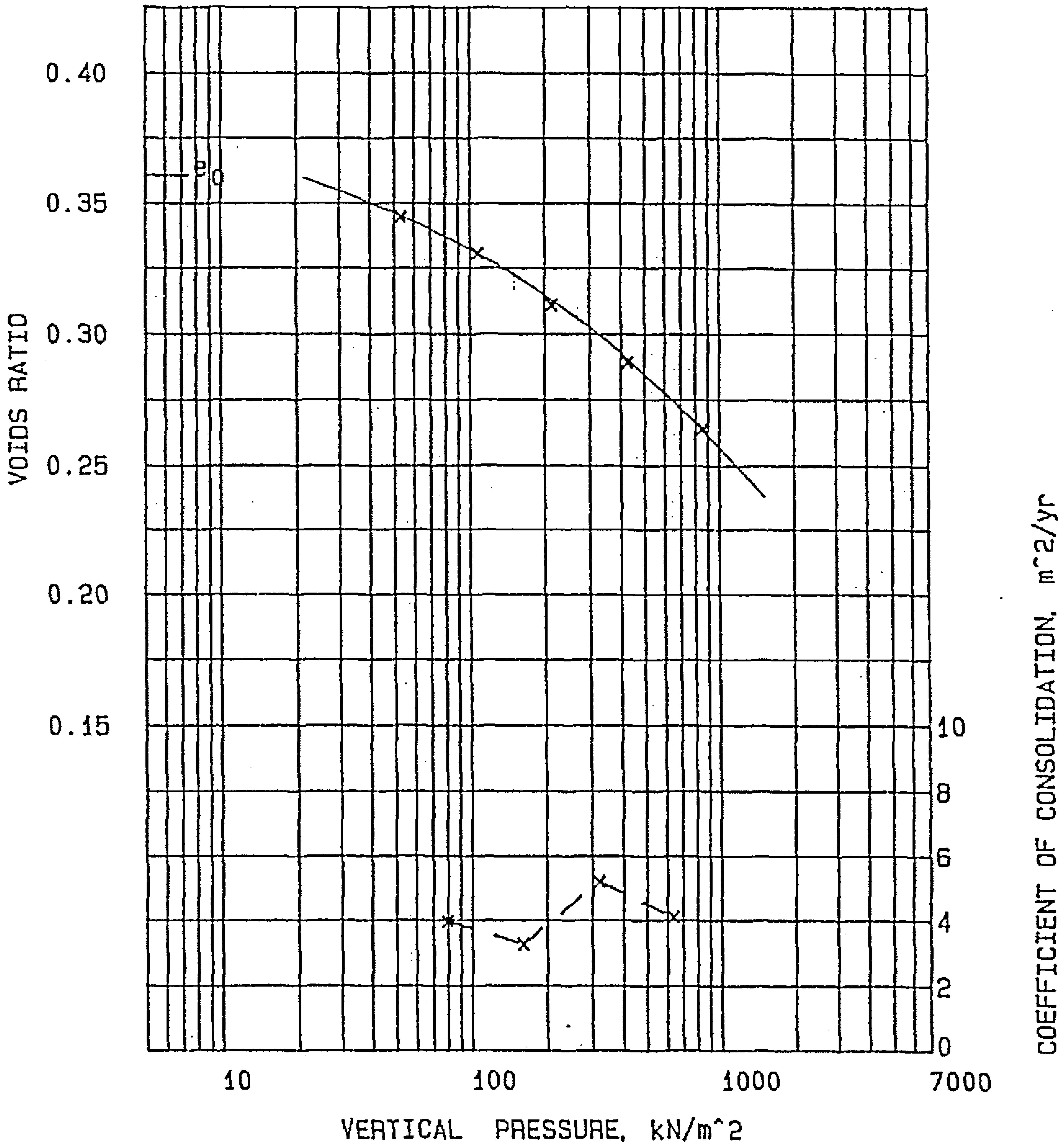


Figure C.12: Example of laboratory testing data sheet for undrained triaxial compression test (Page 2 of 2).

CONSOLIDATION TEST



JOB NUMBER	F8615
LOCATION	PLENMELLER
BOREHOLE NUMBER	S-47
DEPTH	13.60m
INITIAL VOIDS RATIO	0.3603
FINAL VOIDS RATIO	0.2639
INITIAL WATER CONTENT	11 %
FINAL WATER CONTENT	11 %
SAMPLE DIMENSIONS	75.00mm Dia x 19.00mm
FINAL DRY DENSITY	2.14 Mg/m^3
SPECIFIC GRAVITY	2.70

PRESSURE kN/m^2	COEFFICIENTS	
	MV m^2/MN	CV m^2/yr
0		
54	0.2179	----
107	0.1945	3.8
215	0.1384	3.1
429	0.0769	5.0
858	0.0453	3.9

Figure C.13: Example of laboratory testing data sheet for consolidation test.

Appendix D

Description of individual sites

D.1 Description of sites in Northumberland

Site name: Chester House Extension

Location: Chester House near the town Amble in Northumberland

Contractor: Norwest Holst Soil Engineering Ltd.

Date: September to October 1984

Memo: Site investigation was carried out in order to obtain information on the ground conditions. It was proposed to extend the working of coal using opencast methods in this area

Number of Boreholes: 37

Ground Conditions: The general succession encountered in the boreholes consists of a thin layer of topsoil that is underlain by superficial deposits. The deposits consist of clays with numerous bands of clayey sand or occasional gravel layers. The main types of clay found in the boreholes were a soft to firm yellow brown mottled silty sandy clay, which occurred mostly near the surface below the topsoil. A layer of firm to stiff brown silty clay with numerous silty or sandy laminations was encountered below the yellow brown clay. Below this layer a firm to stiff brown or grey silty sandy clay with numerous gravels, cobbles and boulder exists. Rockhead comprised of either mudstone or sandstone and was reached in most boreholes.

Site name: Acklington Extension and Acklington Spoil Heap

Location: Approximately 1.5 km to the west of Amble and south of Warkworth in Northumberland

Contractor: Allied Exploration and Geotechnics Ltd.; Norwest Holst Soil Engineering Ltd

Date: September 1992 to April 1993, December 1981

Memo: Site investigation was carried out and 8 boreholes were sunk in Acklington to obtain information on the ground condition for the construction of an opencast mine. An additional site investigation was carried out to provide information on the ground condition in order to extend Chester House Opencast Site.

Number of Boreholes: 46 and 8

Ground Conditions: A layer of topsoil with a thickness of up to 0.55 meters covers most of the site. Made ground was not proved in most of the boreholes. Below the topsoil a layer of firm orange brown to brown mottled grey slightly sandy clay was encountered in most boreholes. The material below the mottled clay was mainly described as stiff to very stiff sandy gravelly clay. The colour changed from reddish brown to brown and grey brown to grey in some boreholes. Layers of laminated clay and pockets of sand and gravel were encountered across the site within the clay layer. The bedrock relates to the Coal measures and is predominantly composed of sandstones, siltstones, mudstones and coal.

Site name: Coldrife Lake and Chevington Burn Diversion

Location: South of Chevington Drift, near Red Row, Northumberland

Contractor: Northumbrian Drilling Contractors

Date: November 1979 to March 1980

Memo: Investigation were carried out to determine source areas of suitable material to re-line Coldrife Lake to the south of Chevington Drift

Number of Boreholes: 31

Ground Conditions: A layer of topsoil with a maximum depth of 0.5 meters covers the site. Below the topsoil lies the main drift that is defined as stiff brown silty sandy clay with fine to medium gravel. Layers of laminated clay or bands of sand were identified in some of the boreholes. A layer of stiff dark grey sandy silty clay with fine to coarse gravel lies beneath the laminated clay. No consistent depth correlation was found with the colour of the clay.

Site name: East Chevington

Location: East of the village of Red Row, Northumberland

Contractor: Norwest Holst Soil Engineering Ltd.

Date: August 1979 to August 1980

Memo: Site investigations were carried out in order to get information on the ground condition of the site.

Number of Boreholes: 35

Ground Conditions: The dominant material found in the boreholes is a stiff to firm dark brown or brown grey, silty, sandy clay with well graded gravel and cobbles. Within this material are sandy zones, layers of laminated clay, silt and peat. At some places a layer of stiff dark grey silty sandy clay lies underneath the laminated clay.

Site name: Colliersdean (West Chevington)

Location: The site lies approximately 11 km north of Morpeth at West Chevington in Northumberland.

Contractor: Norwest Holst Soil Engineering Ltd

Date: September 1989 to October 1989

Memo: Site investigation was carried out in order to assess the ground condition and extent of superficial materials at Colliersdean to develop the site for opencast coal extraction.

Number of Boreholes: 50

Ground conditions: Layers of made ground or topsoil with variable thicknesses cover most of the site. In most boreholes boulder clay deposits were found below either the topsoil or made ground. The boulder clay throughout the site was found to be relatively consistent with subtle changes in colour. It is mostly defined as dark brown sandy silty CLAY with much gravel. The two main types of boulder clay that could be distinguished by colour were dark grey and dark brown although no consistent depth correlation was found. The clay contains fine to coarse gravel. Cobbles and boulders occur throughout the site. Layers of laminated clay or sand pockets were also identified at some places. The sand and gravel deposits were mostly limited in extent. The bedrock was generally grey-brown weathered sandstone, although siltstone and mudstone were also encountered. The bedrock was found to be commonly overlain by a thin layer of brown clayey sand and gravel representing completely to highly weathered rock material.

Site name: Maiden's Hall

Location: Maiden's Hall in the area of West Chevington approximately 11 km north of Morpeth in Northumberland.

Contractor: Norwest Holst Soil Engineering Ltd

Date: November 1991 to February 1993

Memo: This ground investigation was carried out to assess the geotechnical properties of the ground in order to develop the site for opencast mining.

Number of Boreholes: 77

Ground Conditions: A thin layer of topsoil covers most of the site with a thickness of up to 0.5 metre. Below the topsoil a layer of orange brown or grey brown mottled clay exists up to 4.5 metres deep at some places. The main drift which is very variable in depth and occasionally reaches more than 30 metres at some places. The soil is described as stiff to very stiff or firm sandy silty clay with occasional gravel. Within this layer lenses of silt and pockets of sand and gravel were encountered at different depths. The colour of the material varies from grey to brown but no correlation with depth was found.

Sitename: Widdrington

Location: The site is situated approximately 11.5 km north north east of Morpeth in Northumberland and can be accessed from C115 that runs westwards from Widdrington to Chevington Moor.

Contractor: Allied Exploration and Geotechnics Ltd

Date: November 1992 to March 1993

Memo: Site investigation was carried out in order to obtain information on the ground condition on the land underlying and adjacent to Widdrington Disposal Point. It was proposed to develop an opencast mine at this location.

Number of Boreholes: 40

Ground Conditions: A layer of topsoil covered the site with a thickness of up to 0.45 meters. Below the topsoil a layer of firm brown mottled grey slightly sandy clay was encountered in some of the boreholes. The material below this layer was described as firm to stiff sandy gravelly CLAY with occasional cobbles. The colour of the material varied from reddish brown to brown and grey brown. Below the brown layer the material was mainly grey to dark grey in colour. Pockets of sand and gravel and bands of laminations with variable thickness were encountered in different boreholes across the site.

Site name: Steadsburn

Location: C115 diversion leaves the present A1068 at Widdrington Roundabout and trends predominantly East/West to join Chevington Moor Crossroads

Contractor: Allied Exploration and Geotechnics Ltd.

Date: April 1993 to July 1993

Memo: Investigation was carried out in order to obtain information on the ground condition for a diversion to be made to the existing route of the C115 public road. The plan coincided with British Coal Opencast plans to re-route an existing haul-road to Stobswood Opencast site.

Number of Boreholes: 53

Ground Conditions: A layer of topsoil was encountered in almost all boreholes. Made ground with variable thickness was found in some of the boreholes. The material below the topsoil and the made ground was mainly described as stiff orange brown mottled grey very sandy gravelly clay. Below the mottled clay the material consisted of stiff to very stiff brown sand to very sandy gravelly clay. Below the brown clay the colour of the material changed to grey in many of the boreholes. Bands of sand and gravel with variable thickness and extend were found in some of the boreholes along with layers of laminated clay. The bedrock below the clay material was mainly grey to dark grey weathered mudstone or moderately weathered grey siltstone or light grey sandstone.

Site name: Stobswood

Location: at about 12 kilometres north of Morpeth in Northumberland

Contractor: Norwest Holst Soil Engineering Ltd

Date: October 1988 to December 1988

Memo: Ground Investigations were carried out in order to assess the ground conditions and the extent of superficial material. The site investigation reports were divided into several volumes containing data for the Northern Group, Central Group, Southern Group, the Coal Haul Road and the Water course Diversion.

Number of Boreholes: 147

Ground Conditions: The site investigation results show that a layer of sandy topsoil existed over most parts of the area with a maximum thickness of 300 mm. Below the topsoil a layer of mottled clay existed known as Unit 1 that extended up to 4 meters in thickness. This layer is usually described as Firm to occasionally stiff mottled orange brown and grey sandy, silty CLAY with gravel. Unit 2 that lies beneath Unit 1 is described as stiff dark brown sandy, silty CLAY with gravel, cobbles and boulders. Unit 3 is described as stiff to very stiff, dark grey sandy silty CLAY with gravel, cobbles and boulders where occasional sand or gravel bands are encountered. Different layers exist between Unit 2 and Unit 3 throughout this site. Their description varies from sandy gravels and silty sands to laminated or indistinctly laminated silty sands and clays with thicknesses up to 18 meters in some parts.

