The Effect of Continuous Flight Auger Pile Installation on the Soil-Pile Interface in the Mercia Mudstone Group

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Degree of Doctor of Philosophy

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Declaration

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Abstract

The research reported in this dissertation examines the physical and chemical changes that occur to in situ soil at the soil-pile interface for continuous flight auger piles installed in the Mercia Mudstone Group. Four Continuous Flight Auger (CFA) piles were installed in the Gunthorpe Member of the Mercia Mudstone Group, central England. The effect on the soil-pile interface of over-rotation of the auger during installation, and the addition of water during installation were investigated.

Once the piles had been left to cure, they were excavated and returned to City University, London, with the surrounding soil. The excavated piles and soil were examined using a variety of microscopic and macroscopic techniques including inductively coupled plasma spectroscopy (ICP) and X-ray diffraction (XRD); with water contents, chemical content (ICP) and mineralogical content (XRD) tested. Plastic index and particle size distribution tests were used to show the physical effects of piling on the host soil and preliminary strength testing was carried out to provide insight into the strength characteristics of the soil surrounding the pile.

In all four piles a distinct zone of remoulding was observed around the pile shaft. In each case the remoulded zone was a brown to red, clay rich layer varying between 0mm and 55mm in thickness. In almost all cases this remoulded zone had a structure and fabric which was not related to the in situ soil. Around all piles it was further noted that vertical fissures were present, and fanned out from the pile shaft in a clockwise direction.

Two of the piles were installed with the addition of water. Around these piles it was noted that the remoulded layer often split into two or three distinct layers, with one of these layers often containing millimetre scale aggregations of green silt.

Tests showed a higher percentage of clays present within this remoulded zone, and indicated that SiO_2 (a major rock forming element and considered by some authors to be an aggregating agent within the Mercia Mudstone Group) was more abundant within remoulded than undisturbed soil. The clay fraction showed a low abundance of high swelling clays in all cases.

It was concluded that installing piles within the Mercia Mudstone Group causes remoulding of the soil directly adjacent to the pile shaft. The least remoulding occurred when the pile was augered normally with no added water. All four remoulded zones contained fissures, fanning clockwise from the pile, however, these were more pronounced in the dry piles, while the wet piles had a more massive, granular texture to the remoulded zone. For all piles, except the pile which was over-rotated and installed with no added water, the percentage of clays within the remoulded zone was greater than outside the remoulded zone. This indicates that the aggregates of clays found naturally within the Mercia Mudstone Group may be split into their constituent clays during the piling process.

Definition of Terms

Aggregates from concrete:

Aggregates used as part of concrete mix, seen within this study as millimetre to centimetre scale, sub-rounded to sub-angular flints

Aggregates of clay:

Individual clay minerals cemented together with CaO or SiO_2 into silt sized particles.

Afossiliferous:

Does not contain fossils

bgl:

Below ground level

BGS:

British Geological Survey

c':

effective cohesion

C_c:

Slope of normal compression line

Clasts:

Rock fragment formed by the breakdown of other rocks

Clay Mineral Assemblage:

A group of clay minerals commonly found together in a particular geological unit

CSL:

Critical State Line

Host soil:

Soil into which piles were installed, particularly the soil surrounding the remoulded zone which appeared unaffected by the piling process

ICP:

Inductively Coupled Plasma, a highly powerful technique for analysing the chemical composition of a sample

Laterally Discontinuous:

Does not continue along a horizontal plane, but may appear sporadically along the same horizon

Laterally Extensive:

Continues along a horizontal plane for a large distance

MMG:

Mercia Mudstone Group

Normally Installed Pile:

Where a pile was installed as would usually be required on site, with no special instructions such as over-rotation

p':

Mean normal stress

PI Tests:

Plastic Index tests

Playa Lake:

A temporary shallow lake

PSD Tests:

Particle Size Distribution tests

SEM:

Scanning Electron Microscope

Slurry:

Water and clay at approximately the plastic limit, giving a sludgy material which is hard to pile or tunnel through

Remoulded Zone:

Area surrounding the pile shaft appearing different from the host soil in colour and texture

Soil-Pile Interface:

Where the soil and pile shaft touch

SSG:

Sherwood Sandstone Group

Syn-:
During

v:

Specific Volume

Vertically Discontinuous:
Does not continue along a vertical plane, but may appear sporadically with depth

XRD:
X-Ray Diffraction, a powerful tool in assessing which minerals are present in a sample. Particularly useful for clay species where individual crystals are too small for visual identification

τ':

Shear Stress

ϕ':

Angle of friction

ϕ_c':
Critical state friction angle

The following diagrams indicate some commonly used words of phrases within this thesis:

Diagram showing conventions used to refer to the pile

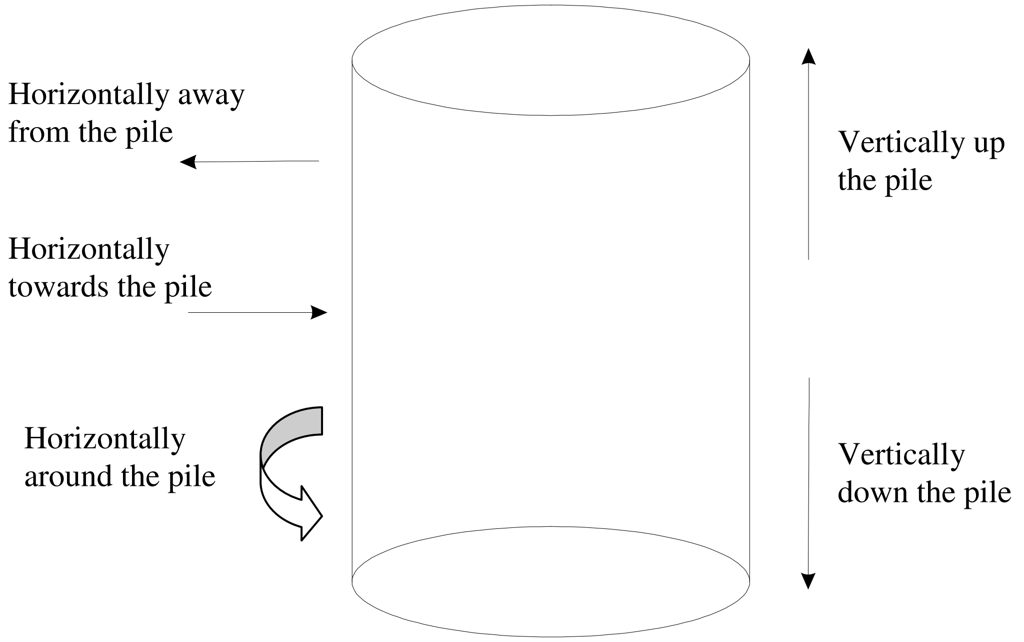


Diagram showing terminology used to describe the soil surrounding the pile

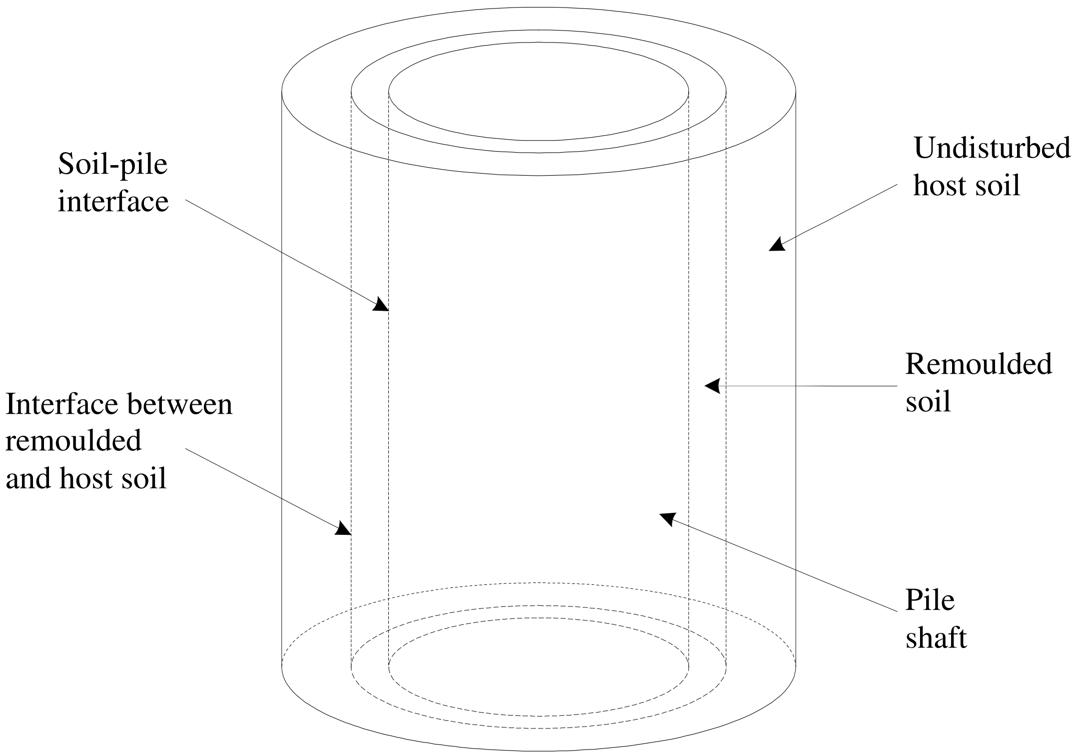
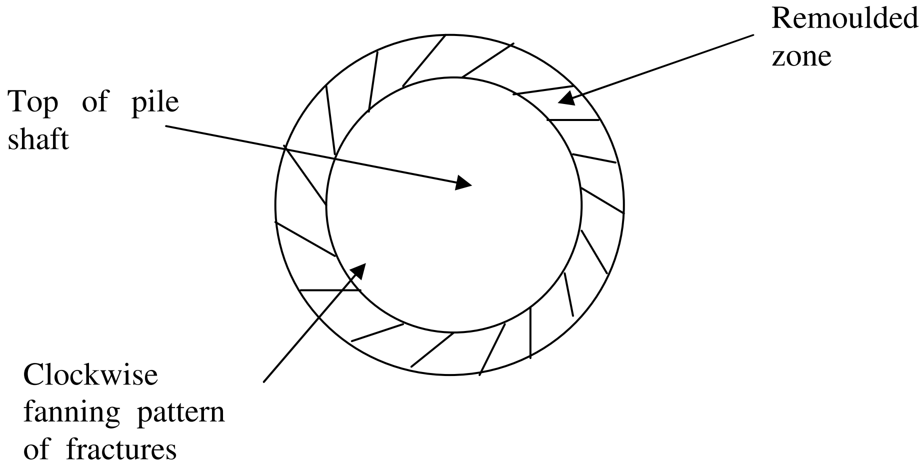


Diagram showing the pattern of fractures commonly seen within the remoulded zones of all four piles as seen from above



1 Introduction

1.1 Background

In 2005 City University London was approached by Stent Foundations to investigate the reasons why some Continuous Flight Auger (CFA) piles augered into mudrocks, in particular the Mercia Mudstone Group, have a shaft capacity which is significantly lower than that expected from calculations. It is commonly understood within the industry that piling in some clay rich soils may become problematic due to the issues of slurrying during installation and unexplained loss of capacity of piles after installation, but sadly case histories where this has occurred have rarely been documented in the literature.

1.2 Aims of the Project

The aims of the project are to look at the changes to the in situ soil at the soil-pile interface caused by installation of Continuous Flight Auger (CFA) piles in the Mercia Mudstone Group, and in particular to:

- Characterise the changes that occur in the soil at the soil-pile interface.
- Investigate the mechanisms that might create these changes.
- Characterise the effect of over-rotating the auger during installation.
- Characterise the effect of the presence of free water during installation.
- Draw preliminary conclusions about the influence of changes in the soil at the soil-pile interface on strength properties of the soil.
- Recommend how to maximise the shaft capacity of piles augured into the Mercia Mudstone Group.

1.3 Objectives of the Project

The aims detailed above were achieved by:

- Organising a field test where Continuous Flight Auger (CFA) piles were installed so that the soil-pile interface could be observed.
- Observing the soil-pile interface within the soil.
- Varying the pile installation method such that water was added, the auger over-rotated, or both.
- Testing the strength and physical properties of material at the soil-pile interface.
- Carrying out detailed logging and observations of the soil structures and fabric of the soil-pile interface at both macro and micro scales.

1.4 Basic Methods Used in the Project

The aims and objectives of the project were met using the following methods:

- Four test piles were augered into the Gunthorpe Member of the Mercia Mudstone Group.
- The four test piles were augered in a manner which varied the free water during augering, and varied over-rotation of the auger.
- The piles and their surrounding soil were excavated and removed from site.
- Each pile and the soil surrounding it were examined in the laboratory, with particular respect to the soil-pile interface.
- Water content measurements were taken at the soil-pile interface of each pile, and, where possible, at distances of 50 and 100mm horizontally from the pile.
- Microstructures of both remoulded and apparently undisturbed soil were observed using axiocam, thin section and scanning electron microscope techniques.

- Plastic index tests were performed on both remoulded and apparently undisturbed soil.
- The effects of piling upon soil chemistry and mineralogical make up were tested using ICP-AES and XRD analysis respectively.
- Particle size distribution tests were used to test the effect of mechanical breakdown of soils during the piling process.
- Limited strength testing was undertaken to establish key features of the behaviour of the remoulded soil and for a preliminary evaluation of changes in strength properties.

1.5 Terminology

This dissertation relies on consistent description of changes in soil fabric, structure and texture. Soil which has undergone a visible change in fabric and structural properties during pile installation will be referred to as "remoulded". Other descriptive terms used in this dissertation, some of which have specific geological definitions, are given in the glossary.

2 Literature Review

2.1 Introduction

In this Chapter, literature is reviewed to provide a background to the project and discuss the facts and assumptions which underpin the work undertaken. To understand the processes affecting Continuous Flight Auger (CFA) piles both during and after installation, it is necessary to also understand the piling process, and the ground into which the piles are being installed. Hence issues relating to the stratigraphy of the Mercia Mudstone Group and the theory and practice of CFA piling are reviewed.

The initial sections in this Chapter provide background information, with later sections discussing some of the reported problems with piling in the Mercia Mudstone Group. Unfortunately there is very little published information, as most cases are relatively small scale problems which have not merited extensive investigation and consequently are not reported in the literature.

The literature describing the Mercia Mudstone Group has been complicated and confused at times. A recent stratigraphy was published by Howard *et al.* (2008) and has been adopted for this project; however, previous stratigraphies dating back to when the Group was called the Keuper Marl have given rise to some confusion in the literature, especially where authors are not using the current nomenclature.

While the Group was extensively studied in the 1960s, work referring to the engineering properties of the group which is more recent than the mid 1970s is sparse and usually uses the old nomenclature. Published work on the Group with specific references to CFA piling (only introduced into the UK in the 1970s) is very limited.

2.2 Continuous Flight Auger (CFA) piling

Piled foundations are a type of deep foundation commonly used to take heavy loads, especially where soils are weak at shallow depths. Piled foundations are designed to take loads from shallow depths – where soil often has a low confining stress – to greater depths, where soil has a high confining stress. Piled foundations are typically made from concrete, steel or timber.

An applied load on a pile is resisted by the bearing capacity of the soil at the base and friction along the shaft. Piles are usually designed with high factors of safety in order to minimise the settlement of the pile. Atkinson (1993) notes that piles installed in clays tend to settle with time due to the dissipation of excess pore pressures generated by undrained loading of the clay. This causes an increase in the effective stress within the soil. Recent changes in pile design have led to the development of an effective stress approach to piling. This method, referred to as the β method, assumes that the transfer of load from a pile to the soil is mainly controlled by the effective stress in the soil and that the resistance at the toe and friction in the shaft are proportional to the effective overburden stress (Fellinius, 1998).

Driven piles (installed by driving concrete or steel into the ground and, optionally, later filling with reinforced concrete) and bored piles (installed by producing a void into which concrete is set) are both commonly used within the construction industry.

Continuous Flight Auger (CFA) piles are installed using a corkscrew-like auger to displace soil in the ground. Concrete is poured into the resulting hole through the hollow auger stem during removal of the auger. This means that, unlike other bored pile methods, when CFA piling is used there is no point where a gap is left in the soil which is not filled with either the auger or concrete. A schematic diagram of a CFA pile is shown in Figure 2.1.

CFA piling is a rapidly increasingly used technique, with reports that bored and CFA piles make up 50% of the world pile market (Van Impe, 2003). CFA piling was first used in the USA in the 1950s and in Europe in the 1970s (Albuquerque *et al.*, 2005). Fleming (1992) cites the major advantages of the CFA technique as being environmental, with little noise and little vibration during the installation of piles. The use of this technique also means that where the water content of the host soil is high, or water bearing layers are present, there is no need to support the hole during construction with either bentonite slurry or a casing.

The auger used for CFA piling has a width dependant upon the dimensions required for the pile which are in turn dependant on load calculations, and the auger is always screwed into the soil clockwise (Heathcote, 2007).

Due to the mode of installation, various problems may occur during CFA piling. Fleming *et al.* (1992) discussed some common problems encountered during CFA piling, and concluded that the most common problems are due to excessively rapid removal of the auger, causing soil to be carried backwards into the pile shaft, meaning that the upper portions of the pile shaft may become contaminated with soil. Other potential problems with CFA piles listed by Fleming *et al.* are all due to over-rotation of the auger (when the auger is allowed to continue to spin without further gain of depth, either at the toe of the pile or at a shallower depth). In particular, when the auger meets hard beds below water bearing beds this can cause the auger to over-rotate, loosening soil adjacent to the pile and allowing water filled cavities to develop. Excessively rapid removal of the auger affects the integrity of the pile; over-rotation of the auger affects the soil-pile interface. Both issues affect the pile load displacement behaviour but for different reasons.

Hird *et al.* (2008) studied the effects of CFA piling on the soil surrounding the piles. They used a transparent, artificial soil, so the effects of piling could be observed within the ground. Tests varied the vertical speed used to install piles, and the number of rotations of the auger used to get to the toe during installation. It was found that when the auger was normally rotated (i.e. installed with the auger screwing into the soil such that one rotation of the auger pushes the auger into the soil by the height of one flight), ground displacements were negligible. When the auger was over-rotated either ground displacements were small and a self supporting hole was formed, or the soil was pulled onto the auger. The study did not discuss why the two differing reactions to over-rotation occur, or the effects this has upon shaft capacity. It is interesting to note the potential for soil to fall into the auger and, presumably, being subsequently removed by the auger. This may account for some widening of piles noted later in this Chapter (see section 2.10).

The factors affecting shaft adhesion in piled foundations were studied by Anderson *et al.* (1985) who installed piles in the laboratory into beds of kaolin, with voids left at the base of the piles. The piles were left to cure for 7 days and then loaded. It was found that maximum adhesion between the pile shaft and adjacent soil was achieved at settlements of 1% of the pile diameter. It was concluded that such small settlements indicate that soil is presheared during augering, and small movements during settlement are sufficient to activate the residual strength created within the clay by this preshearing.

Anderson *et al.* (1985) also concluded that the horizontal effective stresses within the soil before augering are recovered with time, but that the time required to recover these stresses is dependent on the time taken between augering and filling with concrete. If this time increases then so does the time required for recovery of the horizontal in situ stresses. If this is assumed to be correct, it is consistent with the idea that over-rotated augers which become blocked, and therefore take longer to fill with concrete, may have a poor shaft capacity due to horizontal stresses reducing during the augering process, since the auger cannot provide perfect support to the soil.

2.3 Influence of Host Soil on Shaft Capacity

There are many reasons for over predictions of shaft capacity of piles. Poor adhesion between the pile and soil, poor installation technique or a lack of understanding of the host soil leading to poor calculations of required foundations may all be culprits. Mandolini *et al.* (2005) discussed the effects of the installation technique upon bearing capacity and load-settlement behaviour, and state that the dominant factor in the behaviour of piles is the characteristics of the host soil directly adjacent to the pile, as this controls the degree of cohesion between the soil and pile. They also conclude that the installation of piles directly affects the stress states within the soil, and therefore that the original soil present and the stress states within it are of great importance. Whilst knowledge of the stress history of the host soil is important when designing piled foundations, it is also important to consider the geological history and mode of deposition of a soil as in many cases the mode of deposition of a soil may control its behaviour more than its stress history. Particle size distribution, percentage of clay particles and mineralogy should all be considered important factors during pile design, as discussed later within this Chapter.

2.4 Introduction to the Mercia Mudstone Group

The Mercia Mudstone Group (previously known as the Keuper Marl) is a Triassic age (Arthurton, 1980) deposit covering much of central England, up to the north of England, under Cheshire and down as far as Devon (Figure 2.2). The Mercia Mudstone Group is important in engineering terms as it sits under many major cities within the UK, such as Birmingham, Coventry, Bristol and Cardiff. The deposit is often over a kilometre thick.

During the Carboniferous, plate tectonics caused collisions between the continents, leading to the formation of a supercontinent called Pangaea (OUP, 1983, see Figure 2.3). When the Mercia Mudstone Group was laid down, in the Triassic, England was on the inside of the supercontinent Pangaea, to the north of the Variscan mountain belt (Howard *et al.* 2008). At this time, Pangaea had begun to break apart, leading to the formation of many fault bounded extensional basins in southern, central and north-west England (Warrington and Ivimey-Cook, 1992; Chadwick and Evans, 1995)

During the early Triassic, a monsoonal climate meant that the Variscan mountain belt contained a large river system flowing northwards across what is now southern Britain (Howard *et al.* 2008). This caused thick deposits of pebbly sands to be lain down, forming what is now considered to be the lower part of the Sherwood Sandstone Group (Howard *et al.* 2008). Upper parts of the Sherwood Sandstone Group contain aeolian and fluvial sandstones and show onlapping (see glossary) of the sediments onto the Variscan mountain belt.

These depositional sequences are mirrored in the stratigraphy, giving a sandstone sequence, ranging from pebbly to conglomeritic, deposited in a braided stream system flowing northwards. This facies is called the Sherwood Sandstone Group.

Above the Sherwood Sandstone Group lies the base of the Mercia Mudstone Group. Basal beds of the Mercia Mudstone Group indicate a southerly retreat of river systems in the Variscan mountain belt and an onset of "subaqueous hypersaline and evaporitic mudflat environments" (Howard, 2008; Warrington and Ivimey-cook, 1992) meaning a flood plain which repeatedly flooded with saline water and dried out leaving salt rich deposits. According to Arthurton (1980); Warrington and Ivimey-cook (1992) and Talbot *et al.* (1994), four main modes of deposition are seen within the Mercia Mudstone Group; brackish or saline lakes allowing mud and silt to settle out of water; flash flood resulting in rapid deposition of silt and fine sand; wind blown dust settling on wet mudflats and chemical precipitation of evaporating salts, mainly halite and gypsum. Figure 2.4 shows a schematic diagram of the progression of deposits within the Mercia Mudstone Group and Sherwood Sandstone Group.

In contrast with the Sherwood Sandstone Group below, the sequence of deposits in the Mercia Mudstone Group indicate the climate of the UK becoming drier. As the depositional environment of the Sherwood Sandstone Group switched to the depositional environment of the Mercia Mudstone Group, a complex basin sequence of sabkhas, saline mudflats and temporary lakes developed which evolved southwards, prograding over the stratigraphy of the Sherwood Sandstone Group.

2.5 Mineralogy and Stratigraphy of the Mercia Mudstone Group

2.5.1 Introduction

The stratigraphy of the Mercia Mudstone Group has been examined by a number of authors, for example, Howard (2008) and Warrington (1970). It would be usual in a group as large as the Mercia Mudstone Group for fossils to hold the key to matching up sequences (De Freitas *et al.* 2007; Zalasiewicz *et al.* 1988), but due to the largely afossiliferous nature of the group (Howard *et al.*, 2008) other methods must be used. Warrington *et al.* (1980) proposed that the stratigraphy might be defined using the pollen spores or mineralogy. The high clay content of the Mercia Mudstone Group adds further complications to its engineering properties, due to slurrying (see glossary) of the soil during augering and expansion and shrinkage of the soil with the addition of water or mixing during engineering processes. Hence where mineralogy may be an important key for the stratigraphy of the group, it is also useful to look at this from an engineering point of view.

The stratigraphy of the Mercia Mudstone Group was split into 5 lithostratigraphical units (A-E) by the British Geological Survey (BGS) (Howard *et al.*, 2008). A summary of these units is given below, with specific reference to Unit B (the unit containing all members found at the test site used for field tests reported in this dissertation, Ibstock Brick Pit). Figure 2.5 shows a stratigraphy for the Mercia Mudstone Group of the East Midlands shelf, encompassing the Gunthorpe Member - the member used for the field tests described in this dissertation (Ambrose, 2006). Because the Gunthorpe Member was the member used for field tests, it is this level of the stratigraphy which will be mostly concentrated on after an initial overview of the entire group has been given.

2.5.2 Unit A

This unit is the lowest unit stratigraphically and is comprised of brown mudstone and siltstone interbedded with a variable but approximately equal proportion of pale grey-brown sandstone. Beds are planar, with sandstone beds generally being less than 5mm in thickness and sandstones generally being fine to very fine grained, although occasionally medium grained with a high mica content (Howard *et al.*, 2008).

Gypsum and anhydrite are present within Unit A, but less abundant than in higher units and where present are seen as veins and nodules. Unusually for the Mercia Mudstone Group fossils are also present in the form of miospores, with vertebrate tracks and the brachiopod *Lingulida* also found in some regions (Howard *et al.* 2008).

Unit A is the hardest of the five units to constrain stratigraphically as it is not differentiated in all regions, has a diffuse top and base and is interbedded with the top of the Sherwood Sandstone and the bottom of Unit B (Howard *et al.*, 2008).

Unit A has been given different Formation names, according to which basin it is found within and is known variously as the Tarporley Siltstone Formation, Maer Formation, Denstone Formation and Sneinton Formation.

The base of Unit A (or the Mercia Mudstone Group where Unit A is not observed) becomes progressively younger southwards due to the southerly advancement of the basement through time. (Howard *et al.* 2008)

2.5.3 Unit B

This is the unit containing all the members found within the Ibstock Brick Pit site, and ranges from Anisian (240Ma) (Foster, 1985) to Carnian (228-217Ma)

(Gradstein *et al.*, 2004) in age. The unit contains mainly red, and less commonly, green and grey dolomitic mudstones and siltstones, ranging from finely laminated to structureless. Thin beds of coarse siltstone and very fine sandstone are found throughout the unit, with individual beds typically 2-6mm in thickness, green-grey in colour with a strong dolomitic cement (Howard *et al.*, 2008). Dolomite is a carbonate mineral frequently found in sedimentary rocks.

Unit B may be structureless in some regions due to loss of original fabric caused by frequent wetting and drying syn- and post- deposition causing constant growth and dissolution of salts.

Thick deposits of halite (salts) are found within Unit B, in the middle and lower sections. Geophysical log markers (typically thick beds) can be used to correlate strata within the basins, but not between basins due to the local presence of these deposits which may disturb distinctive patterns within the logs (Howard *et al.*, 2008).

The unit is usually 150-300m thick, but has large variations between basins. In the East Midlands shelf the unit contains the Radcliffe, Gunthorpe and Edwarlton Members, which were downgraded from Formations to Members by Howard *et al.* (2008). These are collectively referred to under the umbrella of the Sidmouth Mudstone Formation, with some inclusions of the Cotsgrave Sandstone Member. The type section of the Sidmouth Mudstone Formation is the South Devon coast between Sidmouth [Grid reference: SY 129 873] and Weston Mouth [Grid reference: SY 163 879].

In the East Midlands shelf the Members of the unit are distinguished only by using "fairly subtle lithological characteristics and partly by using skerry beds as mappable markers" (Chandler, 2001).

The Gunthorpe Member of the Mercia Mudstone Group is predominantly dark red, red-purple or red-brown horizontally laminated mudstones with interlayers of greenish grey mudstones appearing in many areas. This sequence of mudstones also contains fine to very fine grained sandstones and siltstones which are massive or blocky, horizontally cross bedded or rippled. Dolomitic sandstones may also be present and make up hard beds, with some secondary veins of gypsum present (Mader, 2002). The member is a deposit from a series of playa lakes present in the UK during the Triassic, and represents a period where stagnant water bodies in a desert environment characterised the environment, with little in the way of disturbances or flood events. Moving bodies of water were isolated, small and sparse.

2.5.4 Unit C

This unit is differs greatly from other units in the Group, with a contrasting colour and unique lithologies and mineralogy. It is heterolithic and consists of grey and green mudstone interbedded with paler grey-green to buff coloured siltstone and fine to medium grained multi-coloured sandstone with localised pebbly horizons. Invertebrate and vertebrate macrofossils are found, in some areas very abundantly (Howard *et al.*, 2008).

The mineral assemblage is rich in mixed layer clays (meaning that clays are of mixed type with one type of clay fitting into the molecular structure of another type of clay), making it distinct from the units above and below (Jeans, 1978).

The thickness of Unit C is typically only 10m with local variations and is known, amongst other names, as the Arden Sandstone, Butcombe Sandstone Member and, in the East Midlands shelf, Hollygate or Dane Hills Sandstone Members.

2.5.5 Unit D

This unit is superficially similar to Unit B but with structureless red-brown dolomitic mudstones dominating. Halite is present only at the base of the unit, and gypsum and anhydrite are abundant (Howard *et al.* 2008).

The unit comprises the Cropwell Bishop Formation in the East Midlands shelf.

2.5.6 Unit E

This unit is the uppermost unit of the Mercia Mudstone Group and is a laterally unevenly spread layer of structureless, greenish grey dolomitic mudstones and siltstones with thickness varying from under 10m up to 67m thick.

This unit is known as the Blue Anchor Formation in all basins and was formerly known as the Tea Green Marl.

2.5.7 Historical Stratigraphy of the Mercia Mudstone Group

The Mercia Mudstone Group has a long and complicated history of stratigraphical classification and was previously called the Keuper Marl. Warrington (1970) discussed the stratigraphy of the Keuper Marl and a summary is given in this section. Figure 2.6 shows a stratigraphy of the Keuper Marl, including the stratigraphy for the East Midlands shelf. It can be seen that although some of the names and classifications have been changed since this stratigraphy was published (for example, the Harlequin Formation is no longer within the formal stratigraphy), much of the understanding of the group has not changed since the 1960s. The stratigraphy is not split into units as by Howard *et al.* (2008), but it may be presumed from the stratigraphy presented that the present Gunthorpe Member would fall roughly within the Harlequin and Carton Formations presented by Warrington (1970).

The Sherwood Sandstone Group underlying the Mercia Mudstone Group was previously defined as the Bunter Sandstones, with a large discontinuity lying between these sandstones and the mudstones of the Mercia Mudstone Group above.

Warrington (1970) describes the mudstones of the Mercia Mudstone Group as being a deposit from a hypersaline, quiet environment where deposition of very fine silts and clays could occur, tying in with the playa lakes which were known to characterise the UK during this time, in line with the later interpretations of the group by e.g. Howard *et al.* (2008).

2.5.8 Brief Description of Clay Mineralogy

According to Eberl (1984) clay minerals are produced in three main ways: inheritance (minerals are bought in from another area by sedimentary processes); neoformation (minerals have precipitated from solution or formed from reactions with amorphous material); and transformation (an inherited clay which has reacted via ion exchange or layer transformation to change species). These processes are controlled by the environment and available energy during and after deposition. The Mercia Mudstone Group contains clays produced by all three methods.

Clay minerals are formed of two fundamental units, silicon tetrahedra and magnesium or aluminium octahedra. The number and arrangement of these units and the manner in which they are held together defines which clay mineral is produced. Clay minerals may be split into three broad types: high swelling, medium swelling and low swelling. When minerals from the smectite group come in to contact with water they are known to expand rapidly in volume, by a greater amount than the kaolinites, thus making them a high swelling clay mineral (Mitchell, 1993). All three types of clays are known to be found within the Mercia Mudstone Group in varying amounts dependant upon location and stratigraphic formation.

2.5.9 Mineralogy of the Mercia Mudstone Group

The mineralogy of the Mercia Mudstone Group is useful to understand when dealing with the group, as it has a number of diagnostic uses. It is generally accepted that the plasticity and mechanical properties of a soil are influenced by the type, size and abundance of clay minerals present (Dumbleton and West, 1966), with any cements present affecting strength, deformation and susceptibility to weathering. Consequently, the predicted engineering behaviour of a soil is highly dependant upon the minerals present and their textures (presence of fractures, fissures and fabrics).

According to Hobbs *et al.* (2002) the main non clay minerals within the Mercia Mudstone Group are quartz, calcium carbonate, magnesium carbonate, calcium sulphates, micas, iron oxides and halite, with a possible presence of feldspar and other heavy minerals. Abundant clay minerals are illite, chlorite, mixed layer illite-smectite or chlorite-smectite and, less abundantly, smectite.

Figure 2.7 shows a generalised clay mineral composition for the Gunthorpe Member and other members commonly found in the Midlands (adapted from Bloodworth and Prior, 1993). The Figure shows highly variable abundances of illite (approximately 38-82% of the total clay fraction), with no vertical sequences of abundances. Moreover there is a highly variable distribution across the thickness of the Gunthorpe Member.

The abundance of chlorite is low across the Gunthorpe Member, with little vertical variation, and never exceeds 20% of the total clay fraction. Chlorite-smectite abundances are highly variable, with their percentage of the clay fraction varying between a few percent to 60% along one lateral horizon. It should be noted that along the same lateral horizon there was also a large variation in the percentage of illite, but the value for chlorite was only slightly affected.

The percentage of smectite interlayers (common in weathering horizons) in multilayered chlorite/smectite is fairly constant at around 55% for the whole of the Mercia Mudstone Group, except at the top of the group (Unit E) where the percentage rapidly decreases to zero.

Jeans (1976) published a comprehensive study of the mineralogy of the Mercia Mudstone Group and proposed two clay mineral assemblages (see glossary). Of these two assemblages, the first was found in all samples and contained approximately the same volumes of mica and chlorite with some regional variations. The second clay assemblage identified by Jeans (1976) showed a sparse distribution of sepiolite, palygorskite, smectite, smectite/mica, smectite/chlorite, corrensite and chlorite with each mineral appearing in well defined regions, correlated with certain cyclic climatic events.

The assemblages identified by Jeans (1976) have not been commonly adopted by some authors, with Howard *et al.* (2008) not acknowledging them within their work. In contrast, Chandler *et al.* (2001) do make reference to these assemblages, indicating that the authors consider them to be accurate.

2.6 History of the Mercia Mudstone Group

As discussed in section 2.4, the Mercia Mudstone Group was deposited in the Triassic, 250 to 205 million years ago (Forster and Warrington, 1985). During this time, England and much of Europe was far closer to the equator than it is now, the Earth had a hotter climate than at present (Kidder and Worsley, 2004) and what is now the UK and central parts of Europe was covered by a large estuarine system within a desert.

The Quaternary (the current era) is a highly debated period of time, with even the base of this time not being agreed by geologists. It began either at 2.6Ma before present (Bowen and Gibbard, 2007; Pillans and Naish, 2004) or 1.8Ma before present (Hilgen, 1991). During this era much of England was subjected to repeated loading and unloading events, as glaciers advanced and retreated. The furthest south any of these ice sheets reached was approximately at the current location of the M4 motorway. Due to the complex stratigraphy of the Quaternary it is not yet known exactly how many glacial events occurred during this period of time (and therefore how many loading/unloading events affected Ibstock Brick Pit, the field area used for work for this dissertation), but it is known that the area was affected a number of times (Bowen *et al.*, 1986), and therefore will be overconsolidated. Overconsolidation of a soil gives rise to undrained strength profiles which are more or less uniform with depth and which are greater than those of normally consolidated deposits at the same depth, except for those soils found near the surface (Atkinson, 1993). Figure 2.8 shows the stiffness properties for an overconsolidated soil. When a soil becomes overconsolidated, it is because it has had an excess load applied to it, usually due to deposition of soils on top of it, or due to glaciation. The application of this load causes the specific volume of the soil to decrease, however, when the load is removed the specific volume only increases very slightly so and overconsolidated soil behaves differently to a normally consolidated soil.

However, the soil may also have been exposed at the surface and weathered by glacial processes, as discussed by Hutchinson, J. (2001). A weathering scheme for the Mercia Mudstone Group, with grades from I (unweathered) to IVb (fully weathered, matrix only) was suggested by Chandler (1969) and is shown in Table 2.1 and the resulting effect on the shear strength properties given in Table 2.2.

2.7 Local Stratigraphy of the Mercia Mudstone Group in Ibstock

Field work for this dissertation was carried out at Ibstock Brick Pit, Leicestershire. Figures 2.9 and 2.10 are adapted from the British Geological Survey (BGS) map, Leicestershire XXIII, S.E. and give the geological setting of Ibstock Brick Pit. The Figure shows that the brick pit is situated on red mudstone with thin bands of sandstone. To the north and south of the site the mudstone is capped with boulder clay. To the east there are outcrops of skerry sandstone, and faulting is noted.

A visit to the pit in summer 2006 with Keith Ambrose and David Entwistle of the BGS was of assistance in gaining an understanding of the local stratigraphy. Ibstock Brick Pit contains three of the members of the Mercia Mudstone Group (all within Unit B): the Tarporley, Radcliffe and Gunthorpe Members. The Gunthorpe Member sits at the top of the Brick Pit, in the area used for this study (Ambrose, 2006)

According to the formalised stratigraphy of Howard *et al.* (2008), Unit B of the Mercia Mudstone Group should contain red, and sometimes green and grey dolomitic mudstones and siltstones ranging from finely laminated to structureless, with thin beds of coarse siltstone and very fine sandstone. The localised stratigraphy observed at Ibstock Brick Pit is given in section 4.2.1 and can be seen to fit with the formalised stratigraphy for the area.

2.8 Engineering Properties of the Mercia Mudstone Group

2.8.1 Introduction

Within this section the common engineering properties of the Mercia Mudstone Group are discussed, along with some discussion of laboratory tests undertaken on soil samples taken from the group, providing a background to the tests performed during this study.

CIRIA published a report in 2001 on the engineering properties of the Mercia Mudstone Group (Chandler *et al.*, 2001), giving a comprehensive summary of the research to that date, which provided much of the information reviewed in this section.

2.8.2 Index Properties

The dominant lithology within the Mercia Mudstone Group is a red brown silty mudstone, particularly within Units B and D as described by Howard *et al.* (2008). Work by Davis (1967) and others suggests that this mudstone has an aggregated structure. This means that while the mudstone has typically 70% clay minerals, these are strongly bonded together so that a particle size distribution (PSD) test gives a proportion of clay sized particles far smaller than the actual percentage of clay minerals.

Davies (1967) discussed aggregation ratios within the Mercia Mudstone Group, and defined the aggregation ratio as the percentage of clay minerals present divided by the percentage of clay sized particles. It was discovered that in the samples Davies used, the percentage of clay minerals was between 60% and 100%, whereas the percentage of clay sized particles was between 10% and 60%, giving an aggregation ratio between 1.4 and 10. Davies concluded that clays had aggregated into silt sized particles, possibly due to calcite or dolomite cementing.

When the percentage of clay sized particles increases (i.e. the aggregation ratio decreases), the plastic index does not greatly increase, typically rising from 12% at a clay fraction of 15% to 17% at a clay fraction of 50% (Chandler *et al.*, 2001). This suggests that aggregated clays do not have a greater affinity for water and therefore do not split into their constituent clays when in the presence of water alone and so the surface area of the clay does not increase greatly under these circumstances. It can therefore be concluded that the plastic index is not necessarily a good indicator of those properties of the clay which are dependant on particle size.

This theory is to some extent backed up by Atkinson *et al.* (2001). For this study, plastic index tests were performed on samples from the Edwarlton Member. The aim was to investigate the reasons why a tunnel boring machine had become stuck after tunnelling in this member, in a tunnel known as the Abbey Sewer tunnel. The Abbey Sewer tunnel has twice caused problems reported within the literature. The first of these reports was from Myers and Sindle (1994) who noted that groundwater leaking into the tunnel caused the spoil to become "sticky". This problem was overcome by using compressed air during tunnelling. In the second of these reports Atkinson *et al.* (2001) proposed that the mudstone in this formation of the Mercia Mudstone Group had aggregated into silt sized clumps during deposition due to being blown across the desert prior to deposition. They further proposed that the observed sudden change in plastic properties of the mudstone which caused problems with the tunnel boring machine at Abbey Sewer was due to destructuring and disaggregation of this aggregated clay within the host soil due to the high pressure created during tunnelling.