Site name: West Linton, Linton Lane, Butterwell Disposal Point

Location: West Linton, near Morpeth in Northumberland

Contractor: Northumbrian Drilling Consultants; BB Drilling; NDC

Date: April 1980; May 1988; December 1974 to September 1981

Memo: It was proposed to extend the working of coal using opencast methods. Site investigations were carried out in order to obtain information on the ground conditions of the site.

Number of Boreholes: 28; 23; 9 (A total of 60 boreholes for all three sites)

Ground Conditions: Although the superficial deposits varied in thickness and type from borehole to borehole they consisted mainly of stiff brown silty sandy CLAY with occasional bands of medium dense clayey sand. Sand bands with clayey partings overlaying the thicker deposits of very stiff dark grey/brown silty sandy CLAY were separating this layer from the thin upper deposit of weathered clay described as firm to stiff mottled brown sandy CLAY. A further 23 boreholes are recorded in the database containing data of site investigation that were carried out in the area west of the village of Linton Northumberland. This investigation was undertaken to provide more information on the superficial deposits in order to assess the potential of the ground to use as a spoil disposal area. The glacial deposits present throughout the site very in thickness from 2 meters up to 14 meters. Mottled CLAY has been identified within the upper 1 to 2 meters throughout the site and is generally described a s firm to stiff orange brown locally grey mottled silty sandy CLAY with some gravel. Laminated clays of between 1 to 2 meters in thickness occur beneath the mottled clays and are generally described as soft to firm brown thinly laminated sandy silty CLAY with occasional gravel and partings or lenses of fine sand and silt. Boulder CLAY occurs below the laminated clays and is described as stiff to very stiff brown / grey silty sandy gravelly CLAY with some cobbles and boulders.

Site name: Hathery Lane

Location: This site is located in Bebside approximately 4 km north of Cramlington near Blyth in Northumberland.

Contractor: Norwest Holst Soil Engineering Limited; Allied Exploration and Geotechnics Ltd.

Date: February to September1992; November to December 1993

Memo: It was proposed to carry out opencast mining on the site. Several site investigations were carried out at this location in order to determine the nature and extent of the superficial deposits overlying the site.

Number of Boreholes: 48 and 37 boreholes in two site investigations (Total of 85)

Ground Conditions: A layer of topsoil with a thickness of up to 0.6 metres covers the site. In some of the boreholes made ground with variable thickness is encountered. Below the topsoil a layer of firm brown to yellow mottled grey sandy gravelly clay or stiff orange brown veined grey sandy gravelly clay exists. The material below this layer is described as firm to stiff sandy silty clay and the colour varies from reddish brown and brown to grey brown and grey. There is no correlation between the colour and the depth. Layers of laminated clay were found in some of the boreholes, which were associated with sand and gravel pockets. These laminations and / or pockets of sand and gravel were variable in thickness and extend.

D.2 Description of sites in Tyne and Wear, South West Northumberland and County Durham

Site name: Herrington Colliery

Location: The site is located 7 km east-north-east of Chester-le-street and 6 km south-west of Sunderland close to the Penshaw Monument.

Contractor: Ian Farmer Associates

Date: August to November 1991

Memo: Site investigation was carried out in order to obtain information on the ground condition.

Number of Boreholes: 69

Ground Conditions: A thin layer of topsoil was found across the whole site. The material below the topsoil comprises as soft to firm silty sandy clay. The colour of the clay varies from red brown and brown to grey brown and grey. There is no consistent depth correlation associated with the colour and layers of brown clay overlay and in some places lay under grey clay. Layers of laminated clay were identified in many of the boreholes at different depths. These are described as soft to firm grey brown or grey silty sandy clays with laminations of silt and / or sand. Pockets of sand and gravel were also encountered at various boreholes across the site, which were often in association with laminated clays.

Site name: Hunters Moor

Location: The site is located on land adjacent to the Town Moor in Gosforth, Newcastle upon Tyne.

Contractor: Ian Farmer Associates

Date: July 1993

Memo: Site investigation was carried out in order to obtain information on the ground condition

Number of Boreholes: 15

Ground Conditions: Most of the site is covered by a layer of topsoil or made ground with a thickness of 0.45 to 0.9 meters. Below the topsoil a layer of mottled clay was identified across the site with variable thickness which is described as a firm orange / brown mottled grey silty slightly sandy clay with some gravel. Below this layer the soil is described mainly as stiff brown or dark brown silty slightly sandy clay with some gravel. In some of the boreholes a layer of stiff grey slightly silty sandy clay with some gravel was found below the brown clay.

Site name: Plenmeller

Location: approximately 3 km south of Haltwhistle in Northumberland. The site is confined in the south east by Fellhouse Fell and to the west by Todhill Fell, and has a general slope northwards down into the river valley of the South Tyne

Contractor: Norwest Holst Soil Engineering Ltd.

Date: Preliminary site investigation1980; Main ground investigation 1982; Supplementary ground investigation 1983 and 1990

Memo: Site investigations were carried out at Plenmeller in order to asses the ground condition to develop the site for the purpose of opencast coal extraction.

Number of Boreholes: 116

Ground Conditions: A layer of peat or peaty topsoil covers a large proportion of the site with a thickness of approximately 0.5 meters. A mottled clay horizon rarely exceeding a depth of 3 meters below the surface was identified in boreholes throughout the site. The colours of the mottled clay varied from mottled grey and brown, grey brown streaked grey to light grey mottled orange and is mostly described as silty sandy gravely clay. It was suggested in the site investigation reports that the mottling effect is possibly associated with oxidation around fissures and roots, thus below a depth of 3 meters where the majority of the fissures are closed and there are virtually no roots the mottling disappears. In areas where the peat deposits were thicker the mottling of the underlying clay was not developed but the clay had a blue grey colour. The drift throughout the site was found to be relatively uniform with only subtle changes in colour but variable in thickness. The main two types of boulder clays that were distinguished throughout the site were the dark grey and the dark brown clay, which contained gravel and boulders. The dark grey coloured clay was the most common. The report mentions that no consistent depth correlation was found although the dark brown clay tended to occur at greater depth. Although laminated clays were not identified in the boreholes but bands of sands and gravels were found in some parts of the site.

Site name: Melkridge

Location: The disposal site lies to the south of the A69 trunk road to the north of the River South Tyne and approximately 800 metres to the south-west of the village Melkridge

Contractor: Norwest Holst Soil Engineering Ltd

Date: February 1983

Memo: Site investigation was carried out in order to obtain information on the ground condition. It was proposed to develop the site for the construction of a rail link disposal point including an overland conveyor route from Plenmeller opencast site.

Number of Boreholes: 13

Ground Conditions: A layer of topsoil covers most of the site with a thickness of approximately 0.5 meters. Below the topsoil a layer of orange / brown silty sandy clay exists. This layer often contains sandy laminations and bands of sand and gravel that vary in thickness. The colour of the clay below the sand and gravel lenses occasionally changes to reddish brown or at some places to grey. The bedrock consisted of yellow weathered sandstone, grey siltstone and silty mudstone.

Site name: Red Barns

Location: The site is located west of the village of Crook.

Contractor: Norwest and Holst Soil Engineering Ltd.

Date: May to June 1983

Memo: It was proposed to develop a site for the extraction of coal by opencast mining methods in Red Barns. Site investigation was carried out in order to obtain general information on the superficial material in the area.

Number of Boreholes: Details of 14 boreholes is stored in the database.

Ground Conditions: A layer of topsoil covers most of the site and in some places made ground with variable thickness was encountered. Below these layers a stiff orange grey-brown mottled silty sandy clay is found. The material below the mottled clay is mostly described as stiff to very stiff very silty sandy clay. The colour of the material varies from brown to grey. Bands of sand and gravel are occasionally encountered in some of the boreholes. The bedrock material in the area is mostly a grey, highly to completely weathered mudstone that is described as weak to very weak.

Site name: Hill Top

Location: The site is approximately 1.5 km south west of Shildon in County Durham

Contractor: Norwest Holst Soil Engineering Ltd

Date: May to June 1986

Memo: It was proposed to develop a site at Hill Top in Brusselton for the purpose of opencast coal mining. Site investigation was carried out in order to determine the ground condition and the extent of superficial material.

Number of Boreholes: 21

Ground Conditions: Opencast mining has been carried out at some parts prior to the site investigation and restored. Various fill material with variable thickness were found at this site. A layer of topsoil covers most of the site. The material below the topsoil is described as firm to stiff sandy silty clay with gravel and cobbles. The colour of the clay varies from brown to grey brown and grey but no correlation to depth was found. In some areas layers occur where gravel is absent and the clay is thinly laminated and mottled in colour. Sand and gravel pockets or layers of silt were occasionally identified in the site. Bedrock was encountered across the site and comprises typical Coal Measure strata of brown to light brown highly to moderately weathered sandstones, grey or brown highly weathered siltstones and grey weathered mudstones with occasional thin coal seams.

Site name: Whitwell

Location: The site is approximately 2.5 km south east of Durham and 1.5 km north east of Bowburn in County Durham

Contractor: James Associates, Allied Exploration and Geotechnics Ltd

Date: 16-24 January 1995

Memo: to determine the ground conditions to enable the design of stable excavation slopes through superficial deposits, and design of stable storage mounds.

Number of Boreholes: 3

Ground Conditions: The superficial cover comprises the Wear Valley glacial deposits which consists of glacial clay, sand, gravelly clay and gravel which varies between 6 and 24 metres in thickness across the site. The site report divides the sequence into four units namely the upper clay, middle sandy clay, lower clay and basal sandy clay. The upper clay described as reddish brown to brown sandy silty clay is reported to have a laminated nature and is stony. The underlying middle sandy clay comprises fine sand and sandy clay. The lower clay described as brown to dark brown sandy silty clay with some gravel is reported to be soft and plastic at the top and becoming stiffer with depth.

D.3 Description of sites in Cumbria

Site name: Oughterside

Location: Cumbria

Contractor: Norwest Holst Soil Engineering Ltd

Date: August to September 1980

Memo: Site investigation was carried out in Oughterside in order to obtain design parameters for the construction of an opencast coal mine.

Number of Boreholes: 8

Ground Conditions: The results of the site investigation show that a layer of silty often clayey sand with gravel, containing various clay bands was identified in most of the boreholes to approximately 6 meters below ground level. This layer overlies a very stiff glacial drift with variable thickness across the site. The drift consists mainly from stiff to very stiff dark brown silty sandy clay. Much gravel and larger boulders were identified in many boreholes. A layer of stiff dark brown laminated silty clay with silt partings was encountered in some of the boreholes.

Site name: Maryport

Location: Grassmere, Maryport in Cumbria

Contractor: Norwest Holst Soil Engineering Ltd

Date: September 1983

Memo: The investigation was carried out in order to obtain information of the ground condition of the site to extend and modify the existing coal disposal point

Number of Boreholes: 6

Ground Conditions: A layer of Made Ground covered the site with a variable thickness between 1.5 to 3.3 meters. Beneath the Made Ground a layer of loose medium sand with occasional gravel was observed which varied in thickness between 1 and 3 meters. Sand and gravel with occasional boulders was found beneath this layer. Below this layer a soft silty, occasionally laminated clay layer was observed that contained occasional bands of sand. Beneath the clay each borehole encountered a band of medium dense to dense gravel.

Site name: Linefoot

Location: This site lays also adjacent to Low Close / Foxhouse Opencast site between Maryport and Cockermouth in Cumbria.

Contractor: Norwest Holst Soil Engineering Ltd

Date: February to May 1986

Memo: Site investigation was carried out to investigate the ground condition in order to extend the working of coal in the area.

Number of Boreholes: 13

Ground Conditions: A layer of topsoil with a thickness of approximately 0.2 to 0.4 meters overlays most of the area. The drift below this layer consists of dark brown sandy silty clay with much gravel. Bands of brown and grey sand are often identified within the site.

Site name: Broughton Lodge

Location: Broughton Lodge and Foxhouse South opencast are both located at Broughton Moor in Cumbria.

Contractor: Norwest Holst Soil Engineering Ltd

Date: March to April 1990

Memo: Site investigations were carried out in order to obtain information on the ground condition of the site. It was proposed to develop the opencast coal reserves of the site.

Number of Boreholes: Details of 28 boreholes are stored in he database.

Ground Conditions: The investigation shows that a thin layer of topsoil or made ground up to 0.6 metres overlay the site. A layer of mottled silty CLAY was identified below the topsoil in some of the boreholes. The rest of the material in the site are variable in thickness and are described as silty sandy clay with fine to coarse gravel. The colour of the clay varies between brown, brownish grey and grey. The bedrock consisted of thinly laminated grey mudstone and siltsone. Medium to coarse grained brown sandstone was also encountered in some boreholes.

Site name: Foxhouse South

Location: between Maryport and Cockermouth in Cumbria

Contractor: Norwest Holst Soil Engineering Ltd

Date: November 1985 to March 1986

Memo: The site investigation was carried out in order to obtain ground information on the area adjacent to Low close / Foxhouse Opencast site, between Maryport and Cockermouth in Cumbria.

Number of Boreholes: 28

Ground Conditions: Low Close / Foxhouse are a group of opencast coal sites in Cumbria where the till is similar to lower till and is generally stiff or hard dark brownish grey, very gravelly or sandy silty clay. Occasionally lenses of sand or sandy gravel are identified, but upper till was not identified at any sites of the Low Close / Foxhouse group (Hughes et al, 1998). Approximately 0.2 to 0.4 meters of topsoil overlays a layer of firm brown grey and yellow brown mottled sandy silty clay. The thickness of the drift below this layer is very variable across the site and consists mainly of stiff dark brown and grey brown silty sandy clay with much gravel and numerous cobbles. Sandy laminations and bands of sand and gravel were occasionally identified. Narrow bands or lenses of stiff grey to brown poorly laminated and fissured silty clays and silts occur sometimes within the site. The bedrock was identified as weathered grey siltstone or mudstone.