A field trial performed by Atkinson *et al.* (2001) tested the comparative index properties of material taken from the Edwarlton Member, and soil taken from another member, taken from Ibstock Brick Pit (see Figure 2.11, note that the member name was not recorded in this paper). The samples from the Edwarlton Member (the same member as the Abbey Sewer slurried material) showed a greater proportion of smectite clay than the comparable samples taken from the un-named member. Both sets of samples were disaggregated by mechanical methods, by passing through a meat mincer. When passed through the mincer at a water content close to the plastic limit, the Edwarlton samples disaggregated and the liquid limit was raised by approximately 30%. Should such disaggregation occur in situ this will cause the soil to swell, as is postulated to have occurred in the Abbey Sewer tunnel, leading to clogging of the screw conveyor in the earth pressure balance tunnel boring machine. The samples taken from the un-named member from Ibstock Brick Pit did not show an equivalent increase in liquid limit when treated in the same fashion, giving an increase in liquid limit of approximately 12%, far smaller than observed in the Edwarlton samples (see Figure 2.11).

Unlike Atkinson *et al.* (2001), the experimental methods used in the CIRIA study (Chandler *et al.*, 2001) were not designed to break apart aggregations of silt sized lumps of clay in such a vigorous manner. Chandler *et al.* (2001) indicated that 10 minutes mixing was sufficient to achieve disaggregation, while Atkinson *et al.* (2001) suggested that, for smectite rich soils, passing through a meat mincer 20 times was required to achieve the correct disaggregated plastic limit. However, it is agreed between the two studies that some working of the Mercia Mudstone Group is required to break apart aggregations within the soil to achieve the true plastic index, and therefore that some modifications to traditional index property tests are required. Due to this, care should be taken when working in the Mercia Mudstone Group as measured index properties may not relate to the engineering properties of the in situ soil as closely as may be expected.

This unreliability of traditional classification tests used to characterise the Mercia Mudstone Group was also noted by Sherwood (1967), where it was observed that the cementing of particles produces anomalous results when classification tests are applied to the Mercia Mudstone Group.

Sherwood (1967) goes on to show large apparent differences between clay percentages obtained for the same samples when using 2 different experimental methods (traditional particle size distribution (PSD) methods and X-ray analysis), with the variation in values was as high as 68%. Traditional PSD methods show only the particle size, and therefore where aggregate clays are present, will give a misleadingly small value for the clay fraction. XRD tests will give the true percentage of clays whether aggregated or not. A series of plastic index tests were then performed on samples taken from the Mercia Mudstone Group to examine how long was required to work the material before it reached the maximum values of plastic and liquid limit, with results showing that the highest values for the plastic index were achieved after only 10 minutes of working, as per British Standard BS 1377:1990 and consistent with the results of the CIRIA study (Chandler *et al.*, 2001).

Like the CIRIA study (Chandler *et al.*, 2001), the results of Sherwood (1967) are in stark contrast with the results of Atkinson *et al.* (2001), where passing through a meat mincer was required to obtain the ultimate values of both liquid limit and plastic limit. Without being able to accurately compare the locations of the soil samples tested in the two papers, it would be impossible to state how similar the two sets of samples were. However, since the Atkinson *et al.* (2001) study found that samples removed from the un-named member of the Mercia Mudstone Group (the member that did not cause problems at Abbey Sewer) did not achieve such high liquid limits as the sample from the Edwarlton Member it may therefore be reasonably suggested that the Sherwood (1967) study used samples taken from strata which were not highly aggregated or were of a different clay mineralogy.

Sherwood (1967) concluded that the aggregating agent within the samples taken from the Mercia Mudstone Group was silica. This was assumed by working out the silica/sesquioxide ratios expected from the clay and quartz contents, and comparing with chemical analysis. If this assertion is correct, it fits with Sherwood's observation that the cementing agent within the Group does not dissolve with chemical treatment as silica is highly resistant to weathering and chemical attack.

2.8.3 Summary of Index Properties of the Mercia Mudstone Group

The index properties of the Mercia Mudstone Group are debated amongst authors and a summary is shown in Table 2.3. It has been agreed that samples from the Mercia Mudstone Group taken directly from the ground do not show index properties indicative of the actual clay content and that these properties are therefore not necessarily representative of how the soil will behave when subjected to engineering work practices. It is also agreed that the Mercia Mudstone Group contains silt sized aggregates of clays within its structure, and that these aggregates may be broken by engineering processes. It is debatable, however, how much force is required to break the bonds creating the aggregates, with authors citing any value from 10 minutes of mixing to passing through a meat mincer 20 times at the plastic limit. It is likely that the degree of aggregation within different members of the group (as discussed in Atkinson *et al.* 2001) is highly variable, and therefore that the differences in behaviour observed within the group may, in part, be down to the degree of aggregation in a given sample.

2.8.4 Shear Strength Testing

According to Chandler *et al.* (2001), due to the fissile nature of strata within the Mercia Mudstone Group, it is best to take samples from boreholes as this gives ready made intact circular samples and reduces the likelihood of breaking during creating a sample.

Chandler (1968) describes both drained and consolidated undrained triaxial compression tests on partially weathered Keuper Marl from Erdington, Birmingham. During these tests it was noted that the failure mechanism often formed diagonal shear surfaces, Gannon *et al.* (1999) discuss which types of triaxial tests are most appropriate. They comment that where friable soils are tested, if insufficient care is taken in preparation of these samples, they may accidentally be tested unsaturated. Once saturated, the strength may be affected by induced pore pressures not allowing sufficient consolidation of the sample, and fissures may remain air filled. It is therefore suggested that to obtain the most accurate results, saturating samples at the in situ stresses is the most reliable method.

Omer *et al.* (2002) performed a number of pile tests on Mercia Mudstone Group and describes pile tests on 5 bored piles 30m deep in the Mercia Mudstone Group around Cardiff (specific location and therefore a Formation/Member name were not given). Piles were settlement tested, and one pile built with a soft toe to test shaft friction. Tests showed a significant variation in pile stiffness; thus load transfers may vary greatly from pile to pile. Results also indicated that the Mercia Mudstone Group in South Wales had a greater strength than observed for other Mercia Mudstone Group locations around the UK, and that where settlement increased beyond the point of maximum shaft resistance it was possible for shaft resistance to decrease to the residual value. These observations lead Omer *et al.* (2002) to state that current design methods are conservative for this area of the Mercia Mudstone Group and to suggest the implementation of new design methods.

The work by Omer *et al.* (2002) gives an interesting insight into the variation of engineering properties within this Group and highlights the need for further testing of the Mercia Mudstone Group and publication of the results from around the UK.

2.8.5 Summary of Shear Strength Testing

Summaries of the strength properties are given in Table 2.4. All authors agree that testing of the Mercia Mudstone Group is difficult to do accurately due to the fissile nature of the in situ soil. Care must be taken when sampling soils for strength testing, to avoid accidental undrained testing due to improper saturation of samples during consolidation and the inclusion of air in the sample.

2.9 Piling in the Mercia Mudstone Group

2.9.1 Introduction

The Mercia Mudstone Group is a laterally extensive deposit underlying many of the major cities in England and Wales such as Birmingham, Coventry and Cardiff. Therefore an understanding of past case histories of piling in the Mercia Mudstone Group is important when designing piles.

It is a widespread view within the industry that problems which occur in the Mercia Mudstone Group may be linked to deposits with unexpectedly high gypsum contents.

2.10 Case Histories of Piling within the Mercia Mudstone Group

In the case histories discussed by the authors of the CIRIA report (Chandler *et al.*, 2001) settlements occurred relatively rapidly, with full settlements appearing during or soon after the construction period.

Foley and Davis (1971) described two pile tests on friction piles in the Mercia Mudstone Group at Leicester. While the stratigraphy of the site is not described in the paper, the location indicates that the site probably fell within Unit B or Unit C (as described in section 2.4). The site investigation described the ground conditions, with the Mercia Mudstone Group appearing 3.05-4.57m below the surface. The mudstone on site was a firm reddish-brown clay with harder bands within, extending down to 15.24m. Below 15.24m it was noted that a large increase in strength was observed. Piles were drilled using a clay cutter with a tripod rig and were left open overnight before pouring concrete. It should be noted that piling using a tripod rig is a highly different technique to piling using the CFA method, and therefore while this study does have some relevance to the work presented in this dissertation it is not an entirely fair comparison. The process of tripod piling takes longer and is less accurate than that of CFA piling and thus some of the results discussed in this section may have been affected by this lack of accuracy. The piles had a nominal diameter of 0.61m but after excavation, the measured diameter of the piles in the top 6m was 0.76m and 0.81 respectively, showing an increase in diameter in the piles over that which was predicted. It is unclear why piles would be of greater diameter than expected, but may have been due to softening of the ground surrounding the pile shaft allowing concrete to expand laterally or due to inaccurate drilling caused by use of the tripod piling technique.

This is directly in contrast with piles monitored by Leach *et al.* (1976) where piles were installed using a continuous flight auger at a length of between 6.37 and 8.98m and a diameter of 740mm and showed a disturbance of 10 to 20mm in the shaft wall. A friable zone of 10-20mm was observed around the pile shaft which was surrounded by remoulded clay of 3mm to 6mm which was visible to the naked eye. Both piles were installed to test the validity of design assumptions with one pile constructed with a soft toe (i.e. not fully concreted to the toe of the pile shaft, so no load could be taken by the base of the pile, see Figure 2.12) to test only the shaft capacity, and the other pile constructed to test shaft capacity and end bearing. Both the pile installed to test shaft friction, and the pile installed to test shaft and toe friction showed a remoulded zone around the shaft of the pile. Shear box and consolidated undrained triaxial experiments were performed on undisturbed samples and samples recompacted to their original densities and moisture contents to mimic the effects of remoulding of material surrounding the pile. The effective stresses recorded from these tests showed a significant reduction of c' but little change in ϕ' in the recompacted samples (see Table 2.5). A graph explaining c' and ϕ' is shown in Figure 2.13 and shows that c' is given by the intercept between the y axis and the critical state line, and that ϕ' is the angle from horizontal of the critical state line.

In another case study presented by Leach (1976), tests were performed on piles installed to determine the shaft resistance of piles installed in the Mercia Mudstone Group at Kilroot, Northern Ireland. Due to not giving a precise location of the site it is not possible to compare this Mercia Mudstone Group site with the one used in this dissertation. Three bored piles (specific technique not given) were installed, with two piles left with a gap at the toe under the concrete so only shaft capacity could be assessed. In all three piles, the Mercia Mudstone Group was reached at a depth of between 6.37 and 7.60m and all piles were loaded after a period of 6-10 weeks. The two piles installed with an air gap at the base showed highly variable shaft resistances, with pile A installed in Zone 2 marl (see section 2.5 for weathering profile) giving an ultimate resistance of 250-280kN/m^2 and pile B, in weathering zones 3 and 4 having almost half the shaft resistance at 150-180kN/m^2. This shows that the shaft resistance of piles in the Mercia Mudstone Group is highly dependant upon the weathering grade of the soil, and that despite being on the same site, highly localised variations in geology can have a large effect upon the capacity of piles.

Meigh (1976) discussed the Triassic rocks of the UK, and in particular engineering within the Mercia Mudstone Group. One example presented was the settlement of three bridges in the Leicestershire area, close to the field area for this dissertation. Two bridges were large and heavily loaded, with the third being long but with little load. All three bridges had small settlements, ranging from 10-14.5mm. Site work here showed that due to the high variation in stiffness of individual beds (clays and silts), the pressuremeter modulus values were not reliable and could not be matched to the Birmingham mudstone modulus profile (K_z = 4MN/m^3) by the author. This once again indicates that the Mercia Mudstone Group is not homogenous with respect to engineering properties, indicating a requirement for individual site investigations combined with geological study.

2.10.1 Summary of Case Histories within the Mercia Mudstone Group

There have been very few case histories of piling within the Mercia Mudstone Group reported in the literature since the mid 1970s. The case studies presented illustrate a complex picture of the properties of the group, with no consistent strength and shear properties for this soil. The high variability of the hardness of the beds, and differences in the degree of weathering appear to be two factors contributing to the large range of values for the soil properties.

The greater than expected pile diameters noted by Foley and Davis (1971) pose an interesting question about the nature of the contact between the Mercia Mudstone Group and the pile shaft. Expansion of the pile shaft further into the soil than had been drilled may be explained by the fact that the hole was left overnight after augering and before infilling with cement. This would have given time for the soil directly surrounding the shaft to have broken away and fallen into the hole during this time, meaning that the soil directly surrounding the pile shaft was poorly attached to the surrounding soil, or possibly that there was a weakness within the soil away from the pile shaft. Sadly a lack of literature in this area means that it is not possible to establish whether this is a one off incident, or a common occurrence for piling in these and similar soils.

Other papers reviewed describe a common theme of piled foundations on the same site having distinctly differing strength and settlement characteristics. This leads to the conclusion that the Mercia Mudstone Group has very different engineering properties both laterally and vertically, due to its variable weathering profile and highly varied modes of deposition. Few authors have explored the idea of disaggregation of the clay minerals occurring during installation of the piles as an explanation for the variable engineering properties observed within the Mercia Mudstone Group.

2.11 Discussion of the Soil-Pile Interface

Baxter (2006) surmised that during installation of piles, the soil adjacent to the pile will be remoulded, and residual shear planes produced. He further surmises that the soil outside this remoulded zone will be displaced and strains will be similar to those developed within a cylindrical cavity expansion. Randolph (2003) describes such remoulding around a driven displacement pile, but does not state the effect that these disturbances had around the pile, or the appearance that the disturbance takes – in fact no record has been found by this author which describes the appearance of such disturbances. Due to the mode of installation Continuous Flight Auger piles will cause less displacement than driven piles.

The problem of remoulding of soil around piles in mudrocks is well known within the industry but has generally not been well reported in the literature due to issues of legality and public relations. As a result, first hand descriptions of excavations of failed piles are rare in the literature. However, a number of projects where problems have occurred have been raised in personal communication with the industry during the course of this research. Consequently, smearing and remoulding are very poorly understood as a process within geotechnical engineering, both from an academic and an industry perspective.

Studies of soil behaviour at the soil-pile interface are limited and have concentrated mainly on engineering properties, forgoing information on textural and mineralogical behaviour. Leach *et al.* (1976) mentioned a 3-6mm remoulded clay layer around the soil-pile interface in the Mercia Mudstone Group without giving specifics on texture and appearance.

The soil-pile interface was studied in the London Clay by Skempton (1959) and Pellew (2002). Skempton (1959) reported a reduction in adhesion of the clay to the pile shaft caused by softening of the clay at the soil-pile interface. Skempton also quotes results from Meyerhof and Murdock (1953) who found an increase in water content of nearly 4% directly adjacent to the shaft of a bored pile at a site in Southall. Meyerhof and Murdock (1953) noted that when moving away from the shaft by 3 inches the water content had already dropped to the value found in the rest of the site. Pellew (2002) studied the soil-pile interface in the London Clay and described a strong crust of remoulded clay surrounding the piles varying from 5-20mm in thickness and appearing to be 5-10 times stiffer and more brittle than the host soil. These observations indicate that remoulding of clays at the soil-pile interface is not a problem that only occurs in the Mercia Mudstone Group, but also occurs in other clay rich soils.

A similar study was performed by O'Neil and Reese (1972) on bored piles in the Beaumont Clay, a stiff clay in Texas, USA. Four piles were augered: S1 was 7.01m long and was cylindrical, S2 was 7.01m long and belled at the base to a diameter of 2.28m, S3 was 7.01m long and had a vented void below the base and S4 was cylindrical, 14.02m long and augered under a bentonite mix. A series of unconsolidated, undrained triaxial compression tests were performed to obtain the strength profile of the soil at the soil-pile interface. It was discovered that pile S4 did not mobilise as much of the shear strength as the three dry piles, which all had consistent peak α values (see Figure 2.14). It was also noted that shear stresses in the soil surrounding this pile were less than those around the other three piles for the top 7.55m, suggesting that the use of bentonite mix reduced the shear stresses surrounding the pile. Water content tests were also taken during this test and results showed that water contents varied significantly from those of the host soil at approximately 19mm from the piles shaft, however, the greatest increase in water content was seen approximately 1.8m from the base of the pile. It was unfortunate for these tests that not all four piles were the same length, as some of the differences in strength profile could, in part, be down to this.

Chandler (1968b) surmised that deformation around a loaded pile is probably in the shape of a narrow cylinder of clay surrounding the pile shaft, which is subject to simple shear during installation of the piles and the initial increase in water content (as discussed above) causes a reduction in the strength of soil directly adjacent to the pile, followed by an increase in strength during the consolidation process. To test the strength of the remoulded material, consolidated undrained triaxial tests were preformed on undisturbed and remoulded material in the London Clay. In these tests, remoulded clay was simulated in the laboratory (process not discussed) and covered in wet muslin for four days to rehydrate before testing. Chandler (1968b) concluded that the effective stress parameters obtained for the remoulded, softened specimens are c'=33.216g/cm^3 (124.56 g/cm^3 in undisturbed samples), ϕ'=21.5^o (22.5^o in undisturbed samples) showing that softening and remoulding reduces c' considerably without markedly influencing ϕ'.

2.11.1 Summary of the Soil-Pile Interface

It has been noted in the literature that a zone of disturbance surrounds piles augered into clay rich soils. However, descriptions of such disturbances and their strength properties have never been properly reported. This leads to some confusion when analysing poorly performing piled foundations.

All authors discussed in this section note the presence of a remoulded zone of clay surrounding the pile shaft of up to 20mm in diameter. This has been noted in various types of clay from the London Clay in the UK to the Beaumont Clay in Texas, USA. Studies have not successfully quantified the effect of this remoulding upon shaft capacity of piles.

2.12 Summary of Literature Review

The literature review above has covered the following points:

- The Mercia Mudstone Group is a laterally extensive deposit which is highly variable both laterally and vertically.
- The Mercia Mudstone Group has a high clay content, with the species of mineral present within the clay fraction at a given site highly variable.
- Due to the mode of deposition of the Mercia Mudstone Group, clay minerals may be aggregated into silt sized, cemented particles.

- Aggregated particles may be split apart using force, but the level of force required to do so is the subject of debate (Atkinson *et al.*, 2001; Chandler *et al.*, 2001).
- The engineering properties of the Mercia Mudstone Group are highly variable.
- The soil-pile interface in various clay rich soils has been recorded to have a layer of remoulded clays, with the properties of these clays poorly understood.
- Continuous Flight Auger (CFA) piling is a commonly used technique, which has the advantage of never leaving an open hole in the ground during installation, making it an appropriate technique for use in sands and clays, where infilling of water or caving may cause problems.

3 Methods

3.1 Introduction

In this chapter the methods used to investigate the aims laid out in Chapter 1 are described. Laboratory observations were taken to give an overview of the soil-pile interface and to show macrotextures. Microscopic techniques (axiocam, thin sections and scanning electron microscopy [SEM]) were used to examine microtextures of the soil by picking representative samples from the soil to examine.

X-ray diffraction (XRD) techniques were used to test whether action of the auger causes alteration or concentration of certain minerals, and also used in conjunction with inductively coupled plasma (ICP) techniques to test for the presence of a cementing agent, and to test soil-concrete interaction.

Plastic index and particle size distribution (PSD) tests were used to assess the degree of destructuring of aggregations of clay at the soil-pile interface, with triaxial tests used to give an idea of the strength properties of the soil.

3.2 Field Tests

A full scale field trial was performed in summer 2007. The aim of the field tests was to better understand the changes that occur in soil adjacent to Continuous Flight Auger (CFA) piles. The piles were installed using four different methods (see section 3.4). In order to examine in detail the affects of interactions between concrete and the host soil, textural changes of the soil at the soil-pile interface and the effect of the piling process upon the host soil. Sections of the piles and surrounding soil were excavated between 7 and 10 days after installation.

3.3 Test Location

The test piles were located at Ibstock Brick Pit, Whitehall Road, Ellistown, Leicestershire, UK [Ordnance Survey grid reference: SK 416 109] courtesy of Ibstock Brick and John Kailofer. Figures 3.1 and 3.2 are Ordnance Survey maps showing the location of Ibstock Brick Pit. Piles were installed in the most accessible part of the brick works as indicated in Figure 3.3, in the Gunthorpe Member of the Mercia Mudstone Group.

Ibstock Brick Pit was chosen as the location for the test as it was easily accessible from the M1 for both staff and heavy plant required for tests and because the owners were prepared to allow piles to be cemented and removed. From a geological perspective Ibstock Brick Pit also contained the stratigraphic member of the Mercia Mudstone Group chosen to host the tests – the Gunthorpe Member. The Gunthorpe Member was chosen as it sits within the middle of the group and has representative characteristics of the Mercia Mudstone Group. While finding a location within the Edwarlton Member was considered, it was decided that a more representative member should be chosen rather than installing the piles in a member already known to cause problems – this would be a case of testing the exception before understanding the majority of cases. Following fact finding trips in 2006 and 2007, it was found that Ibstock Brick Pit has a relatively uniform geology, thus keeping variables between test piles as low as possible.

3.4 Installation of Piles

The piles were all installed on 26th June 2007 between 13:00 and 16:00. Four test piles 5500mm deep and one practice pile 2000mm deep were installed using a Casagrande B125 rig in Continuous Flight Auger (CFA) mode. The concrete was a C28/35 strength structural concrete with a pumpable mix (the concrete specification is included in Table 3.1 and the rig shown in Figures 3.4 and 3.5). All piles were 350mm in diameter.

It was intended that each pile should be installed using different method as follows:

- Pile MR1 was to be installed without the addition or removal of water and the auger over-rotated at the toe for 10 minutes during installation.
- Pile MR2 was to be installed without the addition or removal of water and without additional rotation of the auger at the toe.
- Pile MR3 was to be installed with water added and the auger over-rotated at the toe for 10 minutes during installation.
- Pile MR4 was to be installed with water added and without additional rotation of the auger at the toe.

The practice pile was installed normally and was used to practise excavation techniques. A schematic diagram showing the order in which the piles were installed is given in Figure 3.6.

There had been heavy rain in the quarry area in the week preceding pile installation during flooding events in the UK in summer 2007. Adverse weather conditions were experienced on site during both pile installation and excavation, which affected the smooth running of the planned activities with hiatuses in work occurring especially frequently on Tuesday 3rd July, the first day of pile excavation (see next section).

SIRUS (Stent Integrated Rig Instrumentation System which records information during pile installation) logs were recorded for all four piles and a summary of these included within Table 3.2. Unfortunately due to weather conditions and the nature of the tests being undertaken some deviations from the planned work method occurred. These are listed below together with other observations from the pile installation:

1. The SIRUS logs show that pile MR1 was disrupted at the toe due to a blockage in the auger not allowing cement to flow, which causd a 30 minute pause in activities.
2. Table 3.2 shows that pile MR1 required 40 less revolutions to reach the toe than the other three piles, which all required an approximately constant number of revolutions of between 160 and 165.
3. The time and rotations taken for the over-rotation of the auger at the toe was not constant. For pile MR1 the auger was rotated for 6 minutes 21 seconds and 202 revolutions, whereas for pile MR3 the rotation was for a greater amount of time, 7 minutes 51 seconds, but with only 133 revolutions at the toe.
4. The amount of concrete needed was roughly constant for piles MR2, MR3 and MR4; with pile MR4 using $0.07m^3$ (or 10%) less than the other two. Significantly more concrete was used in concreting pile MR1 (60% greater than used in piles MR2 and MR3) due to removal of the blockage within the auger.
5. It was not possible to monitor and record the exact amount of water added to the shafts of piles MR3 and MR4. The procedure was that a garden hose was used to add water at a constant rate during pile augering and rotation of the auger at the toe, a period of between 7 and 15 minutes.
6. There was a gap of approximately 2 hours between installation of pile MR3 and pile MR4 due to the need to wait for a concrete delivery. This was due to the supply of cement needing to be restocked after the overuse of concrete in pile MR1 due to removal of the blockage. There was also a 20 minute intense rainstorm between the installation of pile MR3 and pile MR4.

3.5 Excavation of Piles

Sections of the piles and surrounding soil were excavated over a period of four days between 3rd July and 6th July 2007. The planned method for the excavation process is given below:

1. A hook was to be drilled into the top of the pile.
2. A backactor with a 600mm wide bucket was to excavate a trench 500mm deep around all four sides of the 650mm x 650mm sample.
3. Industrial cling film (Stretchwrap), was to be immediately wrapped around the 650mm x 650mm x 500mm sample.
4. The sample was to be further wrapped in polythene.
5. A diamond wire saw was to be used to cut a horizontal plane at 500mm depth. Water from the wire saw was to be controlled so as not to cause a hazard.
6. Polythene was to be placed on the base and sides of a 900mm x 900mm x 700mm sample box constructed from plywood. Enough polythene was to be left on one side to be folded over the top of the sample after placing in the box.
7. The backactor was to be used to lift the block sample into a sample box.
8. Once the sample was placed in the centre of the sample box, the void around the sample was to be immediately sealed at the base of the sample with expandable foam. The excess polythene was then to be placed over the top of the sample, more expandable foam placed on top of the polythene, and then the lid to the sample box secured (a diagram is shown in fig. 3.7).
9. The top of the box was to be secured using vertical nails and the sides secured using horizontal nails, so that the box could be taken apart in the lab without being lifted.

This process was to be repeated for all 4 test piles, such that 4x 500mm sections of soil and surrounding soil were retrieved from each pile giving 16 sample boxes. Upon completion, all 16 boxes were to be transported to City University London.

As with most field tests, the reality of performing the tests meant that some adjustments to the method were made. In particular, the backactor did not prove to be a very precise excavation method, especially in the very hard and layered mudstone where it was impossible to make sure that every section of soil and pile excavated was exactly 500mm long. It was found that when a section of the order of 500mm in length was taken, this made it more likely that the soil would become detached from the pile when the sample was lifted out of the trench. Therefore, there was a trade off between excavating sections long enough to obtain results from the whole pile and recovering enough soil from around each section of pile to make it possible to draw valid conclusions (Figure 3.8 shows a photograph of the excavation process).

After excavation of trenches created a soil-pile sample, a hole was drilled in the top of the pile section using a hand drill and a hook secured. The section was covered using at least 10 layers of Stretchwrap to hold the soil onto the pile during removal from the trench and subsequent transport.

The base of the sample was then cut using a diamond wire saw and lifted into the plywood box using the excavator bucket of the backactor. Use of water while using the diamond saw was kept to a minimum. A plywood box filled with concrete was used to provide a reaction for the diamond saw.

The diamond wire saw worked by placing a loop around the sample and tensioning to cut through the sample. Due to the conditions this cut was rarely horizontal, often at an angle of approximately 10^{o}.

On some occasions soil samples became detached from the pile before Stretchwrap was placed. If these samples were deemed sufficiently large to be of use in later tests they were kept. If the location of the sample before becoming detached was known, the sample was separately wrapped in Stretchwrap and stored in Tupperware boxes in the cabin on site, to be bought back to City University London.

Because samples were neither as long nor as wide as had been predicted, for reasons discussed above, securing the samples by filling in the voids using expanding foam was not viable. To overcome this problem, the stretchwrapped samples were lowered into the plywood box and into a plastic brick bag. The plastic brick bag was then secured around the top of the sample, and expanding foam used to secure each sample at the base only. To secure the top of each section of pile, further brick bags were used as padding to fill in the gaps.

Once the sample had been secured, the top of the plywood box was nailed on and the box covered using a plastic brick bag. The boxes were stored on site at the Brick Pit for up to 6 days before being transported to City University London.

3.6 Transport of Piles from Ibstock to the Laboratory

On Monday 9th July 2007, the boxes were picked up and secured to the back of a lorry and transported to City University London. Once at City University London boxes were removed from the lorry and taken to a laboratory storage area using a winch and trolley. The boxes were unpacked one at a time in a temperature controlled research laboratory.

Samples were stored in the research laboratory until the last box was unpacked in September 2007. Consequently, samples were left for between one week and two months before being opened. The only visible consequence of leaving the samples for this length of time was that one sample (MR4, 0-451mm below ground level) had developed mould, and due to this and the time left before measuring there would be a possible effect on measured water contents as discussed in section 4.7.2.

While it is recognised that the methods of moving samples from Ibstock Brick Pit to City University London left room for boxes to be dropped or shaken, no evidence of this occurring (such as samples tipped onto their sides) was observed during unpacking of the boxes.

3.7 Laboratory Tests

The aim of retrieving samples for detailed examination in the laboratory as opposed to examining on site was to avoid the adverse effects of poor weather conditions, lack of time and difficult access and to give a close proximity to experimental equipment.

To avoid samples being left too long before being processed, water contents were taken as boxes were unpacked and samples for the inductively coupled plasma (ICP) tests and X-ray diffraction (XRD) tests were processed on a fortnightly basis during the unpacking process. Samples to be viewed under the microscope were stored in as large a bulk sample as possible in a temperature controlled laboratory to avoid disturbance of textures and drying out. All other samples were processed once the unpacking process had finished.

3.7.1 Opening of Boxes

On being moved to the research laboratory, the plastic brick bag covering the storage box was removed. The top and sides of the box were then removed by unscrewing the top followed by the sides and discarding the plywood, leaving the section of pile and soil on the wooden base of the box. Expanding foam was cut from the base of the pile, and the top of the plastic brick bag cut away. The pile was photographed from both sides before removing the Stretchwrap. The Stretchwrap was removed slowly and gently, taking care not to dislodge any lumps of soil. The pile and surrounding soil were then photographed. Samples were removed from the pile, where possible, by breaking at the soil-pile interface by hand. Where this was not possible a sharp knife was used to tease open the

soil-pile interface. Large pieces of soil still attached to the pile were split into manageable sizes (no larger than 30cm^3) by cutting using a sharp knife before being removed from the pile shaft. After a soil sample was removed from the pile shaft, the distance from the lowest point of the sample to the base of the pile section was recorded, so a depth could be calculated at a later date.
After all soil had been removed from each pile section the largest and smallest height of the pile was measured. As noted earlier, the variations in height of pile sections from one side to the next add an unfortunate zone of error when calculating depths that samples were removed from. However, it is possible to minimise this error by estimating how the pile sections fitted together in the ground, and best attempts have been made to do this.

3.8 Axiocam Microscopy

The axiocam technology is primarily a palaeontological tool, used in analysing small differences in animal morphology, consisting of a binocular microscope with a highly powerful camera attached.

In this study, the axiocam was used to observe in greater detail the textures seen with the naked eye, and to ascertain the composition of the green silt aggregates discussed in section 4.4.

Samples were viewed under a Leica Binocular microscope and photographs taken with a Leica camera using a Planapo 1.0x Leica lens as shown in Figure 3.9.

Samples were removed from the remoulded and undisturbed zone of each pile, with at least one sample from each pile. Samples were broken down to a size of no taller than 2cm^3 by splitting by hand or with a sharp knife to give a fresh surface shortly before placing under the microscope. Samples were photographed in plan view and vertically, perpendicular to the pile.

3.9 Thin Section Microscopy

Thin section microscopy is a commonly used method for the analysis of soils, rocks and concretes. It is primarily used for petrology (the identification of minerals) and observation of textures. Examples of the use of this technique are widespread, with some notable examples being found in Oyen (2001); De Rooij *et al.* (1999); Tellam (1999) and Hesselbo *et al.* (1997).

Eight thin sections were prepared, each with a thickness of 0.03mm. Samples were prepared from within the remoulded zone of the soil, with one thin section prepared as a plan view of the remoulded zone, and another section prepared allowing the soil fabric to be observed from a vertical perspective, from each of the four test piles.

Samples were prepared using a petropoxy 154 epoxy resin to impregnate the soil chips on a hotplate. Once the resin had set, fixed abrasive silicon carbide discs were used to grind the chips flat. When the flat chips had reached a thickness of 0.03mm Loctite 358 ultra violet resin was used to stick the chips to the glass slides and to attach the coverslips.

The finished thin sections were observed both through a hand lens and a light reflected microscope. Scanned sections were taken of each slide using an HP3210 scanner.

3.10 Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) is a highly powerful microscopic technique used to view samples at the grain scale. The Philips XL30 SEM used for this study has an image resolution of 3.5nm, meaning that exceptionally highly detailed pictures may be taken. Examples of where SEM has been used to look at soil microfabric include Collins and McGown (1974) and Hurst (1999).

Samples of less than 1g in weight were removed from a 30cm^3 bulk sample using a wooden toothpick and mounted onto stubs with the fresh surface facing upwards using an Araldite adhesive and dried in an oven at 30^{o}C overnight. After drying, samples were coated in gold to a thickness of 20µm using a Cressington 208HR sputter coater. Three SEM stubs were created from each 30cm^3 bulk sample.

Once coated, samples were removed from the coater using tweezers and placed within the chamber of the Philips XL30 scanning electron microscope (SEM). Once in the SEM, the chamber was pumped to vacuum and the stage set to a distance of 10.0mm. A photograph of the equipment used is shown in Figure 3.10.

Samples were photographed at magnifications of 150x, 500x, 1500x, 5000x and 10,000x where appropriate.

3.11 Water Content Tests

Water content tests were performed to ascertain the amount of water existing within pore spaces in the soil. This does not take account of water within the crystal structure of the minerals present within the soil. The pore water can be removed by drying in an oven at 100-110^{o}C and is expressed as a percentage of the mass of the dry soil.

Water content tests were performed according to British Standard BS1377: Part 2 (1990) and are also described by Head (1980). Samples were taken, where possible, every 100mm vertically up the pile, at the soil-pile interface, and at 10mm, 50mm, 100mm and 150mm horizontally away from the pile on a plane perpendicular to the pile. Samples were typically 10g in weight before drying and, where possible tests were repeated three times.

3.12 Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES)

ICP spectrometry is a highly powerful chemical analytical technique. The two advantages of the technique, as discussed by Thompson and Walsh (1983), are the ability to perform simultaneous multi-element analysis and the small amounts of sample required. Samples are dispersed into a stream of argon gas through a nebuliser and are carried to the ICP machine. Within the ICP, sample atoms are excited causing them to lose electrons. As these electrons are regained, the sample atoms emit photons of light with element characteristic wavelengths. A spectrometer is used to separate the light emitted into the various wavelengths and these are detected and recorded simultaneously using a solid-state detector (Thompson and Walsh, 1983).

Samples were ground to a particle size of $<250\mu m$ using a porcelain pestle and mortar (sufficient to break aggregations down to a diameter of $<250\mu m$) and then prepared using the lithium metaborate fusion method and the hot block method as described below. The grinding of samples to such a fine powder should have the effect of breaking down any potential aggregations, however, it does not seem likely that chemical components would be lost and therefore the grinding of samples should not have an adverse effect on results. A photograph of the equipment used is shown in Figure 3.11.

3.12.1 ICP-AES: Lithium Metaborate Fusion Method

100mg±2mg of ground sample was weighed into a clean platinum/5% gold crucible with 300mg±10mg of $LiBO_2$ flux and mixed together using a platinum rod.

The crucible was partly covered with the lid and heated over a Merken burner with a dull red flame until the flux melted and fusion began. During heating, the mixture was swirled to ensure no powder residue, and the mixture was not removed from the burner until fusion was complete (approximately 10-15 minutes).

Once heating was complete, the molten bead of sample was run along the inside of the crucible to collect all flux and sample residues.

The bead was allowed to solidify on the side of the crucible and then tipped into approximately 100ml of 10% HNO_3 in a plastic beaker using a jet of water against the outside of the crucible to aid removal.

A small amount of HNO_3 from the beaker was poured into the crucible to remove any residue. The beaker was stirred using a magnetic flea until the bead had dissolved and the remaining solution in the crucible was added to the solution in the beaker.

The crucible was reheated uncovered until a bright red colour to check for cleanliness. Iron residue shows up as a dark stain once heated and can be removed using a small volume of HCl – this solution may be added to the solution within the beaker.

The resultant solution was made up to 250ml using 10% HNO_3 in a volumetric flask and transferred to a plastic bottle for storage before being run through the ICP-AES machine.

3.12.2 ICP-AES: Hot Block Method

500mg of sample was weighed into a clean Teflon crucible. 10ml of hydrofluoric acid and 2-4ml of perchloric acid was added, and the crucible placed on a hot block at around 100^{o}C for at least four hours. After four hours, the temperature was increased to 150^{o}C to allow the perchloric acid to evaporate, and the samples removed once dry.

The crucible was allowed to cool and 5ml of nitric acid and 20ml of deionised water was added. The solution was gently warmed for at least 20 minutes, until the solution was clear.

The solution was then allowed to cool, made up to 50ml in a volumetric flask and transferred to a plastic bottle for storage before being run through the ICP-AES machine.

3.13 X-Ray Diffraction (XRD)

X-Ray diffraction (XRD) was used to give a semi-quantitative analysis of mineralogy within a given sample, to establish whether the piling process affects the soil at a mineralogical scale, and if so what changes occur and what is the extent of those changes in the host soil.

XRD is a technique used to ascertain the presence of mineral assemblages within a soil. It works by aiming a beam of X-rays at a sample, these X-rays are deflected according to the size and number of silicon sheets within the clay structure and the angle of deflection is diagnostic of each mineral. An introduction to the technique with reference to clay mineralogy is given by Moore and Reynolds (1997), with examples of the use of this technique being discussed by Sakharov *et al.* (1999).

The small size of individual clay crystals makes hand identification of clay minerals difficult; XRD is a commonly used technique for clay rich soils. Batchelder and Cressey (1998) provide a comprehensive review of the use of this technique for the study of clay rich soils and describe the advantages of this technique.

Samples were taken, where possible, in the remoulded zone of each section of pile, and at the same vertical point, 50mm horizontally away from the pile. This allowed soil from remoulded and undisturbed zones to be compared. Samples were approximately 10g in weight.

The position of the base of the sample was recorded using the exact height above the base of the pile, and the distance from the pile was recorded using the closest and furthest point of the sample.

Each sample that was taken was split in two: one part was tested for the clay fraction (i.e. all minerals with a crystal size of below 4μm) and the other part used for the whole rock analysis (all minerals irrespective of crystal size).

3.13.1 XRD: Clay Fraction

To prepare the sample for analysis of the clay fraction a $1cm^3$ cube of soil was required. The sample was crushed using a pestle and mortar and placed in a 250ml glass bottle with tap water and dispersant (2% ammonia solution) where required and the bottle placed in an ultrasonic bath for an hour to release clays into suspension.

This clay rich suspension was then poured into centrifuge bottles, with all bottles filled to the same level. The samples were centrifuged for 4 minutes at 1000 times per minute.

The sample was then poured into a clean centrifuge bottle and topped up with tap water and re-centrifuged at 4000 times per minute for 20 minutes. While centrifuging, ceramic tiles approx. 2cm x 2cm were labelled on the underside and placed on a warm hotplate ready for preparation.

Once centrifuging was complete, most of the water in the plastic bottles was poured away, with the few remaining drops mixed with the residue to create a slurry. Using a teat pipette, this slurry was dripped onto the ceramic tiles.

Samples were scanned on a Phillips 1820 automated X-ray diffractometer using Ni-filtered CuKa radiation. The clay tiles were scanned at a rate of 5 seconds per 0.02° area step width, using 0.3 mm slits from 2° to 40° 2Θ. Tiles were sprayed with glycol and rescanned from 2° to 26° and twice again after heating at 400°C for 4 hours, and after heating at 550°C, also for 4 hours. The equipment used is shown in Figure 3.12.

An example of an XRD trace if given in Figure 3.13. Each peak denotes a separate mineral species and the area below the peak gives an indication of the quantity of that species present in the sample. Semi-quantitative percentages were determined using weighting factors calculated from known mixtures of clay standards obtained from the Clay Minerals Society of America. Traces were analysed using MacDiff software used to obtain areas below given peaks. Clay fraction analysis of this type has a precision of 1% (Batchelder and Cressey, 1998).

3.13.2 XRD: Whole Rock Analysis

A 2cm^3 cube of sample was crushed into a coarse powder using a pestle and mortar and the sample placed in a mixing pot and 2 drops of anticoagulant added. The sample was then shaken mechanically for 12 minutes and silica tiles labelled on the underside and placed on a hot hotplate. Using a teat pipette, the resulting slurry was dripped onto the silica tiles.

Once prepared, samples were analysed using a Nonius Diffractometer in reflection geometry with CuKa radiation, Ge monochromator and an INEL position sensitive detector. Data was collected for 15 minutes per sample. Processing involving whole pattern matching and stripping, using standard mineral patterns and was carried out according to the procedures detailed in Batchelder & Cressey (1998). Whole rock analysis of this type has a precision of 3% (Batchelder and Cressey, 1998).

3.14 Particle Size Distribution (PSD)

Particle size distribution (PSD) tests are commonly used within engineering to give a quantitative view of the range of sizes of particles within a given soil sample. A basic introduction to this technique is given in Head (1980).