Site name: Potatopot

Location: This site is located 6 km south east of Workington in Cumbria.

Contractor: Norwest Holst Soil Engineering Ltd

Date: January to February 1985

Memo: Site investigation was carried out in order to provide information on the engineering parameters and stability aspects relevant to the site.

Number of Boreholes: 35

Ground Conditions: Made ground was encountered in site investigation boreholes across the site. The remainder of the superficial deposits encountered consist mainly of various types of clay with occasional bands of sand and gravel. Three main types of clay found in the site. A soft to firm grey brown orange mottled silty occasionally very sandy clay with some occasional gravel, which was normally encountered immediately below the topsoil and was maximum 2 meters in thickness. A firm grey very silty occasionally sandy laminated clay with some gravel which occurs below the soft to firm clay and varies in thickness. The laminae are horizontal and very closely spaced and often very silty. A stiff to very stiff grey with occasional brown mottle silty sandy clay with numerous gravels and sand pockets. Larger cobbles and boulders were found in this layer which lies directly above the rockhead. The rockhead comprised of either mudstone or sandstone.

Site name: Workington

Location: an area to the north of Workington in Cumbria

Contractor: Norwest Holst Soil Engineering Ltd

Date: May and June 1990

Memo: Boreholes were drilled in order to obtain preliminary information on the ground condition in potential areas for the possible construction of a coal fired power station.

Number of Boreholes: 7

Ground Conditions: The site investigation results showed that the area was covered by topsoil and made ground with variable thickness across the site. Underlying the made ground a sequence of deposits comprising sands and gravels with numerous cobbles and boulders were found. Layers of stiff to very stiff sandy occasionally gravelly brown to grey clay with occasional cobbles were found beneath the sand and gravel deposits. The bedrock comprised of Coal measure strata consisting generally of interbedded siltstones and mudstones, with sandstones being encountered in some boreholes.

Site name: Lostrigg

Location: This site is situated between Windscales, Branthwaite and Bridge Foot near Workington in west Cumbria.

Contractor: Norwest Holst Soil Engineering Ltd

Date: October and November 1986

Memo: It is proposed to develop the site for the extraction of coal using opencast methods. Site investigation was carried out in order to obtain information on the ground conditions.

Number of Boreholes: 51

Ground Conditions: The investigation shows that a layer of made ground covers most of the site. A soft to firm grey brown mottled silty clay with occasional gravel was normally encountered immediately below the topsoil. The material that lies below the mottled clay is mostly described as soft to firm grey silty sandy clay with some gravel. A layer of firm grey very silty occasionally sandy laminated clay with some gravel occurs below the soft to firm clay and varies in thickness. Sand and gavel pockets were also encountered in a few boreholes.

Site name: Keekle extension and River Keekle Diversion, Moresby and Keekle

Location: Keekle and Moresby near the town of Whitehaven in Cumbria

Contractor: Norwest Holst Soil Engineering Ltd; Soil Mechanics Limited

Date: June and August 1985; February to March 1980

Memo: To extend the working of coal, several site investigations were carried out.

Number of Boreholes: 17; 27; 21 (Total of 65 boreholes)

Ground Conditions: The drift, which varies in thickness across the site, consists primarily of stiff brown silty sandy clay with much gravel. This layer often contains sandy laminations and bands of sand and gravel. A soft grey brown laminated clay occasionally occurs which is often associated with bands of sand and gravel. A layer of firm brown and yellow brown mottled silty clay was found below the topsoil in some places, which in turn covers the drift.

Further investigation was carried out in this area after it was proposed to temporarily divert the course of the River Keekle across the site of the proposed Keekle opencast extension near Whitehaven in Cumbria. Details of samples taken from 27 boreholes have been put into the database. The site investigation was carried out to obtain information on the ground conditions along the route of the channel. The drift in the area is very variable in thickness along the route of the investigation. It mainly consists of stiff to very stiff brown silty sandy CLAY and much gravel and large boulders were encountered in this material. Bands of sand and gravel are encountered at different places. Above the drift a layer of soft to firm yellow brown or grey brown silty clay exists which is in turn overlain by a thin layer of topsoil. A soft layer of brown and grey laminated clay was identified in some of the boreholes.

Appendix E

Summary tables of the properties of individual sites

Site	Unit		TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
		Count	49	46	28	45	47	47	45	45	47	37						
		min	0.50	1.66	1.29	13.0	13.0	22.0	7.0	-0.571	66.0	37.0						
	Unit1	max	5.50	2.13	1.84	30.0	24.0	76.0	52.0	0.357	100.0	347.0						
		avarage	1.69	1.99	1.67	20.3	19.4	41.7	22.6	0.030	96.1	137.8						
		S.D.	1.32	0.10	0.10	3.5	2.4	9.1	7.4	0.177	5.9	66.9						
		Count	35	34	23	34	34	34	34	34	34	35						
		min	1.50	1.44	1.02	16.0	13.0	25.0	6.0	-0.500	75.0	24.0						
	Unit2	max	10.50	2.21	1.94	26.0	25.0	49.0	28.0	0.333	100.0	258.0						
		avarage	4.94	2.04	1.71	20.3	18.5	37.7	19.2	0.082	95.9	125.4						
		S.D.	2.33	0.12	0.17	2.5	2.7	5.6	5.5	0.165	5.5	57.7						
		Count	12	11	9	12	11	11	11	11	11	7						
Chester House		min	2.00	1.86	1.63	8.7	12.0	27.0	10.0	-0.800	63.0	112.0						
(Northumberland)	Unit3	max	12.50	2.22	2.01	15.0	22.0	41.0	24.0	0.063	100.0	334.0						
		avarage	7.23	2.11	1.89	12.1	15.1	31.4	16.3	-0.210	86.5	183.4						
		S.D.	3.22	0.10	0.11	2.0	2.6	3.7	3.4	0.231	8.7	75.6						
		Count	14	2	2	2	1	1	1	1	1	1						
		min	1.50	1.73	1.50	7.4	13.0	22.0	9.0	0.222	86.0	45.0						
	Unit4	max	8.40	2.23	1.92	15.0	13.0	22.0	9.0	0.222	86.0	45.0						
		avarage	4.97	1.98	1.71	11.2	13.0	22.0	9.0	0.222	86.0	45.0						
		S.D.	1.91	0.25	0.21	3.8	0.0	0.0	0.0	0.000	0.0	0.0						
		Count	19	17	8	17	19	19	18	18	19	12						
		min	1.50	1.81	1.50	17.0	13.0	29.0	12.0	-0.714	85.0	29.0						
	Unit5	max	12.00	2.16	1.85	33.0	24.0	50.0	28.0	0.682	100.0	103.0						
		avarage	4.57	2.01	1.63	22.5	18.4	39.5	21.4	0.129	97.0	69.3						
		S.D.	2.63	0.08	0.10	4.1	2.8	6.0	4.3	0.284	4.1	23.8						

Site	Unit		TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
		Count	59	50	50	59	57	57	57	57	58	52	5	5			1	1
		min	0.30	1.70	1.27	7.2	18.0	33.0	15.0	-0.627	62.0	8.0	1.0	15.0			20.0	13.0
	Unit1	max	3.30	2.06	1.74	36.4	30.0	62.0	37.0	0.693	100.0	192.0	11.0	34.0			20.0	13.0
		avarage	1.22	1.95	1.57	23.1	23.3	46.6	23.3	0.017	91.2	91.9	6.2	27.8			20.0	13.0
		S.D.	0.77	0.08	0.11	4.8	2.5	6.6	5.1	0.254	10.7	45.3	4.3	6.9			0.0	0.0
		Count	123	94	94	123	120	120	120	120	119	104	1	1	4	4	9	9
		min	0.40	1.79	1.49	13.4	15.0	29.0	7.0	-0.725	41.0	19.0	10.0	29.0	0.0	20.0	0.0	11.0
	Unit2	max	35.50	2.23	1.87	25.9	27.0	57.0	30.0	0.569	100.0	476.0	10.0	29.0	64.0	34.0	15.0	28.0
		avarage	9.75	2.07	1.73	19.8	19.9	38.9	19.0	-0.004	90.5	113.5	10.0	29.0	25.0	24.8	4.8	17.4
		S.D.	7.09	0.07	0.08	2.9	2.5	5.3	4.3	0.177	12.0	57.9	0.0	0.0	24.4	5.5	4.8	5.8
		Count	56	38	38	56	55	55	55	55	54	39	1	1				
Acklington		min	3.30	1.66	1.48	7.0	13.0	25.0	8.0	-1.183	50.0	91.0	8.0	28.0				
(Northumberland)	Unit3	max	31.50	2.27	2.05	23.2	22.0	38.0	19.0	0.631	100.0	444.0	8.0	28.0				
		avarage	17.27	2.17	1.92	13.3	16.0	30.4	14.4	-0.207	79.4	212.8	8.0	28.0				
		S.D.	6.66	0.10	0.10	2.8	1.8	2.5	2.2	0.268	12.9	89.3	0.0	0.0				
		Count	34	25	25	34	27	27	27	27	27	25	1	1	4	4	7	7
		min	1.00	1.55	1.30	8.2	15.0	25.0	7.0	-1.100	51.0	21.0	4.0	30.0	1.0	25.0	0.0	13.0
	Unit4	max	36.50	2.17	1.82	36.6	30.0	53.0	25.0	2.160	100.0	237.0	4.0	30.0	40.0	30.0	27.0	48.0
		avarage	11.51	1.96	1.58	23.5	22.8	35.8	13.0	0.098	96.4	87.5	4.0	30.0	26.3	27.3	13.1	26.9
		S.D.	8.88	0.13	0.12	5.1	3.1	6.8	4.8	0.515	10.0	51.9	0.0	0.0	16.0	1.9	9.6	10.2
		Count	228	180	180	228	220	220	220	220	223	173	23	23	26	26	61	61
		min	0.77	1.57	1.37	11.8	13.0	24.0	6.0	-0.685	17.0	9.0	4.0	19.0	0.0	6.0	0.0	7.0
	Unit5	max	33.45	2.24	1.97	33.8	29.0	69.0	42.0	0.985	100.0	193.0	25.0	32.0	60.0	35.0	50.0	34.0
		avarage	10.16	1.98	1.60	24.4	22.3	43.7	21.5	0.120	94.3	70.1	11.4	26.1	18.7	24.1	8.9	17.2
		S.D.	6.07	0.08	0.11	3.9	2.9	8.5	7.0	0.212	12.4	31.3	7.0	3.4	11.7	5.7	8.6	7.4

Site	Unit		TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
Acklington Spoil Heap (Northumberland)	Unit2	Count	24	22		22	22	22	22	22	22	22						
		min	0.50	1.89		12.0	14.0	32.0	15.0	-0.133	72.0	45.0						
		max	20.15	2.17		25.0	22.0	47.0	25.0	0.381	100.0	255.0						
		avarage	7.62	2.04		19.4	17.5	39.2	21.7	0.088	89.5	106.5						
		S.D.	6.11	0.07		2.7	1.7	3.5	2.7	0.117	7.2	61.1						
	Unit3	Count	17	15		15	15	15	15	15	15	16						
		min	8.00	2.03		10.0	12.0	25.0	12.0	-0.286	77.0	114.0						
		max	27.55	2.33		18.0	17.0	38.0	21.0	0.200	89.0	540.0						
		avarage	16.68	2.20		13.2	13.8	29.7	15.9	-0.044	83.5	222.4						
		S.D.	6.30	0.07		2.3	1.2	3.2	2.4	0.114	3.4	108.7						
	Unit5	Count	11	7		7	7	7	7	7	7	9			1	1	1	1
		min	1.20	1.78		18.0	18.0	43.0	22.0	-0.375	93.0	29.0			13.0	20.0	0.0	13.0
		max	15.30	2.04		31.0	27.0	56.0	31.0	0.318	100.0	170.0			13.0	20.0	0.0	13.0
		avarage	7.05	1.94		24.7	22.0	47.6	25.6	0.105	96.9	76.8			13.0	20.0	0.0	13.0
		S.D.	4.00	0.08		4.2	3.1	4.2	2.6	0.205	2.8	39.0			0.0	0.0	0.0	0.0

Site	Unit		TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
Chevington Burn (Northumberland)	Unit1	Count	12	12		12						3						
		min	1.00	1.86		19.8						45.0						
		max	3.00	2.11		28.5						110.0						
		avarage	1.27	2.02		23.3						88.3						
		S.D.	0.59	0.06		2.3						30.6						
	Unit2	Count	143	143		143	38	38	38	38	36	90						
		min	1.00	1.81		11.5	15.0	29.0	11.0	-0.365	86.0	25.0						
		max	15.50	2.06		30.4	27.0	71.0	44.0	0.964	100.0	477.0						
		avarage	6.60	2.08		20.8	19.9	46.5	26.6	0.049	92.3	133.1						
		S.D.	3.39	0.07		3.1	3.1	7.5	5.6	0.208	3.5	54.4						
	Unit3	Count	48	43		48	16	16	16	16	16	33						
		min	2.00	1.95		9.0	14.0	26.0	10.0	-0.560	75.0	75.0						
		max	17.50	2.32		19.5	18.0	37.0	20.0	-0.020	88.0	394.0						
		avarage	9.12	2.20		13.0	15.3	30.9	15.6	-0.172	82.4	208.3						
		S.D.	4.07	0.06		1.7	1.2	2.8	2.1	0.120	3.3	90.3						
	Unit5	Count	26	26		26	15	15	15	15	14	29						
		min	2.00	1.86		13.5	18.0	38.0	20.0	-0.327	88.0	35.0						
		max	14.00	2.14		33.1	26.0	66.0	41.0	0.264	100.0	234.0						
		avarage	8.43	1.97		26.6	23.1	55.3	32.3	0.078	96.3	96.9						
		S.D.	4.42	0.07		5.0	2.4	8.6	6.4	0.153	3.2	51.7						