PSD tests were performed using wet sieving tests with a standard series of sieves with mesh sizes of 63µm, 150µm, 210µm, 300µm and 450µm. A photograph is shown in Figure 3.14. Larger sieves did not catch a residue and so were not used in later tests. Each sample used was approximately 10g in mass and was left to soak in distilled water in a plastic bag for up to one month before sieving to allow the breakdown of stiff silt layers and avoid the need for mechanical breakdown of samples during sieving.

Sedimentation tests were performed on the sub 63µm fraction of each sample as described by Head (1980).

3.15 Plastic Index Tests

Index tests have commonly been used as an indicator of soil behaviour and an introduction to this technique is given in Head (1980). Examples of where the technique has been used are seen in Atkinson *et al.* (2003) and are discussed in detail in section 2.8.2.

Tests were performed according to British Standard BS1377 Part 2 (1990). Samples were taken, where possible, from the remoulded zone of each section of pile, with corresponding samples taken from the same horizontal layer at 50mm from the pile, where possible. Approximately 50g of sample was removed and mixed with water until a thick, even, consistency was reached which was at a water content roughly between the liquid and plastic limits. The mixed sample was left overnight in a watertight container and further mixed. Once mixed, samples were tested according to BS1377, with the exception of the adaptations given below, using standard falling cone tests and rolling thread tests. Figure 3.15 shows the cone penetrometer used.

Because the clays were very stiff it was sometimes necessary to soak samples for up to 1 month, as opposed to the 24 hours as recommended in BS 1377. After this time, samples were removed from the watertight container and mixed on a glass slab. Large agglomerations of soil were broken using a small spatula and fully mixed into the overall sample. If required more water was added and the sample replaced in the watertight container for up to one week.

When the sample was removed from the container for the second time, any remaining lumps were discarded and the sample tested according to BS 1377. A 1-2g portion was left at the side of the glass mixing plate to dry and be used for the plastic limit tests. The remaining soil was mixed for approximately 10 minutes using 2 palette knives. A portion of this soil was pushed into a metal cup approximately 55mm in diameter and 40mm in depth taking care not to trap air, and levelling off at the surface using a palette knife.

The metal cup was placed under the penetration cone, and the cone lowered such that the tip just touched the surface of the soil. The cone was released for 5 seconds and the distance dropped recorded. The cone was removed and cleaned, the cup refilled and the cone was released for 5 seconds and the distance dropped recorded. Where the difference between the first and second readings was between 0.5 and 1mm a third test was carried out. Where the difference between the two readings was less than 0.5mm results were noted and a 10g sample from the cup was removed and its water content measured.

The soil in the cup was returned to the main soil sample on the glass plate, water added and the process described above repeated. This was repeated in total four times, each time with a greater water content than the last, with the penetrations aimed to be between 15mm and 30mm.

To test the plastic limit, the 1-2g sample of clay was rolled into a ball and spilt in two. The first was rolled under the fingers until it reached 3mm in diameter (a

3mm bar was used for comparison). This process was repeated until the sample cracked apart before reaching 3mm in thickness. The water content of this sample was taken and the process repeated with the second sample. Where the two samples did not give water contents within 1% of each other the process was repeated. Where the two samples gave results within 1% of each other, an average was taken to give the correct plastic limit.

3.16 Triaxial Testing

Triaxial tests were performed on bulk reconstituted soil, samples taken from in situ undisturbed soil samples taken from in situ remoulded zones. A standard hydraulic stress path cell (Bishop and Wesley, 1975) was used for all samples, with the exact apparatus described in detail in Mašin (2004), Jovičić (1997) and Stallebrass (1990). A photograph of the equipment used is shown in Figure 3.16.

3.16.1 Bulk Reconstituted Samples

Bulk samples were collected from soil taken from site from the excavator bucket and are considered to be representative of the undisturbed soil on site. Samples were chosen to be representative of either the green silt rich material or red clay rich material. Testing samples were taken from bulk samples of predominantly red clay and predominantly green silt material.

Each sample was mixed to 120% water content and left to soak for one month after which hard lumps were broken using a hammer. It was then mixed using a Hobart food mixer for two hours before being returned to a plastic tub and lumps removed.

Each sample was then placed in standard 38mm diameter floating ring consolidation tubes and consolidated under an applied mass of 8kg over a period of one week. Due to the high silt content in the green silt samples, initially it was difficult to consolidate samples uniformly. It was only necessary for very small quantities of silt to get between the upper and lower joints of the piston for the piston to catch and fail to transfer stress to the sample. To counteract this subsequent green silt samples were consolidated to 10kg and the top piston removed and cleaned (to remove any silt which may have stuck to the sides of the tube and prevented the top cap from moving down the tube) before adding the final load.

Once in the triaxial cell, samples were consolidated to an effective stress of 50Kpa, by applying a cell pressure of 250KPa and a pore pressure of 200KPa. An initial state of 50KPa was chosen to represent the approximate stress state of the sample in the ground.

3.16.2 In Situ Samples

Samples of undisturbed and remoulded material were prepared using a bandsaw. Samples of a greater length than 78mm were selected and carefully trimmed down to a square with a side length of approximately 60-70mm.

Due to the highly fissile nature of the samples, great care had to be taken when using the bandsaw, and small increments of soil had to be removed at a time. Moisture content was maintained using a damp cloth which was laid over the sample where possible.

Once in the triaxial cell, samples were consolidated to an effective stress of 50Kpa, by applying a cell pressure of 250KPa and a pore pressure of 200KPa. An initial state of 50KPa was chosen to represent the approximate stress state of the sample in the ground.

Once removed from the triaxial cell, a 5mm slice through the upper portion of the sample was taken and tested for water content.

4 Observations and Results of Experiments

4.1 Introduction

In this Chapter, results of the experiments detailed in Chapter 3 are presented. A discussion of these results is given in Chapter 5.

4.2 Field Observations

Field observations were made at Ibstock Brick Pit during installation and excavation of piles in June and July 2007, as well as at a sample collecting trip in June 2006 and a fieldwork planning trip in May 2007. Observations were recorded in a notebook in both written and diagrammatic form, and where appropriate with a Pentax Optio WP digital camera. Samples of major units of stratigraphy and samples from spoil heaps were removed and returned to the lab.

4.2.1 Stratigraphy

Along with studies of the Gunthorpe Member both nationally and regionally (see section 2.5), studies were made of the local site. During excavation, the southern wall of the pit was logged down to a depth of 2350mm, 388mm lower than the deepest section of pile excavated. During this logging, a large variation in host mudrocks was seen, and, as is shown in Figure 4.1 the dominant lithology was designated as Lithology A: centimetre-scale laminated stiff clay with brick red/brown clay beds, interspersed with centimetre-scale red/purple hard beds. Note that the local (on-site) 'Lithology' nomenclature as detailed in Figure 4.1 is distinct from the nationally described 'Units' notation described in Chapter 2, the local nomenclature being organised to describe specific on-site characteristics). The clays logged within Lithology A range from highly fissile to non fissile, with bedding planes being the main source of fissile behaviour – beds readily breaking apart at bedding planes, but remaining unbroken within the bed.

From 923-1200mm depth, a hard, olive green/grey silt was seen interbedded with the same red/brown clay material that as recorded in Lithology A.

From 1200-1500mm depth consists of Lithology A (as described above).

From 1500-1590mm depth consists of Lithology B. Lithology B is similar to Lithology A with the following differences:

- A high instance of fissile layers and discontinuous lenses of hard green/grey silty material, up to 2cm in height and 12 cm in length.
- Presence of lenses with uneven, erosive bases (an uneven base to a bed where the upper bed appears to cut into the lower bed, indicating that this bed had eroded the bed beneath it during deposition), vertically spaced approximately 4cm apart.
- Presence of beds of (predominantly fine grained) silt, of uniform green/grey colour.
- No apparent grading within beds, and muscovite and biotite mica abundant on bedding planes.

1590-1890mm depth consists of Lithology A interbedded with Lithology C. Lithology C consists of clay rich horizons interbedded with 2 very hard 2cm silt beds. Strong cohesion was observed between the clay rich horizons and the silt beds.

1890-2350mm depth consists of Lithology F. Lithology F consists of hard, olive green beds of silt, with a few layers of red/green clays. Beds are approximately 20mm thick, fissile along bedding planes, but very strong perpendicular to the bedding plane (i.e. beds could not be broken by hand). The beds harden downwards, down to 2350mm where hardness rapidly increased. At this level it was not possible to cut or penetrate the material using the excavation bucket from the backactor. The excavator bucket just scraped along the surface of the upper bed, allowing no more material to be excavated. This layer (a hard fissile olive green bed with low clay abundance) is designated Lithology D.

4.2.2 Discussion of Stratigraphy

Reviewing the stratigraphy of the Mercia Mudstone Group given by Mader (1992) and Howard *et al*. (2008) – discussed in section 2.6 – gives an insight into whether the lithologies observed on site at Ibstock Brick Pit are typical of the Mercia Mudstone Group. The stratigraphy of the Ibstock Brick Pit is predominantly one of red-brown clay rich laminated beds interbedded with very fine to fine grained green-grey silts and sands. Very few bedding features such as cross beds and ripples are observed.

According to Mader (1992) this appears in the main to be consistent with what would be considered normal stratigraphy for the Gunthorpe Member. However, Mader (1992) talks of green clay beds, which were not observed at Ibstock, and also of gypsum veins, again not seen at Ibstock. The site is also lacking in halite deposits which are common within the Mercia Mudstone Group.

Gypsum veining, as is seen in parts of the Mercia Mudstone Group, might have an effect on the engineering behaviour of the Mercia Mudstone Group, introducing hard layers at random angles to bedding. This would affect the piling process, presumably creating a zone of weakness between the vein and the soil, but it was not possible to study this on the Ibstock site.

The clay mineralogy of the green beds mentioned by Mader (1992) has not been described within the literature, and therefore it is not possible to predict the effect of these beds on the piling process. It is likely that the green beds represent anoxic events within the deposition of clays, indicating that iron ions are present in a reduced state.

According to the stratigraphy produced by Howard *et al*. (2008), the Gunthorpe Member appears to be typical of members within Unit B, meaning that apart from the differences listed above, it may be assumed that the site is a representative location for the behaviour of piles in Unit B of the Mercia Mudstone Group in the Midlands.

The pebbly horizons and mixed layer clays of Unit C and the structureless grey-green mudstones in Unit E are the major features of the Mercia Mudstone Group which are not found within the Ibstock Brick Pit site. It should therefore be noted that while results from this dissertation do have a bearing on all units within the Mercia Mudstone Group, care should be taken when dealing with individual members and sites to note differences in local stratigraphy compared to that observed in the Ibstock Brick Pit.

4.2.3 Observations During Installation of Piles

A summary of the installation conditions for the four piles is given in Chapter 3 (also see Table 3.2) and shows that pile MR1 was delayed during concreting due to a blockage in the auger. The time taken to auger varies from 6 minutes and 48 seconds for MR1 to 7 minutes and 35 seconds for MR2. MR1 had the fewest number of revolutions to the toe by approximately 40 revolutions as compared to the other three piles – MR1 required 121 revolutions and the other three piles between 160 and 165 revolutions. MR1 also required the greatest volume of concrete, at $1.19m^3$, as compared to $0.69\text{-}0.76m^3$ for the other three piles. However, when the auger blocked with clay, the blockage was removed with a spade, and concrete run through the auger leaving a spoil heap – this is the most probable reason for the excess of concrete used in the installation of pile MR1.

Of the two over-rotated piles, MR3 (over-rotated with water added) was over-rotated for the greatest length of time, at 7 minutes and 51 seconds, but had the fewest rotations, at 133 revolutions. This is compared to 6 minutes 21 seconds and 202 revolutions for the installation of pile MR1 (over-rotated with no addition of water).

Observations of the spoil heap resulting from the installation of pile MR1 showed that initial arisings were above 10mm in size, ranging up to approximately 200mm diameter, consisting of sharp angular blocks of hard material mixed with fine, red/brown powder (as shown in Figure 4.2). As augering progressed, the instances of blocky material rapidly decreased until only a fine red/brown powder remained (see Figure 4.3) visible at the exterior of the pile heap. It was not noted at the time whether the spoil heap continued to grow in size during over-rotation.

The installation of pile MR2 produced a spoil heap with few angular blocks, and predominantly millimetre scale, sub-angular peds of red/brown clay. Material carried up on the auger during concreting was of a fine, powdery nature, easily falling or being knocked off the auger as shown in Figure 4.4.

The spoil heap obtained from the installation of pile MR3 where water was added to the soil, is shown in Figure 4.5. This shows a mixture of millimetre scale and centimetre scale sub-angular lumps and a watery, red, soup-like mixture rising from the shaft and falling down the top of the spoil heap, with little to no mixing with the dry material. Closer inspection of the shaft (Figure 4.6) showed the presence of an apparently high water content remoulded soil which had separated from the auger. Looking inside the shaft shows that the material appears wet, with sub-horizontal lines running along the inside.

The removal of the auger for pile MR3 during cementing is shown in Figure 4.7. It can be seen that soil was sticking heavily to the flights of the auger, such that it needed to be removed using spades.

The spoil heap obtained during installation of pile MR4 had a similar make up to that from pile MR3, with wet, soupy material pouring over the top of millimetre scale peds of clay (Figure 4.8). The soil-pile interface was similar to that observed for pile MR3. However, unlike the material from the installation of pile MR3, there were some large blocks of sub-angular hard material seen within the spoil heap. As with MR3, material had to be removed from the flights of the auger with a spade.

4.2.4 Summary of Observations During Installation of Piles

Pile MR1 was the only pile where there were any difficulties encountered during installation, with the auger becoming blocked with clay.

Soil arising during augering of the piles and deposited in the spoil heap of the dry piles consisted of blocky peds of clay of mainly millimetre scale, and predominantly a fine red/brown powdery material. This is in contrast with the wet piles where arisings were generally a fine powdery material, with a soup overlying it. In both piles there was very little mixing between powder and soup within the spoil heap. It was also observed that the inner surface of the pile shaft around pile MR3 had a wet, remoulded soil with horizontal markings, presumably from the flight of the auger.

There was a greater abundance of powdery soil in the spoil heaps of the over-rotated piles than the normally augered piles.

4.2.5 Limitations of Method Used in the Field

As with any work undertaken on site, there was some lack of precision in the installation method used for the piles. The over-rotated piles, MR1 and MR3 did not have the same number of revolutions at the toe, and despite an attempt to time the over-rotation, neither of the over-rotated piles had exactly 10 minutes of over-rotation.

Observations made on site were made from a distance of a few metres to comply with Health and Safety requirements. This clearly affected the accuracy of any observations made during installation of the piles. Samples from spoil heaps were collected during a brief pause between augering and infilling with cement.

4.3 Laboratory Observations

Observations were made primarily macroscopically or with the aid of a hand lens with x10 magnification. This section concentrates solely on those features which were observed during the dismantling of boxes and the removal of soil from each section of pile. Details of the samples taken for laboratory tests are given in Table 4.1, and a summary of the main observations from all four piles is included within Table 4.2. A remoulded layer was seen around all four piles, with some differences between piles and depths, and is described individually within each section below.

4.3.1 Pile MR1 (Dry and Over-Rotated): Observations

Four sections were cut from pile MR1, totalling a depth of 1861mm. These sections are shown in Figures 4.9-4.12. Pile MR1 was the least well preserved of all the piles. The fourth section was excavated after the diamond saw broke on the final day of site work, the section hence having to be cut using the excavator bucket to hit the side of the pile until it snapped off.

4.3.1.1 MR1 Section 1: 0-495mm below Ground Level

The upper section of pile MR1 was 495mm in length and poorly preserved, with only a very small amount of soil still attached to the pile. This was due to a vertical plane of weakness at the soil-pile interface, meaning that the soil separated at this interface and was no longer still attached to the pile once returned to the laboratory. Where samples remained, a remoulded zone 22±7mm in thickness was seen. The remoulded zone was observed as a dark chocolate brown, clay-rich layer showing a highly different texture from the host soil which is described in more detail below.

In this section of the pile, the boundary between the remoulded and undisturbed material can be seen at only one point due to the presence of another discontinuity in the sample at the remoulded zone-host soil interface. The remoulded soil is shown in Figure 4.13. It is a red/brown clay rich layer running along the shaft of the pile. The remoulded zone had sub-vertical fissures running along the pile, fanning outwards at a sub-vertical angle from the pile in a clockwise direction. Green silty material was observed in the remoulded zone, consisting of irregularly shaped agglomerations, with tails indicating clockwise movement. In some samples this material made up approximately 2% of the volume of the remoulded zone.

The remoulded zone had a sharp and well defined boundary, as seen in Figure 4.14, but this boundary undulates, meaning that the remoulded zone had a variable thickness which differs from the average of 22mm by approximately 7mm.

Rounded pebbles presumed to be transferred to the soil from the concrete were seen within the remoulded zone, but not within the host soil. These pebbles were up to 12mm in diameter and made up approximately 2% of the total volume of remoulded soil. They were grey/brown in colour, too hard to split by hand and not seen to occur naturally on site.

4.3.1.2 MR1 Section 2: 495-819mm below Ground Level

The second sample from pile MR1 was very poorly preserved, with only a small proportion of material retained at the base. The sample preferentially broke away from the pile at an interface 20mm horizontally from the pile, indicating a zone of weakness. Within the remoulded zone there was sub-vertical fissuring, fanning away from the pile in a clockwise direction at an angle of approximately 30^{o} from the pile (as described above), but otherwise the remoulded zone showed little other fabric. The host soil surrounding this section of pile (Lithology A, see section 4.2.1) was very fissile and brittle, meaning it crumbled in the hand. A sub millimetre film of red clay material was still attached to the pile, which was scraped using a sharp knife and removed for chemical testing.

The photograph in Figure 4.15 shows the rough shaft of the pile with aggregates projecting from the shaft and into the remoulded zone by ~7mm. This may suggest transfer of aggregates from the pile to the clay surrounding it, or possibly the loss of some cement from the concrete of the pile shaft into the surrounding material, leaving behind the aggregate particles.

4.3.1.3 MR1 Section 3: 819-1277mm Below Ground Level

The third section of pile MR1 also showed a remoulded zone of red/brown clay rich material, but with a highly undulating boundary. The zone was 50mm at its thickest and 2mm at its thinnest, as shown in Figure 4.16. The remoulded zone was predominantly a red/brown clay with a sub-vertical fabric of fissures (as in previous sections), containing silt particles of up to 2mm in diameter making up approximately 2% of the total of the remoulded zone. No aggregates from the concrete were observed.

Section 3 of pile MR1 showed a zone of weakness at 18mm horizontally from the pile surface where soil samples became detached from the pile irrespective of the thickness of the remoulded zone.

The host rock of this section was highly fissile and clay rich, causing much of the host soil to have fallen away from the pile during transportation and leaving a poorly preserved sample.

4.3.1.4 MR1 Section 4: 1277-1981mm below Ground Level

The fourth section of MR1 was poorly sampled, as described above, but soil samples adjacent to the pile were preserved for examination.

The remoulded zone of the lower section varied between 2mm and 25mm in width, and can be characterised into two apparent zones. The first zone, closest to the pile, was up to 11mm in thickness and was a brown clay rich layer which was well attached to the pile shaft, containing pebbles presumed to be from the concrete within the layer (up to 2% by volume).

The second layer was separated from the first layer by a vertical discontinuity at this point. The two layers were similar in appearance, with the second layer having a more pronounced fabric in the same orientation to those described above. The second layer also contained a small amount of aggregate from the pile.

The host soil did not appear to be disturbed, apart from a small amount of uplifting of the bedding into the boundary between the host and remoulded soil.

4.3.1.5 MR1: Summary of Observations

Samples of soil and pile retrieved from pile MR1 were 1981mm in length in total. This pile yielded the least soil and poorest preserved samples of all four piles. Vertical planes of weakness at 0-22mm horizontally from the pile meant that soil easily became detached from the pile. This plane of weakness was not visible as a fracture in areas where soil had been prevented from becoming detached from the pile.

At the soil-pile interface there was a remoulded zone of red brown clay rich material of 0-50mm in thickness with a general trend of thickening downwards from an average of 20mm at the top of the pile to a maximum width of 50mm at a depth of 1277mm below ground level. Within this remoulded zone were sub vertical fractures fanning away from the pile at an angle of approximately 30^{o}. These fractures did not reach the undisturbed soil.

The boundary between the remoulded and undisturbed soil was sharp and distinct, but undulated greatly (and hence the thickness of the remoulded layer varied greatly). The greatest variation was seen at the greatest depths, with 23mm in variation seen in the lowest section.

The fabric seen in the remoulded zone around the lowest section of pile MR1 was seen to coherently cross the boundary between the first and second layer of the remoulded zone, indicating that the fissures seen in the remoulded zone were created after remoulding had happened.

The presence of aggregates from the concrete at most depths indicate some mixing between concrete and remoulded material.

4.3.2 Pile MR2 (Dry and Normally Augered): Observations

Three sections were cut from pile MR2, giving a total of length of 1944±107mm. Photographs of the sections are shown in Figures 4.17-4.19. The variability of the total length is due to the angle at which the final cut was made. There is also uncertainty about the length of the first section, as noted below.

4.3.2.1 MR2 Section 1: 0-1000mm below Ground Level

The uppermost section of pile MR2 was knocked off by the excavator bucket before detailed measurements of its length could be taken. The section had to be cut again by the excavator bucket and only one section returned to the laboratory as it was too long to fit into a plywood box for transportation, showing that the length was greater than 750mm. It has been assumed that the section was approximately 1000mm in length. The section did not have any undisturbed soil surrounding it, and only a small layer of remoulded material still attached. This section also lay on site for two days before being boxed.

Due to being left on site before being boxed, the uppermost section of pile MR2 had dried significantly, therefore water contents and textures would have been altered. However, although the boundary between the remoulded zone and host soil was not visible, the remoulding was still evident 22mm away from the pile. Sub-angular to sub-rounded aggregates of up to 12mm in diameter made up approximately 10% of the total zone, showing the same colour and hardness as those described for pile MR1; they were assumed to be aggregate from the concrete.

The remoulded layer of the upper metre of pile MR2 did not break easily (indicating a high clay content) and was hard to remove from the pile in a solid block of sample, often needing to be gently separated from the pile with a sharp knife. The remoulded layer showed localised silt rich agglomerations (Figure 4.20), making up <1% of total volume. These agglomerations were of green/grey colour, of up to 2mm in diameter, with little to no indications of movement or elongation or deformation (stress ellipses) which may have given an indication of direction of greatest stress.

4.3.2.2 MR2 Section 2: 1000-1457mm below Ground Level

The second section cut from pile MR2 provided a good, well preserved soil sample. The remoulded zone was distinctly smaller than in other piles, with an average thickness of approximately 12mm. The contact was highly undulating, with the thickness of the zone ranging from 0-20mm. Remoulded material was present over approximately 99% of the pile surface (albeit a thin layer in places). The remoulded material did not preferentially break at the soil-pile interface, but instead 5-10mm from the interface, indicating a plane of weakness at this point. As with section 1 of pile MR2, a fissured texture was observed within the remoulded layer, with fissures spiralling 25% clockwise from the pile, 5-10mm apart, very similar to those observed around pile MR1.

As with section 1 of pile MR2, the remoulded zone showed localised grey/green silt rich agglomerations of up to 3mm in diameter, showing poorly defined boundaries and tails indicating movement in a clockwise direction (Figure 4.21). In a vertical section taken through the remoulded zone (Figure 4.22), the agglomerations show an uneven but distinct boundary, with no clearly defined shape. The remoulded zone has a clear, sharp but undulating boundary. The remoulded soil appears fissured and remoulded with a rough granular appearance.

At the base of section 2 of pile MR2, a depth of 1457mm, green mottling was seen within the remoulded zone (Figure 4.23). This was the only location where this green mottled appearance was observed across all four piles, and was found directly adjacent to a green silt layer in the bedded material, Lithology B as described in section 4.2.1. The green mottling did not penetrate the entire remoulded zone, penetrating only 12mm into the remoulded zone, on the side of the host rock. This appears to be the only area where either the host soil has directly affected the remoulded soil adjacent to it or the remoulded zone has contained unremoulded soil.

Within the remoulded zone of the second section of pile MR2, round, grey/brown aggregates of a centimetre scale were found, which were presumed to have been sourced from the concrete (Figure 4.24). The aggregate was spread randomly throughout the remoulded zone and made up a ~8% of total volume, never leaving the remoulded zone and pushing into undisturbed material. Some aggregates were also not in contact with the pile, but found free floating within remoulded material.

4.3.2.3 MR2 Section 3: 1457-1979mm below Ground Level

The deepest section obtained from pile MR2 had a remoulded zone approximately 7±4mm thick, with an undulating but sharp boundary. The remoulded zone consisted of two distinct layers. The layer nearest to the pile was on average 4mm thick with a dark red/brown clay rich appearance. It was closest in appearance to the remoulded layer observed in the other sections of the soil surrounding pile MR2. The outer remoulded layer was structurally similar when viewed with the naked eye, but was a pale brown/beige colour, with a gritty texture, implying a higher silt content than seen around other sections from this pile.

The remoulded zone in this section preferentially broke away from the pile at a distance of 4mm, either at the interface of the two layers or within the second layer of remoulding. Areas were also observed where remoulded soil appeared to have intruded into intact bedded material by up to 11mm – this was the only point in all four piles where this was noted (Figure 4.25).

Figure 4.25 shows the contact between remoulded and host soil and illustrates the distinct difference between these soils. The remoulded soil is a dark brown colour, and the host soil an olive green colour (Lithology F, at depths below 1890mm, see Figure 4.1). In this location, the beds of the host soil have been raised by just under 10mm over a 20mm distance at the remoulded soil-host soil interface; this may be due to uplift during removal of the auger, providing an upwards force against the pile shaft, or due to upwards movement of remoulded material during augering.

4.3.2.4 MR2: Summary of Observations

Material to a depth of 1000mm below ground level was poorly preserved and did not give a good indication of the thickness of the remoulded zone. Material recovered from around this pile generally showed a thin (0-20mm) remoulded layer, with the thinnest average thickness observed in the section between 1457mm and 1979mm in depth, where the thickness was constant at 7mm. This lowest section was also the only one from this pile where the remoulded zone was split into two layers visible to the eye, with the innermost layer visually the same as the remoulded zone at all other depths, and the outer layer the same from the point of view of the fabric but of a pale brown colour.

As with pile MR1, localised sections of uplift of bedded material were seen adjacent to the remoulded zone. There was also evidence of mixing between concrete from the pile and the remoulded zone around the pile, in the form of concrete aggregate found within the remoulded zone.

The remoulded zone surrounding pile MR2 had a fabric ranging from the clockwise fanning fissures very similar to those seen around pile MR1 to a granular texture. Very few silt aggregations were seen around pile MR2.

In the top 1000mm of pile MR2, most soil had fallen from the pile, but some remoulded soil remained, with a thickness of up to 22mm. However, there was little evidence to indicate that this represented the distance to the boundary between remoulded and undisturbed soil. Therefore there may be a zone of weakness within the remoulded material. In this section, the remoulded material was very well attached to the pile, implying a high clay content, and could not be removed from the pile by hand.

4.3.3 Pile MR3 (Wet and Over-Rotated): Observations

Four sections of pile MR3 were excavated giving a total length of 1831mm ± 144mm. The sections are shown in Figures 4.26-4.29.

4.3.3.1 MR3 Section 1: 0-510mm below Ground Level

This section was the least well-preserved from this pile with a high proportion of the soil detaching from the pile and falling off at the field site. In this section, the remoulded layer was made up of three vertical layers and in total was 35±6mm in thickness. The layer closest to the pile was up to 9mm thick, chocolate brown in colour with some small, shiny crystals, indicating the presence of mica. The fabric of the remoulded zone was defined by fissures that appeared to be fanning away from the pile sub-vertically in a clockwise direction in a similar fashion to pile MR1 and pile MR2, although the fissures appeared smaller and less frequent.

The second layer of remoulding in section 1 of pile MR3 was seen at between 9mm and 29mm from the pile and was a pale brown, structureless layer. It contained aggregates from the concrete from 2-10mm in diameter, generally sub-rounded and making up 20% of the layer by volume. The layer was silt rich and did not appear to have a high clay content.

The third layer within the remoulded zone was found between 29-35mm from the pile and was a chocolate brown colour, similar to the first layer but with sub angular pebbles from the concrete 2-4mm in diameter and a massive texture showing no fracturing or alignment of minerals.

The remoulded zone in this section showed a distinct boundary with the bedded, undisturbed soil, with this boundary and the soil-pile interface both providing a plane of weakness where the sample broke. This was combined with a particularly fissile area of undisturbed host soil, and perhaps explains why the sample was so poorly preserved.

The inner side of the remoulded zone at the soil-pile interface showed markings as observed during installation (see section 4.2.3) with ridges fanning upwards from the bottom left of the sample to the top right at an angle of ~30^{o}, showing possible movement of the flights of the auger during installation (see Figure 4.30).

4.3.3.2 MR3 Section 2: 510-860mm below Ground Level

In section 2 of pile MR3, the majority of the remoulded zone was in one, dark brown clay rich, structureless layer, averaging 24±5mm in thickness (although small segments show two layers, see below). There was a clear boundary between the remoulded zone and the host soil, although the remoulded soil had the same dark brown colour as the host soil. Nearest the pile, the soil-pile interface had a mottled texture suggesting that it had been wet but subsequently dried. There was a plane of weakness at 5mm from the pile within the remoulded zone, where soil broke away from the pile. The presence of a single layer in the remoulded zone in this section is in direct contrast with the three-layer remoulded zone around section 1 of pile MR3, but no boundary between the differently layered zones in the two sections was observed, and therefore it is unknown whether the change from three remoulded layers to one was a gradual or an abrupt transition.

Very localised uplifting of beds was observed within the host soil, with beds lifted 2mm vertically over a 3mm horizontal distance.

Figure 4.31 shows the boundary between remoulded and undisturbed soil viewed from above, with the boundary visible at approximately 19mm from the pile. The remoulded zone shows aggregates from the concrete, lying within the remoulded soil. The boundary seen in this photograph between the remoulded and host material is undulating but always distinct.

Figure 4.32 shows a vertical section through a sample showing the remoulded and undisturbed material from this section. As with all other piles, there was a sharp boundary between the remoulded and undisturbed soil, but here there were two layers within the remoulded material. As with the boundary between remoulded and undisturbed material, the boundary between the layers within the remoulded zone was sharp but uneven. The inner layer was a green tinged, silt rich clay with a granular structure. The outer remoulded layer was a dark brown clay with a vertical fabric.

In this section, some silt aggregates were observed where the remoulded zone had split into two layers only and were seen in the inner layer as described above. As this section was in Lithology A (see section 4.2.1), a zone low in green silt, this may indicate that the silt originates from further down the pile shaft.

4.3.3.3 MR3 Section 3: 860-1210mm below Ground Level

In this section the remoulded zone had three distinct layers as shown in Figure 4.33. The total thickness of the remoulded zone averaged 33±15mm. The innermost (first) layer was up to 12mm in width and was brown with a slight fanning structure of vertical fissures in the same orientation as those observed in the dry piles, MR1 and MR2. Fissures were observed at the inner edge of this remoulded layer and were millimetre scale, thus less pervasive than those described in other piles. The second (middle) remoulded layer was 10mm thick and had a brown matrix of slightly lighter colour than the inner layer, containing millimetre scale green aggregations of silt (these made up approximately 50% of this layer). The third (outer) remoulded layer was up to 26mm thick and was, at first sight, identical to the inner layer but with no obvious fabric, apart from the presence of some small (millimetre/centimetre scale) aggregates from the concrete were seen. Aggregates were highly variable in size from 5-30mm in diameter, of a dark grey colour and sub-angular to rounded in shape.

The inner surface of the first remoulded layer showed flaking inwards of sub-vertical fractures, as seen in Figure 4.34. It also has a vertical texture, which may be a relict from the sampling methods used in the field. When cut sections of pile were removed from the excavation pit by the excavation bucket, movements at the soil-pile interface where soil was not strongly attached to the pile may have caused a vertical texture to be applied at the surface.

Figure 4.35 shows a side on view of the remoulded zone and host material. As with section 1 of pile MR3, three layers of material are seen, with the boundary between the layers distinct but undulating. The middle and outer layers were the most variable in thickness with the middle layer being an average of 10mm (with a minimum thickness of 2mm) and the outer layer was an average 17mm, but up to 26mm thick in places. The middle layer showed a vertical fabric with apparent transport of green material along the shaft of the pile.

The layers within the remoulded zone are not as apparent in the sample shown in Figure 4.36. There is some green discolouring at the soil-pile interface. There are aggregates of up to 10mm in diameter within the remoulded zone, which are assumed to be aggregate which has migrated from the pile concrete. The soil-pile interface is again different in the sample shown in Figure 4.37, where there is a material similar to a fault breccia that runs along the soil-pile interface, containing sub-millimetre scale brecciated material in a 4mm band. As with the remoulded zone seen in other sections of this pile there was a high abundance of green silt aggregations in the centre of the remoulded layer, showing apparent movement from the right to left of the photograph (clockwise around the pile).

4.3.3.4 MR3 Section 4: 1210-1831mm below Ground Level

This section was poorly preserved, with only a few millimetres of the remoulded zone remaining. This remoulded soil was a dark brown, clay rich layer, with no green aggregates of silt within, but a few aggregates from the concrete of about 2mm in diameter found within the structure.

4.3.3.5 MR3: Summary of Observations

Pile MR3 was installed wet and over-rotated and had a remoulded zone with a very different fabric to that observed around piles MR1 and MR2. The remoulded zone was split into more that one vertical layer in most of the samples retrieved from this pile (insufficient soil was recovered from the fourth section to determine how many layers were present) with between one and three layers present depending upon depth of the sample. Samples taken from a depth of above 510mm below ground level had a remoulded zone consisting of three layers, with the inner and outer layers of a dark brown clay, similar to remoulded zones seen in other piles, and similar to each other. The middle layer had a pale brown matrix, containing approximately 20% green aggregates of silt of 3mm in diameter. These green aggregates were seen to contain green, quartz rich silt sized particles and showed no indication of how they were formed and if they were transported before being deposited within the layer.

A similar but more variable pattern of layers was seen in samples taken from depths of 860-1210mm. Not enough soil was preserved around the section from between 1210mm and 1831mm below ground level to be able to tell how many layers the remoulded zone had split into.

The soil preserved around the pile section between 510mm and 860mm below ground level was highly different from other sections of this pile in that the remoulded zone only had two layers, which were dark brown and clay rich, similar to the remoulded zones seen in the dry piles.

Fissuring within the remoulded zone was observed to be less obvious and less invasive than in the dry piles. Fissures were not always seen within the remoulded zone and often a granular texture was the dominant fabric. Where fractures were seen, they crossed layers of remoulded soil, indicating that the layering within the remoulded zone had been deposited before fractures were created.

As with the dry piles, the boundary between the remoulded zone and the undisturbed soil was sharp and distinct with an undulating boundary. Beds in the undisturbed soil were raised by up to 2mm over a distance of 3mm from the remoulded zone in some areas. However, the boundaries between the layers of remoulded soil within the remoulded zone were also distinct and sharp, with some undulating. The remoulded zone contained some aggregates presumed to have originated from the concrete of the pile, but at 2% of the total volume of the remoulded zone the abundance was less than in the dry piles. In some instances these aggregates were only found in the first remoulded layer.

The thickness of the remoulded zone surrounding pile MR3 was highly variable at between 19mm and 48mm, with no apparent trends in thickening of the layer with depth or according to the hardness of the host soil.

4.3.4 Pile MR4 (Wet and Normally Augered): Observations

Four sections of pile MR4 were excavated giving a total length of 1962mm. Due to poor preservation of section 2 (see below) only three sections were returned to the laboratory. These are shown in Figures 4.38-4.40 with the second section removed from this pile not being photographed.

4.3.4.1 MR4 Section 1: 0-451mm below Ground Level

The first section cut from pile MR4 was 451mm in depth and was poorly preserved, having developed some mould on the inner surface of the soil sample. This was the only sample observed to have grown mould.

There were no samples where the remoulded and undisturbed zones were seen together, so it was not possible to determine the position of the boundary between the two or to determine exactly how thick the remoulded layer was. The remoulded layer was dried out when removed from the box but extended to at least 55mm in parts, with cracks appearing (presumed to indicate the position of the zone of weakness as noted in other sections) at the soil-pile interface and again at 18mm from the pile.

No silt particles, concrete aggregate or fabric were observed around this section of the pile.

4.3.4.2 MR4 section 2: 451-951mm below Ground Level

The second section of pile MR4 was poorly preserved, with most of the soil having fallen off the pile at site, because the pile was hit by the excavator bucket from the backactor during excavation.

One layer was observed in the remoulded zone, as seen in Figure 4.41, containing what appears to be a dark brown fault breccia (where material at the soil-pile interface has been broken into small angular pieces presumed to have been created by the action of the auger) with sub-vertical fracturing throughout as observed in the other piles. The boundary between the remoulded zone and the undisturbed soil is not as well defined as in other samples from the piles. The remoulded zone has become detached from the pile at the soil-pile interface, showing a preferential zone of weakness at the soil-pile interface.

The remoulded zone was 23±3mm and did not appear to contain many silt aggregates.

4.3.4.3 MR4 section 3: 951-1342mm below Ground Level

The third section of pile MR4 was relatively well preserved. There were two layers observed within the remoulded zone. The inner layer was pale brown, and clay rich with millimetre scale sheets of pale green silty clay in a sub-vertical linear fabric similar to that observed around other piles. This layer was 12mm in width. The second layer of remoulding was observed from 12-36mm from the pile, and was the only layer of remoulding to show a diffuse boundary with the undisturbed soil, with a boundary width of 2mm horizontally. The outer layer was red brown in colour with some aggregations of green/grey silty clay up to 10mm in diameter.

The in situ, undisturbed soil was clay rich with a spongy feel and red/brown colour. It had a massive structure and was hard to cut with a knife.

Figure 4.42 shows the two layers of the remoulded zone, along with host material. The remoulded material is highly fissile, and contains aggregations of silt of up to 1cm in diameter. In this Figure, the aggregations are not purely made of silt, but also contain patches of red clay. No aggregates from the concrete were observed.

4.3.4.4 MR4 Section 4: 1342-1962mm below Ground Level

The fourth section of pile MR4 showed one remoulded layer from 7-32mm thick which was a dark brown colour, and apparently clay rich. There was a distinct boundary between the remoulded layer and the surrounding undisturbed material, which was clearly bedded. The beds of the surrounding undisturbed material rose by 2mm over a horizontal distance of 3mm to meet the boundary with the remoulded material.

Figure 4.43 shows the undisturbed, bedded green material, the pile and remoulded material between. The remoulded material can be seen to be intruding and infilling into the host green silt material. There were no observed silt aggregations, aggregates from the concrete or fabric observed in this section.

4.3.4.5 MR4: Summary of Observations

Pile MR4 was installed wet and normally augered, and 1962mm of pile was recovered. The zone of remoulded material recovered from around the pile had either one or two zones, although at both depths where only one zone was observed the samples were poorly preserved. The remoulded layer was a red/brown colour and varied in thickness from over 55mm to 7mm at its smallest diameter, appearing to become thinner with depth. Where the zone was not split into two layers, it was dark brown and clay rich, with a granular texture and sub-vertical fanning fissures similar to those observed in the other piles. Unlike the other piles, aggregates from cement were not seen in the material surrounding this pile.

Where the remoulded zone contained two layers, the inner layer was a pale brown clay, containing 1mm diameter sheets of pale green silty clay within the sub-vertical fractures. The outer layer of the remoulded zone was a red brown clay with some aggregates of green silt up to 10mm in diameter.

It was observed that the contact between the remoulded and undisturbed material was at times diffuse within the material surrounding pile MR4, and as with material surrounding other piles, the beds in the surrounding undisturbed soil were lifted at the boundary with the remoulded soil.

4.3.5 Observations: Limitations of the Method

Samples for detailed observation were not taken on site, but removed from the material transferred to the laboratory over a period of three months after installation. This gave time for the samples that were processed towards the end of the process to have dried out or, in the case of section 1 of pile MR4 (ground level to a depth of 451mm), time for the excess water gained on site to initiate the growth of mould spores. Drying caused obvious complications with loss of textures, for example causing desiccation cracks to form.

Undisturbed material was often highly fissile and easily fell apart upon removal of the surrounding Stretchwrap after opening the sample boxes. This also caused problems when cutting open samples to observe textures. This meant that it was not always possible to obtain samples at the intended depths and horizontal distances from the pile.