Site	Unit		TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
East Chevington (Northumberland)	Unit1	Count	12	9		11	4	4	4	3	4	4						
		min	1.00	1.81		20.7	18.0	29.0	11.0	0.004	95.0	25.0						
		max	3.00	2.08		28.6	23.0	51.0	29.0	0.964	97.0	115.0						
		avarage	1.63	2.00		23.5	21.3	44.8	23.5	0.346	95.8	73.8						
		S.D.	0.74	0.07		2.3	1.9	9.2	7.3	0.437	0.8	39.4						
	Unit2	Count	88	81		87	42	42	42	41	42	69						
		min	1.00	1.92		12.7	15.0	33.0	17.0	-0.196	88.0	64.0						
		max	13.50	2.22		27.4	27.0	71.0	44.0	0.411	100.0	234.0						
		avarage	6.39	2.08		20.2	19.7	45.8	26.1	0.032	92.5	125.4						
		S.D.	3.05	0.06		3.1	2.3	7.2	5.0	0.130	3.3	36.6						
	Unit3	Count	33	20		27	24	24	24	18	23	25						
		min	2.55	1.95		10.3	14.0	26.0	10.0	-0.560	70.0	45.0						
		max	26.55	2.30		27.6	20.0	37.0	20.0	0.060	90.0	423.0						
		avarage	11.62	2.19		13.2	15.4	30.9	15.5	-0.181	82.8	216.9						
		S.D.	4.70	0.07		3.2	1.5	3.1	2.2	0.137	4.7	105.8						
	Unit5	Count	21	17		21	14	14	14	14	13	14						
		min	1.00	1.88		13.5	18.0	38.0	20.0	-0.327	88.0	35.0						
		max	10.00	2.08		31.0	25.0	66.0	41.0	0.264	100.0	132.0						
		avarage	4.71	2.00		24.1	22.5	53.6	31.1	0.083	96.0	70.1						
		S.D.	2.45	0.06		4.5	2.4	9.0	6.7	0.150	3.4	28.9						

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
Colliersdean (Northumberland)	Unit1	Count	56	56	56	56	55	55	55	55	55	56						
		min	0.40	1.72	1.37	11.0	12.0	28.0	15.0	-0.280	73.0	12.0						
		max	6.50	2.08	1.79	30.0	26.0	60.0	38.0	0.579	100.0	210.0						
		avarage	1.71	1.91	1.60	19.7	19.6	46.2	26.6	0.005	91.3	108.2						
		S.D.	1.35	0.07	0.09	4.0	2.5	5.7	4.5	0.134	6.9	57.4						
	Unit2	Count	282	278	275	278	268	268	268	264	268	273			1	1	1	1
		min	0.50	1.61	1.29	9.2	12.0	25.0	10.0	-0.467	46.0	14.0			40.0	25.0	49.0	15.0
		max	33.50	2.15	1.92	32.0	30.0	62.0	43.0	0.480	100.0	600.0			40.0	25.0	49.0	15.0
		avarage	7.47	1.98	1.68	18.3	17.9	41.3	23.4	0.014	87.4	101.8			40.0	25.0	49.0	15.0
		S.D.	6.78	0.07	0.10	3.8	2.6	6.9	5.4	0.125	9.0	59.6						
	Unit3	Count	62	61	60	61	57	57	57	55	57	59						
		min	3.70	2.00	1.77	8.0	10.0	25.0	6.0	-0.333	56.0	25.0						
		max	29.00	2.20	1.98	17.0	18.0	37.0	22.0	0.500	96.0	317.0						
		avarage	11.72	2.11	1.87	12.6	14.1	31.4	17.1	-0.067	79.1	159.1						
		S.D.	6.97	0.04	0.05	1.8	1.5	2.4	2.5	0.111	6.1	58.9						
	Unit4	Count	5	1	1	1	2	2	2	1	2	1						
		min	0.50	2.09	1.80	16.0	15.0	30.0	15.0	0.067	83.0	123.0						
		max	29.60	2.09	1.80	16.0	15.0	30.0	15.0	0.067	86.0	123.0						
		avarage	10.70	2.09	1.80	16.0	15.0	30.0	15.0	0.067	84.5	123.0						
		S.D.	11.36	0.00	0.00	0.0	0.0	0.0	0.0	0.000	1.5	0.0						
	Unit5	Count	70	67	60	66	70	70	70	66	70	60			1	1	1	1
		min	0.55	1.75	1.37	14.0	15.0	30.0	15.0	-0.250	67.0	17.0			15.0	22.0	20.0	12.0
		max	33.00	2.14	1.84	31.0	26.0	61.0	40.0	0.444	100.0	132.0			15.0	22.0	20.0	12.0
		avarage	8.35	1.93	1.57	23.3	20.0	47.1	27.1	0.117	93.9	62.7			15.0	22.0	20.0	12.0
		S.D.	5.69	0.07	0.10	3.9	2.5	6.4	5.3	0.118	7.2	28.9			0.0	0.0	0.0	0.0

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
Maidens Hall (Northumberland)	Unit1	Count	127	115	104	125	124	124	124	124	123	101	3	3				
		min	0.10	1.47	1.30	14.0	12.0	33.0	10.0	-1.000	59.0	19.0	0.0	24.0				
		max	4.55	2.50	1.96	50.0	36.0	75.0	45.0	0.929	100.0	246.0	11.0	33.0				
		avarage	1.53	2.01	1.63	23.3	22.0	50.3	28.3	0.031	95.3	96.9	3.7	29.0				
		S.D.	1.07	0.12	0.10	5.0	4.3	6.4	5.8	0.209	8.0	42.8	5.2	3.7				
	Unit2	Count	533	498	428	530	525	525	526	525	522	463	23	23	4	4	5	5
		min	0.50	1.49	1.32	7.7	12.0	22.0	4.0	-4.750	55.0	16.0	0.0	21.0	15.0	14.0	0.0	8.0
		max	34.85	2.56	2.07	42.0	49.0	68.0	47.0	1.045	100.0	502.0	10.0	41.0	50.0	27.0	37.0	25.0
		avarage	12.88	2.11	1.77	18.7	18.1	40.3	22.4	0.008	91.9	105.1	1.1	27.7	31.8	21.3	15.6	14.8
		S.D.	7.76	0.10	0.13	4.5	3.5	6.2	6.5	0.303	9.5	58.8	2.8	3.8	15.9	5.8	14.4	6.9
	Unit3	Count	351	327	285	347	343	343	342	342	342	302	7	7	1	1	1	1
		min	2.80	1.64	1.40	4.5	3.0	18.0	2.0	-5.500	43.0	14.0	0.0	25.0	140.0	6.0	140.0	4.0
		max	41.85	2.76	2.40	19.0	27.0	41.0	25.0	0.600	100.0	588.0	0.0	39.0	140.0	6.0	140.0	4.0
		avarage	23.38	2.22	1.97	12.4	14.7	31.7	17.0	-0.182	87.8	164.0	0.0	29.1	140.0	6.0	140.0	4.0
		S.D.	7.57	0.09	0.09	1.8	2.4	3.1	3.4	0.472	10.7	95.8	0.0	4.4	0.0	0.0	0.0	0.0
	Unit4	Count	101	26	23	29	26	26	26	26	26	20	2	2				
		min	0.50	1.50	1.40	8.8	8.0	19.0	4.0	-0.500	79.0	11.0	0.0	21.0				
		max	40.75	2.43	2.09	39.0	25.0	64.0	42.0	2.111	100.0	173.0	0.0	31.0				
		avarage	16.91	2.02	1.68	21.7	17.7	36.3	19.7	0.240	97.8	69.9	0.0	26.0				
		S.D.	11.89	0.18	0.19	7.5	4.0	10.3	8.5	0.474	5.3	45.9	0.0	5.0				
	Unit5	Count	352	333	274	347	347	347	347	343	345	313	12	12	13	13	13	13
		min	1.10	1.45	1.19	7.2	13.0	24.0	10.0	-1.083	41.0	4.0	0.0	12.0	0.0	12.0	0.0	7.0
		max	36.55	2.30	2.05	38.0	35.0	71.0	47.0	0.900	100.0	194.0	0.0	31.0	75.0	27.0	37.0	19.0
		avarage	9.76	2.01	1.62	24.4	21.2	49.1	27.8	0.111	96.7	69.2	0.0	25.0	31.1	19.4	10.8	12.8
		S.D.	6.64	0.10	0.11	4.5	3.2	7.7	6.8	0.182	6.5	28.7	0.0	5.1	22.7	4.8	11.8	3.6

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
		Count	49	31	31	49	42	42	42	42	9	31	3	3				
		min	0.40	1.80	1.41	14.9	15.0	38.0	20.0	-0.366	76.0	48.0	6.0	23.0				
	Unit1	max	9.50	2.34	1.92	32.2	30.0	67.0	41.0	0.300	98.0	168.0	15.0	31.0				
		avarage	1.69	2.01	1.64	22.2	21.9	51.2	29.3	0.019	90.3	94.4	10.0	28.2				
		S.D.	1.62	0.12	0.12	3.5	2.9	6.3	4.9	0.127	7.0	33.4	3.7	3.7				
		Count	219	184	184	219	205	205	204	204	93	184	3	3				
		min	0.50	1.92	1.54	10.3	14.0	30.0	8.0	-0.412	58.0	30.0	8.0	26.0				
	Unit2	max	20.10	2.30	1.97	30.9	30.0	71.0	41.0	0.828	100.0	299.0	12.0	29.5				
		avarage	7.05	2.09	1.78	17.6	17.8	39.8	21.7	-0.030	81.1	115.0	9.7	28.2				
		S.D.	3.73	0.06	0.08	3.0	2.1	5.4	4.1	0.138	7.6	45.2	1.7	1.5				
		Count	176	121	121	174	153	153	153	153	109	123	4	4				
Widdrington		min	1.50	1.96	1.67	7.4	13.0	21.0	4.0	-0.950	52.0	29.0	12.0	26.0				
(Northumberland)	Unit3	max	21.15	2.30	2.11	17.0	20.0	37.0	31.0	0.463	96.0	510.0	30.0	28.5				
		avarage	10.32	2.16	1.90	12.8	15.8	32.2	16.8	-0.172	77.6	173.5	18.0	27.4				
		S.D.	4.10	0.05	0.06	1.4	1.4	2.6	2.9	0.175	6.9	79.4	7.0	1.0				
		Count	21	20	20	21	21	21	21	21	3	17	1	1				
		min	0.55	1.90	1.45	16.5	17.0	25.0	18.0	-0.172	92.0	37.0	10.0	33.0				
	Unit5	max	20.20	1.99	1.62	32.0	26.0	63.0	37.0	0.216	98.0	141.0	10.0	33.0				
		avarage	10.48	1.97	1.63	23.0	20.0	49.0	27.3	0.057	94.0	71.2	10.0	33.0				
		S.D.	5.94	0.08	0.11	4.3	2.2	8.9	5.1	0.104	2.8	27.1	0.0	0.0				

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
		Count	21	13	13	20	21	21	21	20	19	13						
		min	0.50	1.90	1.48	16.1	17.0	32.0	12.0	-0.226	80.0	25.0						
	Unit1	max	7.00	2.06	1.75	28.8	27.0	63.0	38.0	0.649	99.0	249.0						
		avarage	1.21	2.00	1.66	21.3	21.7	45.8	24.5	0.009	91.1	92.9						
		S.D.	1.36	0.04	0.06	2.6	2.6	8.3	5.9	0.168	5.9	51.5						
		Count	58	48	48	58	58	58	58	58	58	48						
		min	1.00	1.90	1.52	13.4	17.0	33.0	15.0	-0.280	67.0	34.0						
	Unit2	max	17.50	2.17	1.91	25.6	29.0	52.0	30.0	0.237	100.0	218.0						
		avarage	6.67	2.05	1.72	19.8	20.3	43.7	23.0	-0.027	91.0	107.9						
Steadsburn		S.D.	4.09	0.06	0.10	3.3	2.3	5.3	3.9	0.105	7.0	39.6						
(Northumberland)		Count	28	21	21	28	27	28	27	27	28	21						
		min	1.00	2.11	1.83	10.8	15.0	22.0	6.0	-0.358	72.0	35.0						
	Unit3	max	14.50	2.23	1.98	15.2	18.0	35.0	23.0	-0.061	91.0	298.0						
		avarage	8.92	2.17	1.93	12.6	15.9	31.5	15.8	-0.219	80.8	163.0						
		S.D.	3.30	0.03	0.04	1.2	0.7	2.8	2.9	0.079	5.3	80.2						
		Count	24	12	12	22	24	24	23	21	23	12						
		min	1.85	1.84	1.48	14.8	16.0	26.0	10.0	-0.120	60.0	43.0						
	Unit5	max	8.50	2.17	1.88	25.8	25.0	62.0	44.0	0.156	100.0	155.0						
		avarage	4.56	1.98	1.62	22.0	21.1	47.3	26.6	0.026	92.3	79.0						
		S.D.	1.94	0.08	0.11	2.5	2.2	6.9	5.6	0.073	8.5	33.5						