4.4 Axiocam Microscopy

Axiocam microscopy was used to look at three samples from each of the four piles. This microscope technique is used to photograph magnified images of samples and does not require the soil samples to be made into slides (as with thin sections), or mounted on stubs (as with scanning electron microscopy – please refer to sections 3.8 and 3.9). The use of the axiocam technique enabled characteristics the characteristics observed in the section above to be verified and expanded upon.

4.4.1 Axiocam Microscopy: Pile MR1

Samples from pile MR1 were taken from the third and fourth sections, at depths between 1177mm and 1861mm below ground level. Samples 13A and 13B were taken from between 1177-1277mm depth and Sample 14A was taken from 1581mm below ground level and less than 11mm horizontally from the pile, within the remoulded zone surrounding the pile (see Figures 4.44 to 4.46). All samples show a series of small fissures running from the top right corner of the picture to the top left when viewed in plan view – this indicates fractures fanning out clockwise from the pile, as discussed in section 4.3. Microscopic fissures can be seen in Sample 14A (Figure 4.46) covering the remoulded zone with varying degrees of intensity. A lower percentage of fissures, all up to 5mm in length, are seen in sample 13A (Figures 4.44 and 4.45). This sample also shows a massive, granular texture with some small aggregates of crystals with a green, silt-like appearance, the largest of these aggregates being 4mm in diameter.

When viewed at greater magnification (Figure 4.45), it can be seen that these green lumps are comprised of fine green silt, surrounded by a low proportion (<2%) of red clays. These lumps are of irregular size and shape and do not appear to show a preferred orientation, with no tails.

Some small, sub-rounded pebbles, presumed to be from the aggregate within the cement can also be seen in Figure 4.44. This indicates that smaller particles than those observed in section 4.3 had moved from the concrete to the remoulded zone.

Sample 14A (Figure 4.46) has a less granular texture than sample 13A (Figure 4.44). It contains fewer pebbles, with only one being visible within the field of view of Figure 4.46. One main fracture may be observed within this picture with many smaller fractures running sub-parallel. There is a small amount of brecciation (as described in section 4.3) around a fissure in the top right hand corner of the picture.

4.4.2 Axiocam Microscopy: Pile MR2

The majority of samples were taken from part of section 3 of pile MR2 at 1690-1779mm below ground level, due to this being the best preserved sample removed from site. Figure 4.47 shows two distinct layers of colour within the remoulded zone, the inner layer being a dark brown colour, with an undulating but distinct boundary at approximately 4mm width. There is a 0.5mm crust at the boundary between the two layers, of a deep brown colour. The outer layer is a light brown colour, containing horizontal, sub-millimetre scale dark brown lines running through it, parallel to the boundary between the two colour changes. Inside this layer is a 3mm diameter aggregate of silt, in a sub-angular, regular block. This block appears to show evidence of clockwise rotation, shown by tails of dark brown clay appearing from the top left and bottom right hand corners of the aggregate. A close up of this block in Figure 4.48 shows a sub millimetre scale dark brown crust.

Figure 4.49 shows a sample taken from the section 2 of pile MR2, taken from 1337mm below ground level. This shows the boundary between the undisturbed material (shown here as a green silty material) running vertically down the centre of the photograph, with two layers of brown, remoulded material at the left of the picture. The remoulded material is comprised of one main, light brown layer, with a 1mm-thick lining of dark brown material between the disturbed and undisturbed soil. Both layers of remoulded material have a massive, grainy texture, and no major textural differences are observed across the boundary. As discussed in section 4.3, the boundary between remoulded and undisturbed material is sharp, with millimetre-scale intrusions from the remoulded material into undisturbed material. However, the 1mm thick dark brown layer between the remoulded and undisturbed parts of soil was not observed in during the observations related in section 4.3.

4.4.3 Axiocam Microscopy: Pile MR3

Figure 4.50 shows the remoulded zone from the section 1 of pile MR3 (from depths of 0-510mm below ground level). It shows a granular, highly fissured texture, with centimetre scale long fissures fanning clockwise from the pile in a sub-parallel pattern. The lower half of the Figure shows these fractures in plan view, with a clean, sub-vertical surface. The sample also shows millimetre-scale pebbles within the remoulded structure, which are presumed to have come from the concrete.

Figure 4.51 shows silt particles within the remoulded layer, with particles of up to 1mm in diameter. This indicates that the aggregations of silt observed in section 4.3 are made of fine grained quartz. Within this layer, a green colouration can be seen running through the picture, parallel to the pile.

4.4.4 Axiocam Microscopy: Pile MR4

Figure 4.52 shows the remoulded zone from section 1 of pile MR4 (0-451mm below ground level). It shows a massive fabric, with few fissures fanning outwards from the pile and a dark brown clay rich matrix. Little silt is seen within the structure, and what is present is in the form of lone silt particles, not aggregations as seen in other pile sections. Dark material is seen along the fractures in the top of the photograph, together with a slightly paler area of remoulded material.

A different part of the same remoulded zone is shown in Figure 4.53 where shearing is seen within the dark brown clay matrix. Unlike Figure 4.52, the silt within the matrix is aggregated in clumps. A centimetre-scale piece of aggregated silt can be seen clearly embedded within the structure. A pale crust of approximately 1mm can be seen on the outer edge of the remoulded zone.

Figure 4.54 shows a close-up image of a 2mm diameter silty aggregation, containing very fine grained quartz with only small lumps of clay within. There does not appear to be a rim around the aggregation as seen in other piles, and the boundary of the aggregation is poorly defined and irregular.

4.4.5 Axiocam: Summary of Observations

The axiocam was used to make more detailed observations than could be made macroscopically or using a x10 magnification handlens and was useful for looking at textures. A summary of observations from this technique is given in Table 4.3.

Samples taken from the remoulded material around pile MR1 showed fissuring and a massive granular texture with little alignment of minerals. Aggregations of silt of up to 4mm in diameter were observed, and aggregations were seen to be predominantly made of sub-angular quartz. No preferred orientation was observed within the aggregations of silt and aggregations themselves were irregular in shape.

Some pebbles of 1-3mm in diameter were observed within the red brown matrix of the remoulded material.

An axiocam photograph of the remoulded material from around pile MR2 showed layering within the remoulded zone with the inner layer being darker than the outer layer. A thin crust separates the two layers and is distinct by being the darkest of the layers. This layering was not common to all samples removed from pile MR2. A massive, grainy texture was seen within both examples viewed by this technique.

Samples taken from around pile MR2 showed some aggregations of silt, with a regular, blocky boundary. Close examination of tails on the aggregate indicated a clockwise rolling movement during deposition.

Samples from around pile MR3 showed fissuring fanning from the pile in a clockwise direction (as also seen in other piles). Figure 4.51 shows green silt aggregations, but also green fine grained silt within the matrix of the remoulded zone. The silt within the matrix appears to be aligned parallel to the pile.

Samples taken from around pile MR4 showed a dark brown matrix of clay with some fractures. In these samples aggregates from the concrete can be seen embedded within the remoulded zone, this is differs from lower magnification hand lens observations where no concrete could be observed. As with the other samples, some aggregates of silt were observed within the remoulded zone, however, unlike other observations in other piles, these had an irregular shape and appear to be filled with green sub angular quartz.

4.4.6 Axiocam: Limitations of the Method

The axiocam technique was particularly useful as samples did not have to be dried or impregnated, therefore textures viewed were as accurate a representation of what would be seen under the ground as possible.

Due to the size and brittle nature of the samples, reducing the samples to a size where they could fit under the binocular microscope onto the stage caused some problems. However, with careful use of a sharp knife, samples could be cut down to a size where they could be examined. The samples were illuminated using fibre optic lights and the rough surface of each sample made it hard to achieve photographs with natural type light.

As with any magnification technique, by looking at a small area in great detail, it is possible to lose information from other areas. In this study, this was avoided by taking samples that were thought to be representative, and looking over the whole sample.

While the axiocam was good for observing structures, it did not give any indication of mineralogy.

4.5 Thin Section Microscopy

Thin section microscopy was carried out on one sample from each of the four piles. Two slides were created from each sample, one taken in a horizontal plane and the other in a vertical plane perpendicular to the soil-pile interface. The slides were viewed using a light reflected microscope and scanned for inclusion in this thesis using a HP Photosmart 3210 scanner.

4.5.1 Scanned Slides

All eight slides were viewed under a hand lens and scanned. Figure 4.55a shows a vertical section through the remoulded zone of a sample from section 1 of pile MR1 (the upper 495mm). The slide shows millimetre scale, highly laminated sub-angular grey-green clasts. Closer inspection of these clasts showed them to be made primarily of silt sized quartz, and the matrix to be made of amorphous clays.

The slide shown in Figure 4.55a shows a fabric characterised by random distribution of silt clasts in a clay matrix, with fissures at sub-millimetre scale spacing at an angle of 30^o from horizontal running across the sample, especially in the lower half of the slide. Fractures do not appear to bisect silt clasts.

The horizontally taken section taken from pile MR1 (Figure 4.56a) shows an amorphous clay matrix with sub angular blocks of very fine grained quartz which are aligned either parallel to the pile or at a 45^o angle.

Figure 4.55b (vertical section from section 1 of pile MR2, taken from between 690-1000mm below ground level) also shows a matrix of amorphous clays, containing angular clasts of grey/green laminated quartz rich silt. The matrix shows a dark brown clay, with randomly distributed regions of differently coloured clays (from pale to dark brown). No fissuring is seen within this slide.

The horizontally taken slide from pile MR2 (Figure 4.56b) shows an amorphous clay matrix with sub angular clasts of very fine silt sized quartz, with the clasts not showing a preferred orientation.

Figure 4.55c (vertical section from section 1 of pile MR3, taken from between 0-510mm below ground level) shows the boundary between remoulded and undisturbed material. The lower half of the slide shows a dark brown, clay rich matrix, containing sub-angular clasts of laminated grey-green silt. Above this is seen a millimetre scale, light brown layer of clay containing only few, sub-millimetre scale clasts. The boundary between the dark and light brown clay material is rough and undulating on a sub-millimetre scale, and therefore would appear to be sharp and straight to the naked eye. Both brown materials show a fissured fabric running horizontally from left to right (note that this photograph is orientated differently to others in this Figure).

The brown, remoulded material shown in Figure 4.55c is in sharp contrast to the grey/green host soil. This shows a mottling of brown clay material within a large, unbedded, textureless green silt structure. The boundary between the light brown and green material is a sharp contact with limited to no undulating at this magnification, in contrast to observations made in section 4.3.

The horizontal section taken from the soil surrounding pile MR3 (Figure 4.56c) shows a fabric consisting of fissures with a spacing of the order of 1mm. Asymmetrical clasts of quartz are aligned perpendicular to the pile. The slide shows three distinct layers of remoulding, each with a 1-2mm crust at the boundary. Different layers can be identified by colour changes, with the brown layers becoming darker further from the pile. Very fine grained quartz clasts are present, with a diameter of 5mm on average.

Figure 4.55d (vertical section from section 1 of pile MR4, taken from between 0-451mm below ground level) shows a sharp contrast to material taken from around pile MR3, with four distinct areas of brown clay material running vertically up the slide. On the left of the slide is a dark material, which has a highly undulating boundary with the adjoining soil. This darker material contains few large silt clasts (similar to those observed in the slides from pile MR3). The middle of the slide contains a pale brown matrix with a randomly distributed fabric and clasts of up to 5mm in diameter showing alignment to the pile. To the right hand side of the slide are two parallel layers. The inner (leftmost) layer is a very pale brown matrix of clays, with very few small clasts, and the outer layer (to the right of Figure 4.55) is a dark brown clay with no clasts and no obvious fabric.

The horizontally taken section from pile MR4 (Figure 4.56d) shows three layers, each with a different shade of brown matrix, darkening away from the pile. The average size of very fine grained quartz clasts is lower than as seen in other thin sections at 1-2mm. A fissured fabric is seen running perpendicular to the pile.

4.5.2 Thin Sections Viewed Under Light Reflected Microscope

Figure 4.57a shows the thin section taken from pile MR1 in the horizontal plane magnified under the reflected light microscope. The image shows amorphous clays in a red/brown matrix. Holes in the matrix, showing up as white in the Figure, indicate the presence of shards or clasts which have fallen out of the matrix during sampling. The matrix appears to have coloured banding in the vertical plane and a random arrangement of quartz/silt particles mostly less than 1mm in diameter.

Figure 4.57b shows the thin section taken vertically from the soil surrounding pile MR1 and as with the section taken horizontally, this predominantly consists of a matrix made of amorphous red/brown clays showing some vertical banding of dark and light brown remoulded material less than 1mm in diameter. Clasts of very fine grained quartz of up to 0.4mm in diameter are present (as with the horizontal section), indicating that silt sized lumps were present within this remoulded zone.

Figure 4.57c shows a detail of the horizontal section through the remoulded zone from around pile MR2. It shows larger clasts of the very fine grained silt sized quartz than seen around pile MR1, with clasts reaching approximately 2mm in diameter. The boundary of the clast is distinct, with no apparent mixing between the clay matrix and the aggregation and the clasts. The opaque area at the bottom right hand corner of the photograph indicates the presence of a mineral such as haematite or magnetite.

The detail from the vertical section for pile MR2 is shown in Figure 4.57d shows amorphous clays in a red/brown matrix which is aligned vertically across this picture. Dark and light brown layering is seen within this photograph with each layer less than 0.5mm in diameter. Individual grains of quartz are seen scattered randomly throughout the slide, with an aggregated clast of quartz grains seen in the bottom right hand corner.

The horizontal section taken from the remoulded zone around pile MR3 is shown in Figure 4.57e and shows the contact between the brown clay matrix and an aggregation of silt sized quartz grains approximately 2mm in diameter. Very fine grained quartz grains are seen within the matrix. The matrix is layered, with layers of 0.1mm in thickness appearing to be wrapped around an aggregated clast of silt sized quartz.

Figure 4.57f is a thin section through the thin layer of pale brown material between the remoulded soil and the in situ soil next to pile MR3. This is a highly layered remoulded clay with layering perpendicular to the pile disrupted by a rotated block of layered clays to the bottom right of the picture.

Figure 4.57g shows the mottling of brown clays within the in situ soil next to pile MR3. Green host material shows as very fine grained silt intermixed with the clay rich material also noted in the matrix of other slides. Black areas indicate a fully opaque mineral, such as haematite or magnetite, this mineral is as abundant in green silt rich areas as in red clay rich areas. Similarly, Figure 4.57h shows the boundary between the predominantly green silt rich and predominantly red clay rich areas with a fine, sub-mm scale thick layer of haematite or magnetite separating the two layers. Within the clay rich red layer, angular clasts of quartz rich material are seen within the clay rich matrix. These clasts are more abundant directly adjacent to this boundary.

A detail from the vertical section taken from the remoulded zone surrounding pile MR3 is shown in Figure 4.57i. There is a dark red-brown clay matrix with a layered fabric with layers running from the top right of the picture to the bottom left hand side. Very fine silt sized quartz, where apparent, appears in 0.2mm scale clasts within the matrix and appear to show movement towards the right hand side of the photograph.

The horizontal section from the remoulded zone around pile MR4 is shown in Figure 4.57j and shows a dark brown clay matrix, with lighter brown areas to the left of the photograph. There are millimetre scale clasts of very fine quartz. A low percentage of haematite or magnetite is seen within this slide.

Figure 4.57k shows the vertical section from the soil surrounding pile MR4 and does not show any distinct aligning of minerals or a dominant texture.

4.5.3 Summary of Observations from Thin Sections

A summary of the main observations is given in Table 4.4. The thin sections were a useful tool in showing small scale features of soil surrounding the pile. In all thin sections, sub-angular clasts containing predominantly quartz were observed. In all four slides, the proportion of clasts found within the remoulded layer was greater than observed by the naked eye or the axiocam. The clasts were not observed to be aligned in any slides, possibly due to the small scale being observed.

The slides all show a relatively mixed matrix of amorophous clays showing various textures. The slides taken from around pile MR1 show fractures fanning upwards away from the pile. The slides taken from around pile MR2 show a highly disorganised clay matrix indicating a plastic flow of soil. The matrix of the remoulded material in the slides taken from around pile MR3 shows layering parallel to the pile indicated by colour changes. The slides taken from the soil surrounding pile MR4 also show layering parallel to the pile indicated by a linear texture and colour changes.

The slides show the presence of matrices of red/brown amorphous clays, often aligned to show a texture. Crusts of either dark brown clays or opaque minerals (for example, haematite) are seen surrounding agglomerations of very fine grained quartz, sometimes giving indicators of directions of movement.

The thin section analysis shows that the remoulded zone in all cases contains a greater percentage of silt sized quartz particles than observed by other methods. Within layers in the remoulded zone, it can be seen that the layers themselves are not homogenous but contain very small scale colour changes and a layered and often fractured fabric. The undulating boundary of the remoulded zone observed in section 4.3 was observed to be not undulating at the microscopic scale, but regular in nature.

4.5.4 Thin Sections: Limitations of the Method

During the preparation of slides, the soil was impregnated with a resin, which was necessary to prevent the sample from falling apart when sectioned. However, this would have effects upon textures, although only of a limited nature.

Due to the difference in hardness between the aggregates from the concrete described in section 4.3 and the clay matrix, no aggregates were preserved during the slide preparation procedure and thus were not viewed under the microscope.

4.6 Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) was used on samples taken from all four piles to observe grain-scale disturbances to structure.

4.6.1 SEM: Pile MR1

Samples were taken from soil retrieved from depths of 1177-1277mm below ground level from around pile MR1 (i.e. taken from section 3 of pile MR3). Sample 13A was taken 50mm horizontally from the pile and was not in the remoulded zone around the pile. Figure 4.58 shows the overall texture of the sample. Platy flakes of a silt size can be seen in a disorganised texture, with few books of clay (the original state that clay forms in). The sample does not show an obvious fabric. The sample contains crystals of approximately 10μm in diameter.

In contrast, Figure 4.59 from the remoulded zone of pile MR1 shows a cemented, clay rich, mass with a slightly denser fabric. Individual grains do not appear altered compared to the undisturbed sample. Platy material can no longer be seen, and the grains appear less well defined, with a smoother texture. The sample is not highly porous with voids all less than 5μm in diameter making up 2% of the total volume.

4.6.2 SEM: Pile MR2

Samples were taken from the section of pile MR2 removed from 1000-1337mm below ground level (section 2), samples being taken from the remoulded and undisturbed zones of the pile. Figure 4.60 is from a sample 50mm from the pile (in the undisturbed zone) and shows a disorganised mass of sub-63μm sized silt and clay particles. The Figure shows few pores of up to 5μm in diameter. Figure 4.61 shows a close up view of sub-5μm flakes of clay, with 5μm pores making up to 5% of the total volume. The clay particles are aligned from both left to right and vertically within the picture, although on such a small scale, this may be just localised random alignment.

Figure 4.62 is a sample taken from the remoulded zone of MR2, and shows an alignment of larger crystals in the vertical plane of the photograph with closely packed crystals highly varying in size. The same Figure shows a low porosity (less than 1% pores) and has a granular texture. Individual crystals are up to 50μm in diameter with an average of 20μm.

4.6.3 SEM: Pile MR3

Samples were taken from the section of pile MR3 removed from 860-960mm below ground level (section 3). Figure 4.63 shows an SEM photograph of the first, innermost, remoulded layer of pile MR3. It shows a very poorly crystalline material with small crystals of flaky clay just visible at under 2μm in diameter, with few other mineralogical groups easily defined. There is a high abundance of a fine grained matrix of undefined mineralogy, covering all crystals in a blanket. The sample appears to contain some pores, all smaller than 5μm in diameter taking up 2-3% of the whole sample. Figure 4.64 shows the same area in higher magnification where individual crystals of ~10μm are seen, as well as plates of under 5μm in diameter which appear to make up these grains. The matrix appears structureless, with one pore observed of approximately 1μm in diameter.

As with layer one, the middle layer of the remoulded soil from around pile MR3 shows poorly defined crystals shrouded in a structureless matrix, however it is more porous than the inner layer, with pores of up to 6μm in diameter taking up approximately 7-8% of the whole sample (shown in Figure 4.65). Figure 4.66 is a closer view of the same area showing 5μm crystals, and a matrix with a flaky appearance. Figure 4.67 shows a close view of the second layer of remoulded soil around MR3 with highly defined, well crystallised calcite.

The outer layer of the remoulded zone in MR3 is shown in Figure 4.68 and is very different in crystal structure and texture from the first two layers, with easily observed angular crystals of 25μm sitting in random orientation within the sample. It has a greater porosity than the other two remoulded layers with approximately 10% of the total mass being pores. This is in contrast with the observations made in section 4.3 where it was noted that the first and third remoulded layers are practically identical in appearance to the naked eye and when viewed under a hand lens.