Site	Unit		TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
Stobswood (Northumberland)	Unit1	Count	114	108	62	100	111	111	111	97	111	89	1	1	2	2		
		min	0.50	1.65	1.09	12.0	13.0	25.0	11.0	-0.158	72.0	11.0	11.0	24.0	21.0	20.0		
		max	3.25	2.12	1.88	54.0	25.0	70.0	47.0	0.853	100.0	368.0	11.0	24.0	59.0	26.0		
		avarage	1.10	1.97	1.60	21.8	18.1	41.7	23.6	0.134	92.2	99.7	11.0	24.0	40.0	23.0		
		S.D.	0.64	0.09	0.15	6.8	2.4	7.1	5.7	0.188	5.8	64.0	0.0	0.0	19.0	3.0		
	Unit2	Count	552	536	215	538	547	547	547	534	547	521	3	3	4	4		
		min	0.50	1.73	1.36	11.0	12.0	21.0	6.0	-0.500	68.0	11.0	1.0	22.0	0.0	13.0		
		max	26.10	2.31	1.97	29.0	25.0	65.0	42.0	1.083	100.0	537.0	43.0	28.0	88.0	28.0		
		avarage	6.26	2.03	1.69	17.5	16.4	36.0	19.6	0.054	88.9	105.7	17.0	25.3	46.5	19.8		
		S.D.	4.81	0.07	0.09	3.0	2.2	5.0	3.8	0.143	5.8	73.5	18.5	2.5	33.2	6.1		
	Unit3	Count	312	290	95	291	309	309	309	309	309	292	2	2				
		min	1.00	1.75	1.60	7.0	11.0	20.0	6.0	-0.600	63.0	14.0	9.0	25.0				
		max	31.55	2.29	2.06	21.0	20.0	43.0	25.0	0.667	100.0	818.0	15.0	27.0				
		avarage	11.52	2.13	1.89	12.7	14.1	28.9	14.7	-0.103	81.7	180.9	12.0	26.0				
		S.D.	6.68	0.07	0.07	1.9	1.3	3.1	2.7	0.149	6.0	121.2	3.0	1.0				
	Unit4	Count	83	19	13	23	17	17	17	16	17	16	1	1				
		min	0.50	1.83	1.46	12.0	10.0	21.0	6.0	-0.333	73.0	4.0	2.0	36.0				
		max	21.50	2.25	2.01	36.0	25.0	59.0	34.0	0.909	100.0	346.0	2.0	36.0				
		avarage	6.04	2.01	1.71	19.2	16.2	33.5	17.3	0.257	90.3	105.3	2.0	36.0				
		S.D.	4.48	0.10	0.15	6.3	3.6	9.9	6.8	0.368	9.2	99.9	0.0	0.0				
	Unit5	Count	53	51	31	51	53	53	53	51	53	51						
		min	0.50	1.70	1.34	14.0	14.0	25.0	10.0	-0.211	81.0	4.0						
		max	21.00	2.18	1.79	32.0	25.0	54.0	35.0	0.455	100.0	164.0						
		avarage	7.02	1.96	1.57	22.3	19.6	42.1	22.5	0.114	97.3	76.6						
		S.D.	4.20	0.08	0.08	3.7	2.6	7.1	6.0	0.140	4.1	39.6						

Site	Unit		TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
West Linton (Northumberland)	Unit1	Count	14	12		13	12	12	12	11	6	8	2	2				
		min	0.50	1.90		12.0	16.0	32.0	16.0	-0.333	81.0	40.0	0.0	24.0				
		max	2.60	2.20		26.0	24.0	57.0	33.0	0.500	100.0	290.0	0.0	28.0				
		avarage	1.23	2.02		19.8	20.2	45.3	25.2	0.001	91.0	163.4	0.0	26.0				
		S.D.	0.71	0.07		3.8	2.1	6.6	5.1	0.204	5.6	80.7	0.0	2.0				
	Unit2	Count	18	14		17	17	17	17	16	4	13	1	1				
		min	0.70	2.08		11.0	14.0	30.0	11.0	-0.645	78.0	75.0	0.0	28.0				
		max	15.50	2.30		19.6	23.0	49.0	29.0	0.163	85.0	237.0	0.0	28.0				
		avarage	5.46	2.14		15.5	17.7	36.2	18.5	-0.136	82.3	134.0	0.0	28.0				
		S.D.	3.93	0.05		2.1	2.5	3.9	4.0	0.195	2.7	45.8	0.0	0.0				
	Unit3	Count	34	23		25	34	34	34	25	2	29	2	2				
		min	0.80	2.12		9.6	15.0	30.0	13.0	-0.333	82.0	65.0	0.0	28.0				
		max	13.00	2.29		19.9	22.0	44.0	24.0	0.053	83.0	549.0	0.0	28.0				
		avarage	4.42	2.20		13.8	16.7	35.8	19.1	-0.168	82.5	247.1	0.0	28.0				
		S.D.	2.27	0.05		2.1	1.6	2.9	2.2	0.086	0.5	90.5	0.0	0.0				

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
Linton Lane (Northumberland)	Unit1	Count	16	16		16	15	15	15	15	15	16						
		min	0.50	1.91		15.2	19.0	40.0	20.0	-0.240	93.0	45.0						
		max	1.50	2.14		30.3	26.0	61.0	35.0	0.145	100.0	185.0						
		avarage	0.69	2.02		22.4	21.9	49.2	27.3	0.012	96.3	93.8						
		S.D.	0.31	0.06		3.4	1.7	6.4	4.9	0.109	2.2	34.9						
	Unit2	Count	45	45		45	37	37	33	33	33	41	4	4				
		min	1.00	1.78		14.0	14.0	28.0	11.0	-0.182	81.0	20.0	6.0	16.0				
		max	8.00	2.22		24.7	23.0	56.0	33.0	0.215	97.0	185.0	10.0	27.5				
		avarage	3.60	2.08		18.1	17.7	37.8	19.6	0.021	89.7	93.7	8.3	23.6				
		S.D.	2.01	0.09		3.1	2.7	6.5	4.4	0.090	3.8	41.3	1.8	4.6				
	Unit3	Count	51	50		50	41	41	41	41	41	47	3	3				
		min	2.20	2.04		11.0	14.0	26.0	11.0	-0.375	84.0	97.0	10.0	27.0				
		max	12.60	2.27		16.0	17.0	35.0	19.0	0.107	98.0	384.0	18.0	29.3				
		avarage	7.13	2.20		12.4	15.0	31.1	16.2	-0.156	87.4	235.9	14.3	27.0				
		S.D.	2.25	0.04		1.3	0.8	2.1	1.8	0.105	2.3	71.6	3.3	3.3				
	Unit4	Count	3	2		2	1	1	1	1	1	2						
		min	1.00	1.87		15.0	16.0	22.0	6.0	-0.167	88.0	37.0						
		max	5.00	2.07		31.9	16.0	22.0	6.0	-0.167	88.0	45.0						
		avarage	2.40	1.97		23.5	16.0	22.0	6.0	-0.167	88.0	41.0						
		S.D.	1.84	0.10		8.5	0.0	0.0	0.0	0.000	0.0	4.0						
	Unit5	Count	24	24		24	21	21	21	21	21	20						
		min	1.50	1.90		15.8	19.0	43.0	22.0	-0.153	93.0	30.0						
		max	9.00	2.14		30.1	28.0	69.0	41.0	0.170	100.0	146.0						
		avarage	3.47	2.01		23.6	22.7	51.3	28.7	0.023	97.3	67.8						
		S.D.	2.09	0.06		3.6	2.3	7.5	5.4	0.090	2.5	29.4						

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
Butterwell Disposal Point (Northumberland)	Unit1	Count	2	2		2	1	1			1	1						
		min	0.50	1.70		30.0	25.0	49.0			100.0	35.0						
		max	0.50	1.81		35.4	25.0	49.0			100.0	35.0						
		avarage	0.50	1.76		32.7	25.0	49.0			100.0	35.0						
		S.D.	0.00	0.06		2.7	0.0	0.0			0.0	0.0						
	Unit2	Count	10	10		10	6	6	5	5	2	8						
		min	0.50	1.76		15.4	16.0	26.0	11.0	-0.075	87.0	10.0						
		max	3.50	2.16		27.0	23.0	40.0	20.0	0.750	97.0	361.0						
		avarage	1.82	1.97		21.3	18.8	33.5	15.6	0.167	92.0	117.1						
		S.D.	1.01	0.11		3.8	2.5	5.2	3.8	0.314	5.0	100.4						
	Unit3	Count	34	29		34	22	22	22	22	2	28						
		min	2.00	1.81		8.9	14.0	26.0	8.0	-1.438	87.0	25.0						
		max	15.00	2.27		17.0	24.0	36.0	20.0	0.118	91.0	575.0						
		avarage	6.79	2.17		12.7	16.8	32.6	15.9	-0.306	89.0	257.5						
		S.D.	3.61	0.08		1.9	2.4	2.1	3.3	0.360	2.0	137.0						

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
		Count	72	52	52	69	56	56	56	56	20	49	7	7				
		min	0.50	1.84	1.33	10.8	16.0	32.0	13.0	-0.327	44.0	18.0	6.0	22.5				
	Unit1	max	8.05	2.16	1.88	37.5	28.0	63.0	37.0	0.289	96.0	204.0	9.0	30.0				
		avarage	2.28	2.00	1.64	21.7	21.2	47.2	26.1	-0.008	78.7	98.1	8.0	26.9				
		S.D.	1.74	0.06	0.09	4.4	2.8	6.9	5.0	0.141	14.1	34.3	1.1	2.8				
		Count	93	70	70	88	84	83	83	81	53	67	11	11				
		min	0.55	1.77	1.38	11.9	14.0	27.0	8.0	-0.525	49.0	15.0	5.0	23.0				
	Unit2	max	19.00	2.19	1.97	29.7	26.0	59.0	35.0	0.856	92.0	325.0	17.0	36.0				
		avarage	8.59	2.08	1.78	17.3	18.2	38.7	20.5	-0.065	73.1	126.2	11.3	27.6				
		S.D.	4.79	0.09	0.12	4.0	2.8	6.3	4.2	0.174	10.5	54.9	3.0	3.7				
		Count	101	83	83	99	94	94	94	94	83	72	14	14	2	2	2	2
Bebside		min	2.30	1.87	1.65	9.0	13.0	25.0	10.0	-0.550	48.0	16.0	4.0	25.0	15.0	28.0	0.0	27.0
(Northumberland)	Unit3	max	24.30	2.24	2.01	17.9	21.0	40.0	22.0	0.160	90.0	479.0	15.0	31.5	15.0	33.0	0.0	32.0
		avarage	12.70	2.15	1.90	12.6	16.2	33.5	17.3	-0.221	74.4	219.1	10.4	27.5	15.0	30.5	0.0	29.5
		S.D.	5.68	0.06	0.07	2.0	1.2	2.5	2.1	0.129	9.6	105.1	3.4	1.7	0.0	2.5	0.0	2.5
		Count	16	13	13	10	1	1	1	1	1	1						
		min	1.60	1.89	1.50	5.6	16.0	30.0	14.0	0.229	70.0	86.0						
	Unit4	max	20.60	2.08	1.79	25.8	16.0	30.0	14.0	0.229	70.0	86.0						
		avarage	6.98	1.98	1.66	19.3	16.0	30.0	14.0	0.229	70.0	86.0						
		S.D.	4.50	0.06	0.09	5.3	0.0	0.0	0.0	0.000	0.0	0.0						
		Count	54	46	46	51	48	48	48	48	9	39	6	6	4	4	4	4
		min	0.60	1.89	1.48	14.7	13.0	26.0	13.0	-0.192	44.0	19.0	2.0	23.0	6.0	21.0	0.0	10.0
	Unit5	max	13.30	2.17	1.89	31.2	26.0	59.0	35.0	0.340	96.0	160.0	12.0	32.0	10.0	34.0	3.0	26.0
		avarage	5.52	2.01	1.65	21.6	19.9	44.1	24.2	0.066	79.7	87.8	7.0	26.7	8.5	26.8	0.8	18.0
		S.D.	2.73	0.07	0.10	3.1	2.8	7.5	5.4	0.114	17.8	29.6	3.4	3.1	1.7	4.7	1.3	6.7

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
		Count	121	104	94	118	119	119	119	119	119	88	6	6	1	1	1	1
		min	0.50	1.76	1.41	8.9	12.0	32.0	14.0	-0.404	52.0	7.0	0.0	25.0	20.0	31.0	20.0	13.0
	Unit1	max	14.00	2.41	2.01	31.0	27.0	89.0	69.0	0.556	100.0	311.0	21.0	30.0	20.0	31.0	20.0	13.0
		avarage	2.36	2.05	1.70	20.8	20.0	48.7	28.8	0.030	92.9	120.2	4.8	26.8	20.0	31.0	20.0	13.0
		S.D.	2.27	0.08	0.10	4.1	2.5	8.7	7.7	0.159	6.8	67.9	7.6	1.8	0.0	0.0	0.0	0.0
		Count	102.0	63.0	56.0	89.0	91.0	91.0	90.0	89.0	91.0	53.0	6.0	59.0				
		min	0.50	1.85	1.53	7.6	13.0	27.0	9.0	-0.438	64.0	5.0	0.0	0.0				
	Unit2	max	11.45	2.27	1.98	26.0	26.0	55.0	37.0	0.636	100.0	329.0	32.0	35.0				
		avarage	4.72	2.11	1.79	17.2	17.8	40.1	22.3	-0.018	92.1	126.2	14.0	2.7				
		S.D.	2.22	0.08	0.09	3.4	2.5	6.0	5.1	0.188	7.0	71.2	10.0	8.1				
		Count	117	77	67	114	116	116	116	116	116	61	6	67				
Hathery Lane		min	1.85	1.61	1.45	6.5	10.0	21.0	7.0	-2.125	44.0	14.0	0.0	0.0				
(Northumberland)	Unit3	max	18.95	2.34	2.13	18.0	27.0	49.0	26.0	0.176	100.0	438.0	14.0	31.0				
		avarage	7.94	2.20	1.95	12.4	15.8	34.0	18.1	-0.211	87.0	194.4	7.3	2.3				
		S.D.	3.26	0.09	0.09	2.1	2.8	4.3	3.4	0.277	9.2	103.0	5.5	7.5				
		Count	32	3	3	4	3	3	3	3	3		1	1				
		min	0.55	1.99	1.66	11.0	13.0	29.0	9.0	-0.778	100.0		0.0	29.0				
	Unit4	max	9.70	2.20	1.96	20.0	20.0	35.0	19.0	-0.105	100.0		0.0	29.0				
		avarage	5.91	2.11	1.85	14.0	17.0	32.0	15.0	-0.412	100.0		0.0	29.0				
		S.D.	2.25	0.09	0.13	3.5	2.9	2.4	4.3	0.278	0.0		0.0	0.0				
		Count	26	22	20	25	25	25	25	25	25	12	4	4	3	3	3	3
		min	1.85	1.97	1.57	12.0	16.0	28.0	12.0	-0.346	82.0	54.0	0.0	20.0	10.0	26.0	10.0	20.0
	Unit5	max	11.70	2.17	1.89	27.0	26.0	57.0	31.0	0.583	100.0	155.0	22.0	33.0	30.0	38.0	30.0	37.0
		avarage	4.39	2.06	1.71	21.1	19.7	43.9	24.2	0.089	96.8	90.7	9.3	27.3	16.7	31.3	16.7	26.7
		S.D.	2.47	0.06	0.08	3.7	2.5	7.5	5.6	0.221	4.2	37.1	8.3	5.4	9.4	5.0	9.4	7.4

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
Hunters Moor (Tyne and Wear)	Unit1	Count	23	18	18	22	21	21	22	22	21	8	7	15				
		min	0.50	1.85	1.52	16.7	18.0	33.0	13.0	-0.246	57.0	50.0	0.0	0.0				
		max	2.80	2.21	1.87	28.1	24.0	42.0	21.0	0.319	95.0	149.0	21.0	33.7				
		avarage	1.45	2.10	1.76	20.0	20.6	38.0	17.7	-0.032	81.6	104.4	14.0	14.2				
		S.D.	0.57	0.08	0.08	2.8	1.6	2.1	2.1	0.143	11.3	31.5	6.5	15.3				
	Unit2	Count	5	5	5	5	5	5	4	4	5	3						
		min	1.40	2.12	1.78	15.5	19.0	37.0	17.0	-0.242	72.0	99.0						
		max	4.10	2.24	1.93	21.4	22.0	41.0	19.0	0.082	92.0	182.0						
		avarage	2.76	2.16	1.86	17.3	20.0	39.2	18.5	-0.127	82.2	131.0						
		S.D.	0.95	0.04	0.05	2.1	1.1	1.3	0.9	0.132	7.1	36.5						
	Unit3	Count	20	20	20	20	20	20	20	20	20	16	3	3				
		min	1.30	2.10	1.84	9.3	16.0	30.0	12.0	-0.621	64.0	30.0	9.0	28.0				
		max	4.90	2.29	2.09	17.6	21.0	36.0	18.0	0.094	93.0	235.0	35.0	35.4				
		avarage	2.96	2.19	1.92	14.3	18.0	33.6	15.7	-0.243	80.8	137.8	24.3	31.3				
		S.D.	1.02	0.04	0.05	1.8	1.4	1.6	1.6	0.153	8.3	56.4	11.1	3.1				
	Unit4	Count	2	2	2	2	2	2	2	2	2	2						
		min	3.40	2.06	1.73	14.9	17.0	32.0	14.0	-0.221	85.0	15.0						
		max	4.00	2.14	1.86	19.6	18.0	35.0	18.0	0.144	91.0	25.0						
		avarage	3.70	2.10	1.80	17.3	17.5	33.5	16.0	-0.038	88.0	20.0						
		S.D.	0.30	0.04	0.07	2.4	0.5	1.5	2.0	0.183	3.0	5.0						

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
Herrington (Tyne and Wear)	Unit1	Count	44	40	40	42	35	35	35	35	39	37	1	1				
		min	0.30	1.66	1.14	10.0	16.0	26.0	6.0	-1.333	54.0	7.0	2.0	28.2				
		max	3.90	2.25	1.98	47.0	44.0	73.0	32.0	1.417	95.0	197.0	2.0	28.2				
		avarage	1.20	2.01	1.68	20.3	22.7	39.6	16.9	-0.172	79.7	71.8	2.0	28.2				
		S.D.	0.83	0.15	0.19	8.2	5.5	9.5	5.1	0.564	9.8	47.0	0.0	0.0				
	Unit2	Count	73	64	64	70	63	63	63	63	66	50	7	7				
		min	0.25	1.60	1.30	11.0	16.0	28.0	8.0	-1.200	55.0	9.0	2.0	13.0				
		max	42.80	2.34	2.02	32.0	29.0	62.0	38.0	0.688	100.0	250.0	64.0	24.3				
		avarage	9.09	2.09	1.72	21.0	21.3	40.2	18.9	-0.014	82.2	80.5	22.9	20.3				
		S.D.	11.06	0.14	0.16	4.9	3.3	7.4	5.6	0.299	11.2	59.5	23.1	3.8				
	Unit3	Count	342	308	308	342	317	317	317	317	319	264	30	30	1	1	1	1
		min	0.10	1.89	1.42	8.0	7.0	23.0	7.0	-1.182	28.0	12.0	1.0	21.1	137.8	24.8	65.0	24.7
		max	55.50	2.43	2.17	29.0	24.0	44.0	25.0	0.636	100.0	519.0	55.0	37.0	137.8	24.8	65.0	24.7
		avarage	12.25	2.26	1.99	13.7	17.3	32.0	14.7	-0.250	72.4	134.0	15.6	26.5	137.8	24.8	65.0	24.7
		S.D.	11.36	0.07	0.09	2.3	1.9	2.9	2.4	0.203	10.5	92.5	11.9	3.3	0.0	0.0	0.0	0.0
	Unit4	Count	123	35	35	92	10	10	10	10	36	34						
		min	0.10	1.72	1.38	3.0	17.0	23.0	5.0	-1.286	55.0	11.0						
		max	25.90	2.34	2.09	49.0	40.0	53.0	15.0	0.833	100.0	334.0						
		avarage	7.40	2.03	1.69	18.4	23.0	34.1	11.1	-0.094	84.3	53.6						
		S.D.	6.30	0.17	0.15	7.6	6.5	7.6	3.6	0.657	12.0	63.2						
	Unit5	Count	123	119	119	122	118	118	118	118	119	95	1	1	2	2	2	2
		min	1.50	1.78	1.31	11.0	14.0	25.0	7.0	-0.533	58.0	8.0	16.0	20.2	19.3	25.5	15.0	1.0
		max	41.80	2.40	2.06	41.0	36.0	74.0	40.0	0.895	100.0	174.0	16.0	20.2	32.4	26.3	28.1	22.6
		avarage	9.92	2.05	1.63	26.3	24.2	44.1	20.0	0.129	85.2	44.9	16.0	20.2	25.9	25.9	21.5	11.8
		S.D.	9.02	0.09	0.11	4.2	3.7	9.5	6.7	0.266	9.6	27.0	0.0	0.0	6.5	0.4	6.6	10.8

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
Melkridge (South Tyne)	Unit2	Count	23	18	18	23	23	23	23	23	23	15						
		min	0.50	1.83	1.45	15.0	17.0	23.0	4.0	-1.500	47.0	23.0						
		max	3.50	2.30	1.90	30.0	27.0	40.0	20.0	0.727	100.0	101.0						
		avarage	1.16	1.97	1.60	22.7	20.1	30.6	10.5	0.144	87.7	45.9						
		S.D.	0.78	0.12	0.13	3.9	2.5	4.2	3.8	0.508	17.0	19.5						
	Unit3	Count	11	10	10	11	10	10	10	10	10	6						
		min	1.00	2.09	1.81	8.0	10.0	23.0	6.0	-1.286	51.0	32.0						
		max	17.00	2.54	2.33	16.0	20.0	27.0	17.0	0.059	85.0	188.0						
		avarage	9.00	2.26	2.05	10.2	13.1	25.0	11.9	-0.290	77.7	98.5						
		S.D.	4.38	0.13	0.14	2.4	3.1	1.4	3.2	0.355	9.4	57.9						
	Unit4	Count	38	4	4	6	3	3	3	3	3	2						
		min	0.50	1.93	1.51	7.0	21.0	38.0	10.0	-1.400	100.0	48.0						
		max	13.50	2.08	1.94	28.0	28.0	40.0	17.0	0.133	100.0	90.0						
		avarage	5.80	2.00	1.67	19.7	24.7	38.7	14.0	-0.403	100.0	69.0						
		S.D.	3.36	0.05	0.16	7.3	2.9	0.9	2.9	0.706	0.0	21.0						

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
Plenmeller (South Tyne)	Unit1	Count	106	86	86	104	90	90	90	89	90	43	1	1				
		min	0.10	1.46	1.11	12.0	12.0	21.0	1.0	-0.750	22.0	11.0	7.0	28.0				
		max	5.70	2.19	1.88	50.0	56.0	97.0	48.0	4.000	100.0	172.0	7.0	28.0				
		avarage	0.97	1.95	1.58	23.7	20.7	38.1	17.5	0.271	85.7	64.8	7.0	28.0				
		S.D.	0.84	0.14	0.19	8.1	5.7	11.1	7.0	0.616	12.2	51.6	0.0	0.0				
	Unit2	Count	57	46	46	55	50	50	48	48	50	11	2	2				
		min	0.50	1.83	1.23	11.0	12.0	26.0	8.0	-1.250	56.0	7.0	0.0	29.0				
		max	23.60	2.27	1.95	33.0	25.0	46.0	50.0	1.714	100.0	177.0	0.0	34.0				
		avarage	3.50	2.07	1.75	17.8	17.7	35.6	18.0	0.002	79.6	67.9	0.0	31.5				
		S.D.	5.17	0.10	0.15	4.8	2.6	3.7	6.0	0.407	8.4	59.1	0.0	2.5				
	Unit3	Count	234	182	182	227	197	197	197	197	197	42	7	7				
		min	0.30	1.79	1.61	5.0	4.0	20.0	6.0	-2.167	40.0	25.0	0.0	24.0				
		max	28.70	2.34	2.13	23.0	26.0	38.0	25.0	0.625	100.0	352.0	14.0	37.0				
		avarage	6.99	2.17	1.93	11.9	14.4	30.6	16.0	-0.188	77.7	170.8	3.6	30.3				
		S.D.	6.45	0.08	0.09	2.5	2.7	3.2	3.7	0.297	9.8	72.7	5.4	4.4				
	Unit4	Count	14	3	3	4	3	3	3	3	3	1						
		min	0.40	1.80	1.50	9.0	14.0	21.0	4.0	-0.714	60.0	24.0						
		max	9.10	2.27	2.06	23.0	22.0	29.0	7.0	0.250	79.0	24.0						
		avarage	3.18	2.03	1.73	15.5	18.3	24.3	6.0	-0.107	67.3	24.0						
		S.D.	2.78	0.19	0.24	6.1	3.3	3.4	1.4	0.432	8.3	0.0						

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
		Count	19	19	19	19	19	19	19	19	19	2						
		min	0.45	1.67	1.3	15	16	26	8	-0.667	64.0	54						
	Unit1	max	2.4	2.11	1.79	33	29	50	27	0.438	100.0	94						
		avarage	0.916	1.946	1.605	21.42	21	34.89	13.89	-0.018	91.0	74						
		S.D.	0.554	0.105	0.122	4.683	3.325	6.577	4.951	0.25	9.7	20						
		Count	33	31	31	33	33	33	33	33	33	3	4	4				
		min	0.4	1.75	1.47	14	16	28	10	-0.333	69.0	44	3	18				
	Unit2	max	10.4	2.19	1.89	22	26	57	32	0.364	100.0	130	7	27				
		avarage	3.9	1.972	1.685	17.18	18.76	39.67	20.73	-0.061	88.4	96.67	4.5	23.75				
		S.D.	2.717	0.1	0.1	2.181	2.161	6.371	5.136	0.133	8.6	37.68	1.658	3.7				
		Count	18	17	17	18	18	18	18	18	18	3	1	1				
Hill Top		min	1.4	1.88	1.66	12	14	26	7	-0.571	52.0	46	1	29				
(County Durham)	Unit3	max	9.4	2.18	1.93	17	21	38	20	0.083	100.0	132	1	29				
		avarage	4.917	2.067	1.804	14.5	16.89	31.39	14.5	-0.18	83.3	79.67	1	29				
		S.D.	1.959	0.082	0.068	1.424	2.258	3.53	3.114	0.208	12.1	37.51	0	0				
		Count	4			1	1	1	1	1	1							
		min	1.8			10	14	22	8	-0.5	58.0							
	Unit4	max	11			10	14	22	8	-0.5	58.0							
		avarage	8.1			10	14	22	8	-0.5	58.0							
		S.D.	3.676			0	0	0	0	0	0.0							
		Count	7	7	7	7	7	7	7	7	7.0	2	1	1				
		min	1.5	1.8	1.34	21	19	41	21	0.042	92.0	27	1	22				
	Unit5	max	8.5	1.93	1.56	34	23	52	29	0.536	100.0	53	1	22				
		avarage	4.986	1.871	1.479	26.57	20.57	47	26.43	0.224	98.9	40	1	22				
		S.D.	2.196	0.039	0.064	3.736	1.178	3.381	2.718	0.141	2.8	13	0	0				

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
		Count	14	14	14	14	13	13	13	13	13	14						
		min	0.5	1.75	1.38	18	17	29	10	0	72.0	14						
	Unit1	max	2.5	2.13	1.81	28	23	45	24	0.5	93.0	101						
		avarage	1	1.979	1.611	23.29	19	37.92	18.92	0.253	84.4	51.93						
		S.D.	0.732	0.118	0.135	3.452	1.881	4.428	3.54	0.166	6.5	27.67						
		Count	14	13	13	14	12	12	12	12	12	13						
Red Barns		min	0.5	1.9	1.65	13	15	33	16	-0.091	65.0	12						
(County Durham)	Unit2	max	8.5	2.17	1.85	24	20	42	23	0.368	92.0	167						
		avarage	3.986	2.058	1.769	16.79	16.75	37.5	20.75	0.03	79.7	84.77						
		S.D.	2.564	0.078	0.058	3.075	1.233	2.63	2.046	0.122	6.4	42.74						
		Count	17	17	17	17	17	17	17	17	17	17						
		min	0.5	2.03	1.79	10	14	27	10	-0.7	54.0	58						
	Unit3	max	10.7	2.28	2.05	16	18	37	21	0.05	94.0	250						
		avarage	4.976	2.145	1.885	13.82	16.35	34.12	17.76	-0.161	77.9	155.7						
		S.D.	2.575	0.063	0.068	1.723	1.135	2.587	2.881	0.176	9.4	47.02						

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
		Count	9.00	6	6	9	9	9	9	9	1	6	3	3				
Whitwell		min	2.50	1.88	1.42	13	19	42	23	-0.261	86.0	28	14	18				
(County Durham)	Unit2	max	22.00	2.04	1.67	30.4	29	64	38	0.164	86.0	116	15	24				
		avarage	9.60	1.94	1.527	24.4	24.3	55.5	31.22	-0.008	86.0	65.17	14.66	21.17				
		S.D.	5.67	0.059	0.079	5.2	2.708	6.73	4.589	0.118	0.0	32.91	0.47	2.46				

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
Oughterside (Cumbria)	Unit2	Count	1	1	1	1	1	1	1	1	1	1						
		min	1.30	2.17	1.72	26.0	19.0	30.0	11.0	0.636	90.0	6.0						
		max	1.30	2.17	1.72	26.0	19.0	30.0	11.0	0.636	90.0	6.0						
		avarage	1.30	2.17	1.72	26.0	19.0	30.0	11.0	0.636	90.0	6.0						
		S.D.	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.000	0.0	0.0						
	Unit3	Count	33	30	30	30	22	22	22	22	22	22	9	9				
		min	3.00	2.05	1.85	7.0	12.0	22.0	9.0	-0.714	82.0	90.0	0.0	25.5				
		max	22.50	2.44	2.28	14.0	22.0	36.0	18.0	0.077	95.0	500.0	20.0	32.0				
		avarage	11.55	2.31	2.09	10.4	14.5	28.4	13.9	-0.282	89.5	297.1	13.9	29.9				
		S.D.	5.84	0.08	0.09	1.6	2.0	3.1	2.2	0.192	3.0	119.5	8.7	2.5				
	Unit4	Count	14	3	3	4		2				2	1	1				
		min	1.50	1.91	1.62	15.0		23.0				135.0	10.0	37.0				
		max	7.90	2.04	1.77	18.0		24.0				215.0	10.0	37.0				
		avarage	3.28	1.99	1.72	16.3		23.5				175.0	10.0	37.0				
		S.D.	1.85	0.06	0.07	1.3		0.5				40.0	0.0	0.0				
	Unit5	Count	8	4	4	4	2	2	2	2	2	2	5	5				
		min	8.00	1.86	1.54	17.0	13.0	35.0	22.0	0.115	100.0	45.0	0.0	22.0				
		max	13.00	2.09	1.76	21.0	16.0	42.0	26.0	0.364	100.0	150.0	5.0	31.5				
		avarage	10.83	2.01	1.70	18.5	14.5	38.5	24.0	0.240	100.0	97.5	4.0	23.9				
		S.D.	1.69	0.09	0.09	1.7	1.5	3.5	2.0	0.124	0.0	52.5	2.0	3.8				

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
Maryport (Cumbria)	Unit2	Count	9	9	9	9	3	3	3	3	3	8						
		min	7.50	1.80	1.32	28.0	20.0	39.0	18.0	0.364	100.0	13.0						
		max	11.50	1.99	1.55	38.0	22.0	45.0	23.0	0.696	100.0	49.0						
		avarage	9.06	1.90	1.43	33.1	21.0	42.0	21.0	0.538	100.0	25.9						
		S.D.	1.12	0.05	0.07	3.4	0.8	2.4	2.2	0.136	0.0	12.1						
	Unit3	Count	4	4	4	4												
		min	7.60	2.12	1.81	10.0												
		max	19.00	2.26	2.03	17.0												
		avarage	12.85	2.21	1.95	13.0												
		S.D.	4.68	0.06	0.08	2.7												

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
Linefoot (Cumbria)	Unit2	Count	14	12	12	14	14	14	14	14	14	4						
		min	0.40	1.81	1.36	15.0	16.0	29.0	13.0	-0.059	71.0	17.0						
		max	3.50	2.19	1.86	33.0	27.0	54.0	27.0	0.357	100.0	45.0						
		avarage	1.75	2.07	1.73	20.1	18.1	36.8	18.6	0.103	80.9	25.8						
		S.D.	0.91	0.10	0.13	4.3	2.8	5.8	3.8	0.127	7.3	11.3						
	Unit3	Count	71	63	63	71	71	71	71	71	71	25						
		min	0.30	1.87	1.65	8.0	12.0	24.0	3.0	-3.333	47.0	58.0						
		max	40.20	2.32	2.12	15.0	23.0	39.0	22.0	-0.050	100.0	340.0						
		avarage	7.90	2.20	1.97	11.5	15.4	32.1	16.7	-0.276	72.8	161.0						
		S.D.	5.98	0.09	0.08	1.4	1.8	3.0	2.9	0.393	9.6	71.7						
	Unit4	Count	17	2	2	4	2	2	2	2	2							
		min	0.30	1.90	1.72	8.0	15.0	29.0	6.0	-0.667	84.0							
		max	39.00	2.08	1.73	20.0	24.0	30.0	14.0	-0.357	100.0							
		avarage	14.70	1.99	1.73	12.3	19.5	29.5	10.0	-0.512	92.0							
		S.D.	11.60	0.09	0.00	4.6	4.5	0.5	4.0	0.155	8.0							

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
Broughton Lodge (Cumbria)	Unit1	Count	31	26	23	28	29	29	27	27	29	17	3	3	5	5	5	5
		min	0.50	1.35	0.96	12.0	15.0	30.0	12.0	-1.000	34.0	41.0	1.0	26.0	16.0	17.0	4.0	8.0
		max	4.20	2.15	1.90	41.0	34.0	66.0	38.0	0.438	100.0	202.0	5.0	35.0	42.0	35.0	18.0	27.0
		avarage	1.26	1.94	1.61	19.1	19.9	39.3	19.8	-0.101	82.4	88.1	2.7	31.3	28.4	27.4	10.8	21.4
		S.D.	0.94	0.14	0.19	7.5	4.4	8.6	6.2	0.309	17.0	43.2	1.7	3.9	9.7	6.3	5.0	6.8
	Unit2	Count	27	20	18	24	24	24	24	24	24	18	2	2				
		min	0.50	1.84	1.54	10.0	16.0	30.0	13.0	-0.615	39.0	35.0	4.0	27.0				
		max	9.20	2.28	1.86	25.0	23.0	45.0	24.0	0.278	100.0	146.0	6.0	30.0				
		avarage	2.09	2.02	1.71	17.1	18.3	36.5	18.3	-0.077	78.8	85.2	5.0	28.5				
		S.D.	2.34	0.10	0.09	3.7	2.0	3.8	3.2	0.190	16.8	36.0	1.0	1.5				
	Unit3	Count	46	38	38	44	44	44	44	44	42	32			1	1	1	1
		min	1.05	1.86	1.61	8.0	13.0	24.0	10.0	-0.625	35.0	44.0			17.0	34.0	10.0	33.0
		max	11.10	2.21	1.99	17.0	22.0	38.0	21.0	0.000	100.0	380.0			17.0	34.0	10.0	33.0
		avarage	4.20	2.09	1.86	11.8	15.3	32.3	16.9	-0.221	72.3	165.6			17.0	34.0	10.0	33.0
		S.D.	2.22	0.08	0.09	1.5	1.8	2.8	2.5	0.142	14.7	73.4			0.0	0.0	0.0	0.0

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
Foxhouse (Cumbria)	Unit1	Count	16	11	11	14	11	11	11	11	11	3						
		min	0.00	1.77	1.31	19.0	19.0	41.0	16.0	-0.188	73.0	9.0						
		max	3.00	2.15	1.81	44.0	33.0	62.0	32.0	0.458	100.0	45.0						
		avarage	0.76	1.97	1.60	26.4	23.9	48.9	25.0	0.128	87.5	26.3						
		S.D.	0.70	0.11	0.13	7.6	4.6	7.4	4.9	0.186	10.2	14.7						
	Unit2	Count	17	15	15	17	16	16	16	16	16	7	1	1				
		min	0.50	1.98	1.64	12.0	15.0	30.0	13.0	-0.294	60.0	10.0	13.0	26.0				
		max	17.50	2.24	1.93	25.0	27.0	49.0	23.0	0.643	100.0	84.0	13.0	26.0				
		avarage	6.26	2.11	1.79	18.8	20.2	38.6	18.4	-0.052	78.1	29.9	13.0	26.0				
		S.D.	4.60	0.07	0.08	3.8	3.2	4.2	2.8	0.236	11.8	23.9	0.0	0.0				
	Unit3	Count	109	89	88	107	98	98	97	97	98	17	5	5				
		min	0.50	1.94	1.72	8.0	12.0	18.0	6.0	-1.333	32.0	13.0	5.0	28.0				
		max	42.00	2.48	2.28	20.0	21.0	44.0	29.0	0.222	91.0	325.0	12.0	36.0				
		avarage	9.51	2.24	2.00	11.8	16.4	30.6	14.3	-0.344	67.1	94.2	8.8	31.6				
		S.D.	9.61	0.10	0.11	2.2	1.8	5.0	4.3	0.222	12.9	72.4	2.3	2.7				
	Unit4	Count	13	2	2	3	2	2	2	2	2		1	1				
		min	5.20	2.09	1.65	9.0	16.0	22.0	6.0	-1.000	58.0		12.0	32.0				
		max	40.00	2.33	2.14	27.0	25.0	41.0	16.0	0.125	100.0		12.0	32.0				
		avarage	19.69	2.21	1.90	15.3	20.5	31.5	11.0	-0.438	79.0		12.0	32.0				
		S.D.	11.16	0.12	0.24	8.3	4.5	9.5	5.0	0.563	21.0		0.0	0.0				
	Unit5	Count	2	2	2	2	2	2	2	2	2	1						
		min	6.70	1.87	1.47	15.0	19.0	38.0	19.0	-0.211	72.0	79.0						
		max	19.50	2.23	1.94	27.0	30.0	62.0	32.0	-0.094	100.0	79.0						
		avarage	13.10	2.05	1.71	21.0	24.5	50.0	25.5	-0.152	86.0	79.0						
		S.D.	6.40	0.18	0.23	6.0	5.5	12.0	6.5	0.058	14.0	0.0						

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
		Count	20	19	19	19	11	11	12	12	11	17						
		min	0.00	1.89	1.15	13.0	17.0	31.0	14.0	-0.357	71.0	18.0						
	Unit1	max	2.60	2.15	1.93	47.0	28.0	49.0	28.0	0.643	88.0	165.0						
		avarage	0.90	2.03	1.68	21.3	20.2	38.1	18.0	-0.033	80.7	83.9						
		S.D.	0.70	0.08	0.18	8.3	3.2	6.1	4.3	0.254	4.6	41.3						
		Count	9	9	9	9	5	5	5	5	5	6						
		min	1.25	1.91	1.58	15.0	18.0	35.0	16.0	-0.235	75.0	24.0						
	Unit2	max	7.50	2.22	1.95	29.0	21.0	46.0	25.0	-0.056	100.0	196.0						
		avarage	3.46	2.09	1.78	18.4	19.6	39.2	19.6	-0.142	84.4	94.5						
		S.D.	2.02	0.09	0.12	3.8	1.2	3.8	3.4	0.058	8.9	55.6						
		Count	131	126	126	128	74	74	71	71	74	64	21	21				
Potatopot		min	0.50	1.88	1.05	9.0	13.0	22.0	5.0	-0.586	57.0	39.0	0.0	23.0				
(Cumbria)	Unit3	max	25.05	2.38	2.19	19.0	19.0	46.0	29.0	0.500	100.0	453.0	25.0	33.0				
		avarage	6.60	2.21	1.95	13.0	16.1	32.1	16.1	-0.160	74.9	174.3	1.4	26.8				
		S.D.	5.32	0.07	0.12	2.1	1.3	4.1	3.7	0.160	8.8	81.1	5.4	2.1				
		Count	13	6	6	7	5	5	5	5	5	1	1	1				
		min	0.35	2.08	1.69	12.0	15.0	27.0	4.0	-1.250	69.0	160.0	0.0	31.0				
	Unit4	max	8.00	2.28	1.97	23.0	23.0	38.0	19.0	-0.053	100.0	160.0	0.0	31.0				
		avarage	4.01	2.16	1.86	16.0	18.4	30.8	12.2	-0.516	80.0	160.0	0.0	31.0				
		S.D.	2.51	0.06	0.09	3.3	2.7	4.4	6.6	0.445	11.8	0.0	0.0	0.0				
		Count	8	8	8	8	3	3	3	3	3	4	1	1				
		min	2.00	1.93	1.64	9.0	15.0	29.0	14.0	-0.429	73.0	42.0	0.0	30.0				
	Unit5	max	15.50	2.11	1.79	24.0	24.0	52.0	28.0	-0.050	100.0	196.0	0.0	30.0				
		avarage	8.99	2.01	1.71	17.8	19.3	40.0	20.7	-0.195	88.3	121.0	0.0	30.0				
		S.D.	4.78	0.06	0.05	4.1	3.7	9.4	5.7	0.167	11.3	57.7	0.0	0.0				

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
		Count	3	2		3	3	3	3	3	2	2						
		min	7.50	1.77		19.0	11.0	21.0	9.0	0.000	55.0	11.0						
	Unit2	max	13.10	1.95		35.0	20.0	41.0	21.0	0.714	94.0	24.0						
		avarage	9.53	1.86		28.3	14.7	28.0	15.0	0.460	74.5	17.5						
		S.D.	2.53	0.09		6.8	3.9	9.2	4.9	0.326	19.5	6.5						
		Count	14	3		13	12	12	12	12	9	3						
Workington		min	11.50	2.07		7.0	11.0	20.0	8.0	-0.833	35.0	14.0						
(Cumbria)	Unit3	max	30.00	2.22		12.0	19.0	31.0	16.0	2.000	80.0	130.0						
		avarage	20.70	2.15		9.2	13.0	24.1	11.1	-0.124	60.4	61.7						
		S.D.	5.51	0.06		1.6	2.1	3.7	2.3	0.687	11.7	49.6						
		Count	26	1		1	1	1	1	1	1	1						
		min	1.00	2.01		10.0	10.0	19.0	9.0	0.000	57.0	80.0						
	Unit4	max	26.50	2.01		10.0	10.0	19.0	9.0	0.000	57.0	80.0						
		avarage	12.07	2.01		10.0	10.0	19.0	9.0	0.000	57.0	80.0						
		S.D.	6.69	0.00		0.0	0.0	0.0	0.0	0.000	0.0	0.0						
		Count	7	5		6	5	5	5	5	5	5						
		min	14.50	1.99		15.0	12.0	29.0	13.0	-0.077	83.0	33.0						
	Unit5	max	21.50	2.09		24.0	19.0	37.0	25.0	0.240	100.0	110.0						
		avarage	18.21	2.03		18.8	15.8	33.6	17.8	0.093	93.2	63.8						
		S.D.	2.63	0.03		2.9	2.1	2.7	13.3	0.287	7.8	36.4						

Site	Unit		TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
Lostrigg (Cumbria)	Unit1	Count	19	19	19	19	9	9	9	9	9	4	1	1				
		min	0.10	1.72	1.27	11.0	19.0	36.0	14.0	-0.571	64.0	8.0	3.0	24.0				
		max	1.50	2.16	1.95	39.0	33.0	49.0	24.0	0.458	100.0	26.0	3.0	24.0				
		avarage	0.76	1.95	1.60	22.6	22.6	42.7	20.1	-0.057	84.7	17.0	3.0	24.0				
		S.D.	0.40	0.12	0.17	7.1	4.2	4.2	3.4	0.293	9.6	6.4	0.0	0.0				
	Unit2	Count	8	7	7	7	8	8	8	7	8	2	1	1				
		min	1.00	1.93	1.51	22.0	12.0	28.0	7.0	0.000	63.0	50.0	16.0	28.0				
		max	15.20	2.21	1.73	31.0	25.0	41.0	21.0	0.625	100.0	51.0	16.0	28.0				
		avarage	5.06	2.03	1.61	25.9	19.4	34.0	14.3	0.321	93.3	50.5	16.0	28.0				
		S.D.	5.54	0.09	0.07	3.0	3.5	3.5	4.4	0.247	11.7	0.5	0.0	0.0				
	Unit3	Count	83	75	75	78	44	44	44	42	44	5	6	6				
		min	0.50	1.84	1.56	8.0	12.0	28.0	10.0	-1.100	51.0	83.0	5.0	21.0				
		max	18.00	2.35	2.14	18.0	20.0	41.0	23.0	0.846	95.0	162.0	15.0	32.0				
		avarage	4.74	2.13	1.88	12.9	16.8	35.1	18.4	-0.192	74.8	120.8	7.8	27.5				
		S.D.	3.59	0.08	0.09	2.1	1.6	3.3	2.9	0.233	12.0	32.5	3.4	3.6				
	Unit4	Count	26	2	2	3	2	2	2	2	1							
		min	0.50	1.76	1.47	14.0	15.0	25.0	5.0	-0.400	100.0							
		max	17.00	1.97	1.66	20.0	22.0	27.0	10.0	-0.100	100.0							
		avarage	4.66	1.87	1.57	17.7	18.5	26.0	7.5	-0.250	100.0							
		S.D.	4.14	0.11	0.09	2.6	3.5	1.0	2.5	0.150	0.0							
	Unit5	Count	4	4	4	4	3	3	3	3	3	2						
		min	2.50	1.73	1.48	17.0	20.0	37.0	11.0	-1.091	100.0	60.0						
		max	12.15	2.07	1.68	29.0	29.0	44.0	23.0	0.529	100.0	87.0						
		avarage	6.43	1.92	1.56	23.3	23.3	40.3	17.0	-0.144	100.0	73.5						
		S.D.	3.81	0.12	0.08	4.3	4.0	2.9	4.9	0.689	0.0	13.5						

Site	Unit		TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
Moresby and Keekle (Cumbria)	Unit1	Count	2			2	1	2	2	2								
		min	1.50			13.0	18.0	22.0	13.0	-0.385								
		max	1.60			16.0	18.0	31.0	22.0	0.727								
		avarage	1.55			14.5	18.0	26.5	17.5	0.171								
		S.D.	0.05			1.5	0.0	4.5	4.5	0.556								
	Unit2	Count	6			6	6	6	6	6	2							
		min	0.90			12.0	15.0	28.0	11.0	-0.500	35.0							
		max	6.00			24.0	21.0	39.0	18.0	0.600	73.0							
		avarage	2.55			17.8	17.8	32.2	14.3	0.015	54.0							
		S.D.	1.70			4.1	2.1	3.9	2.4	0.385	19.0							
	Unit3	Count	51	17		51	50	51	51	51	12	16						
		min	1.10	2.08		7.0	13.0	21.0	8.0	-0.875	38.0	51.0						
		max	11.00	2.30		18.0	19.0	34.0	21.0	0.524	96.0	396.0						
		avarage	4.70	2.24		12.0	15.4	28.8	13.7	-0.244	72.3	212.3						
		S.D.	2.33	0.05		2.0	1.4	3.0	2.5	0.215	16.2	107.1						
	Unit4	Count	1			1	1	1	1	1	1							
		min	1.25			23.0	27.0	28.0	1.0	-4.000	51.0							
		max	1.25			23.0	27.0	28.0	1.0	-4.000	51.0							
		avarage	1.25			23.0	27.0	28.0	1.0	-4.000	51.0							
		S.D.	0.00			0.0	0.0	0.0	0.0	0.000	0.0							

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
River Keekle (Cumbria)	Unit1	Count	9	8	8	9	9	9	9	9	9	2						
		min	0.50	1.77	1.39	14.0	13.0	27.0	9.0	0.000	72.0	13.0						
		max	2.00	2.18	1.88	41.0	32.0	48.0	21.0	1.000	93.0	18.0						
		avarage	0.89	2.02	1.69	22.6	18.8	35.2	16.4	0.268	84.8	15.5						
		S.D.	0.46	0.12	0.15	8.1	5.1	6.0	3.2	0.323	5.6	2.5						
	Unit2	Count	2	1	1	2	1	1	1	1	1							
		min	1.00	1.97	1.60	23.0	19.0	32.0	13.0	0.308	82.0							
		max	7.00	1.97	1.60	30.0	19.0	32.0	13.0	0.308	82.0							
		avarage	4.00	1.97	1.60	26.5	19.0	32.0	13.0	0.308	82.0							
		S.D.	3.00	0.00	0.00	3.5	0.0	0.0	0.0	0.000	0.0							
	Unit3	Count	88	70	70	88	78	78	78	78	78	15	6	6				
		min	0.50	2.09	1.78	9.0	13.0	20.0	4.0	-0.750	36.0	76.0	4.0	25.0				
		max	22.00	2.32	2.10	19.0	22.0	49.0	27.0	0.750	95.0	625.0	22.0	39.0				
		avarage	6.43	2.22	1.97	12.6	15.1	29.9	14.9	-0.168	77.7	242.1	13.2	29.3				
		S.D.	5.22	0.06	0.07	1.9	1.6	4.3	3.9	0.189	10.3	153.8	6.2	5.3				
	Unit4	Count	24	1	1	24	8	8	8	8	8							
		min	1.00	1.93	1.62	10.0	13.0	22.0	6.0	-0.364	50.0							
		max	8.00	1.93	1.62	23.0	19.0	29.0	11.0	0.857	99.0							
		avarage	4.25	1.93	1.62	14.8	15.8	24.5	8.8	0.185	67.3							
		S.D.	2.01	0.00	0.00	3.2	1.8	2.4	1.6	0.365	15.7							
	Unit5	Count	4	4	4	4	3	3	3	3	3	2	1	1				
		min	6.50	1.88	1.19	18.0	15.0	24.0	9.0	0.083	98.0	14.0	3.0	24.0				
		max	8.00	2.04	1.70	60.0	22.0	48.0	29.0	1.414	100.0	26.0	3.0	24.0				
		avarage	7.50	1.96	1.52	31.5	18.7	39.3	20.7	0.832	99.3	20.0	3.0	24.0				
		S.D.	0.61	0.07	0.20	16.6	2.9	10.9	8.5	0.556	0.9	6.0	0.0	0.0				

			TOP	BDEN	DDEN	NMC	PL	LL	PI	LI	425mm	CU	COH	PHI	PCOH	PHI	RCOH	RPHI
Keekle Extension (Cumbria)	Unit1	Count	3	3	3	3	3	3	3	3	3	3						
		min	0.50	2.06	1.66	16.0	16.0	33.0	15.0	-0.133	76.0	65.0						
		max	1.50	2.11	1.82	24.0	18.0	38.0	20.0	0.300	84.0	108.0						
		avarage	1.00	2.09	1.76	19.0	17.3	34.7	17.3	0.075	81.3	90.3						
		S.D.	0.41	0.02	0.07	3.6	0.9	2.4	2.1	0.177	3.8	18.4						
	Unit2	Count	4	3	3	4	4	4	4	4	4	3	1	1				
		min	1.00	2.13	1.78	13.0	18.0	35.0	16.0	-0.438	73.0	23.0	6.0	34.0				
		max	9.50	2.15	1.89	20.0	20.0	42.0	23.0	0.059	88.0	179.0	6.0	34.0				
		avarage	3.25	2.14	1.85	16.5	19.0	37.3	18.3	-0.150	79.0	112.0	6.0	34.0				
		S.D.	3.61	0.01	0.05	2.7	0.7	2.8	2.8	0.186	5.5	65.6	0.0	0.0				
	Unit3	Count	43	32	32	43	39	39	39	39	39	27	3	3				
		min	0.50	1.99	1.79	8.0	11.0	21.0	8.0	-0.692	46.0	47.0	7.0	26.0				
		max	8.40	2.36	2.13	15.0	21.0	39.0	24.0	0.286	100.0	376.0	13.0	32.0				
		avarage	3.87	2.24	2.00	12.0	14.7	29.2	14.5	-0.193	80.3	190.4	10.0	29.3				
		S.D.	2.07	0.09	0.09	1.5	2.0	3.7	3.0	0.167	10.2	93.2	2.4	2.5				
	Unit4	Count	17	2	2	17	2	2	2	2	2	1						
		min	0.50	2.11	1.85	8.0	12.0	27.0	12.0	-0.083	87.0	33.0						
		max	7.50	2.37	2.10	20.0	15.0	28.0	16.0	0.063	88.0	33.0						
		avarage	2.82	2.24	1.98	14.4	13.5	27.5	14.0	-0.010	87.5	33.0						
		S.D.	1.70	0.13	0.13	2.9	1.5	0.5	2.0	0.073	0.5	0.0						
	Unit5	Count	5	5	5	5	5	5	5	5	5	4	1	1				
		min	1.00	2.02	1.70	14.0	14.0	34.0	19.0	-0.036	87.0	45.0	7.0	17.0				
		max	5.00	2.26	1.97	19.0	18.0	46.0	28.0	0.125	90.0	120.0	7.0	17.0				
		avarage	3.00	2.12	1.83	16.6	16.0	38.2	22.2	0.028	88.8	79.5	7.0	17.0				
		S.D.	1.41	0.08	0.09	1.9	1.4	4.4	3.4	0.056	1.2	28.1	0.0	0.0				