4.6.4 SEM: Pile MR4

Samples were taken from the section of pile MR4 removed from 922mm below ground level (section 2). Figure 4.69 shows the remoulded zone in the soil surrounding pile MR4 with highly disorientated books of very fine grained silt and clay, covered in a very fine grained matrix. The size of the individual crystals is comparable to the other samples at approximately 25µm diameter with crystals randomly aligned and a granular to platy texture. The sample shows very low porosity, with pores of approximately 5µm in diameter taking up less than 1% of the total volume of the sample.

4.6.5 SEM: Summary of Results

A summary of the observations made using the scanning electron microscope is given in Table 4.5. The SEM showed that remoulded material has a very small grain size, often significantly below 63µm, with average grain sizes ranging from 5µm to 2µm. There is often a very disorganised texture, ranging from granular to platy. Clays were often not found in books, as they would be expected to be found in undisturbed material. However, when undisturbed material was viewed under the SEM, clay was also found in a disorganised manner with no obvious fabric. There is no obvious difference in average grain size between the remoulded and undisturbed material as might have been expected.

In some locations there appeared to be evidence of silt sized grains with platy material flaking from it, this may be the silt sized aggregation of clay discussed in Chapter 2.

Around pile MR3, where the remoulded zone was split into layers, it was noted in section 4.3 that the inner and outer layers (layers 1 and 3) were near identical in appearance; this was observed to not be the case under the SEM, with the third layer having a larger average grain size. The middle layer (layer 2) contains zones of highly crystalline material – the aggregations of silt discussed in section 4.3. These were shown to have a very low clay content.

All samples showed some porosity to varying degrees, with pores rarely reaching a width of over 5µm.

4.6.6 SEM: Limitations of the Method

The SEM used was the Philips XL30, which is capable of producing very high quality images of very small material, however, unlike some other scanning electron microscopes, it did not give any chemical or mineralogical analysis of the material being viewed.

As with other microscopic methods, a very small field of view was used on each sample, so to limit this, a sample from each pile was repeated. Where samples gave different mineralogical or textural appearances, all have been presented. Where samples gave images showing the same texture, grain size and composition, only one image was shown.

4.7 Water Content Tests

Water content measurements were performed on soil samples taken from the full range of depths from each pile. The results of these have been plotted separately on two different graphs, one taking into account the horizontal distance of the sample from the pile and the other taking into account the depth of the sample. The results are shown in Figures 4.70 and 4.71. The greatest variation of results is seen in the remoulded layer in pile MR1, with samples appearing to decrease in water content down the pile from an average of 19% water content at the top of the pile, to an average of 14% in the lower section of the pile. As pile MR1 was installed with no added water, the greater water contents observed at the top of the pile may have been derived from the high rainfall during installation and excavation. The wet conditions during the first two days of pile excavation may also have contributed to the high water contents at the top of the pile, as the upper sections were the first to be excavated in these wetter conditions. The same trend is seen around pile MR3, the other over-rotated pile but was not seen in piles MR2 or MR4, the normally augered piles. It is unclear why this might be the case.

The water content tests from pile MR2 did not show a significant trend, but one outlier contained 29% water at 100mm horizontally from the pile and 1292mm from the top of the pile. It should be noted here that water contents from the top 1000mm of this pile were not recorded due to the poor samples retrieved at this level.

Water contents from the soil surrounding pile MR3 showed no trends with distance from the pile, but, similarly to pile MR1, results show a loose trend of decreasing water content with depth down the pile.

It is interesting to note that the wet and dry augered piles do not show notably different water contents. It should be noted that the piles were in the ground for six days before excavation began, and therefore fully drained conditions could reasonably be expected. It is also possible that the zone of weakness created at the soil-pile interface provided a good drainage channel for water to escape from the remoulded zone, and water may have drained all the way to the toe if it is assumes that the soil around the pile was as heavily fissured when in the ground as after exhumation.

With all four piles it is likely that the adverse weather conditions, during installation, curing and excavation may have affected the trends seen of greater water contents towards the tops of the piles. It should especially be noted that weather conditions were worst during the first two days of excavation (3rd and 4th July 2007) when the uppermost metre of each pile was being excavated.

4.7.1 Summary of Results from Water Content Tests

There were no clear trends in the variation of the water contents of the soil surrounding the piles. In particular, there was no trend to the changes in water content with distance from the pile in any of the four piles. Loose correlations of water content with depth were seen in the soil surrounding piles MR1 and MR3. In both cases there was a decrease in water content with depth, while pile MR4 showed a weak increase in water content with depth. Water content tests from around pile MR2 showed no clear trend.

4.7.2 Water Content Tests: Limitations of the Method

The volumes of soil recovered around each pile meant that often only one sample could be taken from a given depth on each pile. This often did not allow measurements to be repeated and therefore it is hard to gauge the accuracy of the results, although data is remarkably consistent near the pile.

Samples were taken during removal of soil from pile sections in the laboratory, this meant that while pile sections and their surrounding soil had been well protected against drying out, some pile sections had been stored in the laboratory for up to three months, so some drying was inevitable. However, it was not noted that water contents decreased as time taken for unpacking increased.

4.8 Chemical Analysis: ICP-AES

Major, minor and trace elements were analysed from soil surrounding all four piles using inductively couple plasma atomic emission spectroscopy (ICP-AES) – a list of samples is given in Table 4.1. Only the results from the major element analysis are presented here, with the full set of results given in Appendices 1, 2 and 3.

Results of the major element analysis are split into three categories: remoulded zone, undisturbed material, and material scraped from the outside of the pile shaft. Within each group of samples, results were plotted to show highest abundance, lowest abundance and average abundance of each element, as shown in Figures 4.72-4.74.

The greatest abundance of all the major elements was SiO_2, a major component of many rock forming minerals such as quartz, clays, micas and feldspar. The remoulded zones of all piles contained a greater percentage of silica than the undisturbed material, being on average 13.3% lower in the undisturbed material.

Figures 4.75-4.77 show the percentages of major elements with SiO_2 removed. The greatest variation in abundance between remoulded and undisturbed material was for CaO with the average for the remoulded material being 9.24%: 2.66% lower than undisturbed material. Figures 4.78-4.81 show the major element abundance of the soil surrounding all four piles, and show no difference in the abundance of CaO between the wet and dry piles. Calcium ions often behave as a cement in nature (Sherwood, 1967) and may have been acting to aggregate the clay particles into silt sized particles. If the suggested mechanism of disaggregation during remoulding is correct, it is likely that any calcium cement would be broken down during the remoulding process and this 2.66% difference between undisturbed and remoulded material may represent the breaking of these cementing bonds and subsequent leaching of calcium ions.

A chemical analysis was also carried out on samples removed from the pile by scraping a knife along a thin film gathered on the shaft. Highest, lowest and average values are shown in Figures 4.74 and 4.77. There is only an 11% difference between the highest and lowest values of SiO_2 – a smaller difference than those seen in the samples from either the remoulded or undisturbed zones of the piles. The average value for SiO_2 in the scraped samples was 5% higher than values for the remoulded zone and 18.3% greater than values for undisturbed material.

Variation in Al_2O_3 (a very hard aluminium ore which may appear in many forms, e.g. corundum), Fe_2O_3 (iron oxide, most commonly known as haematite, giving the samples their red colour), K_2O and MgO is significantly greater in the remoulded zone of all four piles than undisturbed material, with the abundance of MgO lower in the remoulded zone than the undisturbed soil, but lowest in the scraped samples. The same abundance of Al_2O_3 was seen in the undisturbed and scraped samples, with the remoulded samples showing the same average but a greater variation in values.

Soil from the two over-rotated piles, MR1 and MR3 showed the greatest variation in abundance of SiO_2, with soil around pile MR4 having the greatest average abundance. The other element showing variations in abundance between the four different piles was CaO (a cementing agent).

4.8.1 Summary of Results from ICP-AES

Results of major element analysis showed that the most abundant element was SiO_2, a major rock forming component. Remoulded material from around all piles showed a greater abundance than material from undisturbed areas of SiO_2, but a smaller abundance of CaO.

Soil from around pile MR3 had the greatest abundance and variation in abundance of SiO_2, with samples taken from the remoulded zone showing a decrease in SiO_2 away from the pile. Pile MR3 also had the greatest variation in abundance of CaO, with samples taken from the remoulded zone showing an increase in CaO away from the pile. The soil from around pile MR2 showed the least variation in all elements.

4.8.2 ICP-AES: Limitations of the Method

The ICP machine used has a precision of 2-5% and is known to be incredibly powerful and accurate.

Samples were chosen to be representative of a given location, and in each case 20g of sample were used to grind to <250µm, the sample mixed and 7g used for analysis.

4.9 X-Ray Diffraction (XRD)

Both the clay sized particles (the clay fraction) and a whole rock sample from each of the 4 piles were analysed for their mineral contents. In this section, the results of these tests are outlined.

4.9.1 X-Ray Diffraction: Clay Fraction

Soil samples used for this technique are given in Table 4.1 and the results shown in Figures 4.82-4.83, with summary tables of raw data given in Appendix 4 and Appendix 5. The results indicate that, in most samples, illite is the most abundant mineral, making up to 98% of the clay fraction, and on average between 50-60%.

Illite-smectite interlayers (where smectite becomes incorporated into the structure of the illite) were present in approximately 50% of samples tested. In samples from around pile MR3 where more than one layer of the remoulded zone was tested using this method, the middle layer of remoulding had no illite-smectite interlayers, while the inner and outer layers of remoulding contained 85-95% illite-smectite.

Chlorite was present in almost all samples, with only one sample (24B, from pile MR2) showing an abundance of more than 10%. No apparent correlation is seen between abundance of chlorite and depth or distance from the pile shaft of the sample.

The proportion of the clay fraction which was kaolinite was below 10% in all cases and did not show any correlation between depth and distance from the pile.

Clay sized micas, gypsum and feldspars were also present within most samples, with haematite, quartz and pyrophillite present in some samples. Haematite is the ore that iron is mined from, is often a red to black colour, and is probably responsible for giving samples their red colour. Pyrophyllite is an aluminium rich sheet silicate clay mineral which is a member of the smectite group, but has a low swelling potential. As can be seen in Appendix 4, no samples removed from around pile MR4 were seen to contain pyrophillite, however most other samples did contain this mineral, with the notable exception of the samples taken from the remoulded zone around pile MR1.

4.9.2 X-Ray Diffraction: Whole Rock Analysis

Whole rock analysis of the samples shown in Table 4.1 gave results as presented in Appendix 5 and Figures 4.84-4.85. In all samples, quartz, K-feldspar and haematite make up a large proportion of the non-clay sized fraction. Quartz abundance within the remoulded and undisturbed areas was 34% of whole rock abundance in the undisturbed soil and 30% in the remoulded soil. Where remoulded soil was split into layers, the percentage abundance of quartz decreased with distance from the pile shaft. For example, for the remoulded zone in the soil surrounding pile MR3 the percentage of quartz in the inner remoulded layer was 50%, decreasing to 24% in the third, outermost layer.

Calcite is present in nearly all samples, potentially as a cementing agent, with a maximum of 15% abundance in sample 41A (pile MR4) and an average for all four piles of 5%. No correlation is seen between calcite abundance and distance of sample from the pile.

K-feldspar was found in all samples, with an average of 23% in the undisturbed samples, and an average of 28% in remoulded samples. The percentage of plagioclase feldspar remained constant between remoulded and undisturbed samples at 1-2%.

4.9.3 Summary of XRD results

The results of the XRD analysis showed that the most common of the clay minerals was illite, which was present in a high abundance in most samples, with illite-smectite interlayers present in approximately 50% of all samples. A high swelling clay mineral, pyrophillite, was seen in almost all samples in both the remoulded and undisturbed zones.

No pattern was found within the distribution of clay minerals around a pile, so the distribution of an individual clay species did not appear to change with distance from the pile or depth down the pile. The whole rock analysis showed that where the remoulded zone was split into layers, the percentage of quartz present decreased with distance from the pile.

4.10 Particle Size Distribution (PSD) Curves

Particle size distribution curves were plotted for soil taken from the remoulded zone and from undisturbed soil on the same horizon for all four piles, with results shown in Figures 4.86-4.89.

The graph showing the particle size distribution for two samples taken from around pile MR1 is shown in Figure 4.86. These results show a greater percentage of clay in the undisturbed sample compared to the remoulded sample (5.3% in the remoulded sample and 7.3% in the undisturbed sample). The graphs show a trend of greater percentage of particles in the undisturbed sample passing through all sieves of diameter of 0.063mm and below, and a greater percentage of particles above this size in the remoulded sample.

The graph for the samples taken from around pile MR2 is shown in Figure 4.87 and shows results from the first and second layer of remoulding around the pile. The sample taken from the section of the pile where there was one layer of remoulding had a 7% clay fraction, with the sample taken from the second layer of remoulding containing 17.9% clay. The second layer of remoulded soil had a greater percentage of particles passing through all sieves below a 0.063mm diameter, with the single remoulded layer having a greater abundance of particles above 0.063mm diameter. This shows that the first remoulded layer had a similar clay content to the undisturbed soil around pile MR1 but the second layer had a 10.6% greater abundance of clay.

Figure 4.88 shows the particle size distribution curves for the three layers of remoulding around pile MR3. The first and second layers of remoulding contain similar abundances of clay, at 10.7% and 11.7% respectively, with the third layer containing a greater percentage of clay at 13.8%. The second layer of remoulded soil has a greater percentage of particles above 0.15mm in diameter than the other two layers. All three remoulded layers have a higher percentage of clay than the undisturbed soil tested from around pile MR1.

The particle size distribution curves for the samples surrounding pile MR4 are shown in Figure 4.89. This shows a higher percentage of clays within the remoulded soil than the undisturbed soil, but a lower percentage of silt sized particles. The remoulded soil has a higher percentage of particles of a diameter of 0.063mm and above.

4.10.1 Summary of Results from Particle Size Distribution Tests

The samples taken from around pile MR1 showed a higher percentage of particles below the size of 0.063mm in the undisturbed soil, with a higher percentage of particles above the size of 0.063mm in the remoulded zone.

The samples taken from around pile MR2 contained one sample from a single remoulded layer, and another sample taken from the second remoulded layer where the zone had split. These samples showed a higher percentage of clay and silt sized particles within the second remoulded layer, with a higher percentage of coarse silt and larger diameter particles seen within the single remoulded layer.

The remoulded zone around pile MR3 shows the greatest percentage of clay within the third, outermost, layer, with the second layer of remoulding having a greater percentage of coarse silt sized and larger particles.

The remoulded soil round pile MR4 had a higher percentage of clays and a smaller percentage of silt sized particles within it than the undisturbed material.

With the exception of the soil surrounding pile MR1, remoulded soil tended to have a higher percentage of clay sized particles than undisturbed soil.

4.10.2 Particle Size Distribution Tests: Limitations of the Method

The sieving and sedimentation methods used within this study are commonly used and accepted methods to obtain the particle size distribution curves for a given sample. However, using these methods to test the Mercia Mudstone Group has some limitations. The highly aggregated nature of the Mercia Mudstone Group meant that despite soaking samples, there were aggregations of clay/silt sized particles which could not be broken with a spatula and therefore were removed before testing. While these were a small percentage of the actual sample tested, they do add a small error.

4.11 Plastic Index Tests

Plastic index tests carried out on bulk samples of the Gunthorpe Member show that the red clay rich soil had a liquid limit of 26% and a plastic limit of 19%. A bulk sample of green silty beds was taken for plastic index tests, but had a clay content too low for testing. Plastic and liquid limits taken from soil around all four piles are shown in Figure 4.90.

Plastic index tests on two samples from the remoulded zone around pile MR1 showed liquid limits of 29% and 34%, both higher than the bulk sample. An adjacent, apparently undisturbed, sample had a liquid limit of 30%. The plastic limit remained roughly constant at between 16% and 19%.

The remoulded zone around pile MR2 had a liquid limit of 33% and a plastic limit of 20%. Around pile MR3, the second layer of remoulding had a slightly lower than average liquid limit of 27% and a plastic limit of 19%, and the third layer had a liquid limit of 29% and a plastic limit of 20%.

The first remoulded layer around pile MR4 had a liquid limit of 32% and a plastic limit of 19%. The second remoulded layer had a liquid limit of 28% and 17% as the plastic limit.

The remoulded zones of the dry augered piles (MR1 and MR2), on average, had liquid limits of 7% higher than those formed around the wet piles. Where it was possible to differentiate layers in the remoulded zones around the wet augered piles there was a great variation in liquid limit observed. Darker layers from the remoulded zone around the wet augered piles had a higher liquid limit than the lighter layers around those piles, but still a slightly lower value to that observed for the remoulded zone surrounding the dry augered piles. Paler and green silty layers from around the wet augered layers showed far lower liquid limits of between 27% and 28%.

The plastic limit remained fairly constant throughout, varying only by 2% between tests.

4.11.1 Summary of Results from Plastic Index Tests

Results from the plastic index tests showed that samples, irrespective of whether they were from remoulded or undisturbed soil had a plastic limit of approximately 19%. This is approximately equal to the value of the bulk sample of the Gunthorpe Member of the Mercia Mudstone Group.

Samples taken from the remoulded zones surrounding the dry augered piles MR1 and MR2 gave a higher value of liquid limit (generally around 31%) than samples taken from the remoulded zone around the wet augered piles MR3 and MR4 (showing an average liquid limit value 2-3% lower).

In all samples taken from the remoulded zones from around all piles, the liquid limit was raised above the value measured for the bulk sample.

4.11.2 Plastic Index Tests: Limitations of the Method

Due to the stiff and brittle nature of material surrounding the piles, it was often hard to produce a homogenous mixture of clay to use in plastic index tests. It was also hard to produce two comparable samples to test against each other.

In order to reduce these limitations, samples were left soaking in water for up to one month before testing, and all lumps within the material removed before testing, thus slightly altering the bulk properties.

4.12 Triaxial Tests

4.12.1 Results of Triaxial Tests

Figure 4.91 shows the results from all five triaxial tests with the mean effective stress plotted against deviator stress. Three tests were carried out on bulk samples of the Gunthorpe Member of the Mercia Mudstone Group (from material collected on site) – two of which were carried out on green silt rich samples and the third on a red clay rich sample. Two further tests were carried out on intact samples taken from around pile MR3, the pile which was installed over-rotated and with added water. This was chosen because pile MR3 showed the greatest thickness of remoulded zone of the four piles and therefore had the greatest potential to show variation in behaviour between the remoulded and undisturbed areas.

The intact soil adjacent to the pile, the red clay rich soil and the two tests on green silt rich soil are approaching a critical state consistent (see Figure 4.92) with a critical state line of gradient, M equal to 1.46 and therefore an angle of friction of 36.2^o. However the remoulded soil adjacent to the pile approaches a decidedly different critical state line with a lower value of M equal to 1.24, giving an angle of friction of 30.7^o.

Figure 4.93 shows axial strain against deviator stress for all five tests and shows that while the intact undisturbed soil does not appear to have reached the critical state line, even at these higher strains it is tending to an undrained strength that is lower than that measured for the remoulded soil. Because the remoulded soil has a lower angle of friction this implies that it started at a lower water content than the intact undisturbed soil as the shear stress of an undrained soil is dependant on the water content as shown in figure 4.94. Unfortunately measurements of water content before and after the test were not sufficiently accurate to verify this.

Figure 4.95 shows the compression tests performed on the bulk samples. The two green silt rich samples do not show exactly the same behaviour but do show that the bulk red clay rich soil behaves differently to the bulk green soil and does not compress to the same state. The bulk red soil has a λ of 0.063 and a C_c of 0.108, these are consistent with a soil with a low percentage clay content and low plastic index as observed for the Mercia Mudstone Group.

4.12.2 Triaxial Tests: Limitations of the Method

Intact samples for testing using the triaxial method were prepared by using a bandsaw, meaning that samples were not a perfect cylindrical shape.

It should also be noted that the triaxial tests performed within this study are by no means exhaustive, but were performed to give an overview of behaviour of these soils.

5 Discussion

5.1 Introduction

In this Chapter, the results of the observations and experiments detailed in Chapter 4 are combined with other available information so that conclusions may be drawn from the work presented in this dissertation.

The properties common to all four piles will first be presented, followed by a summary of the results of observations and laboratory results. The four piles will then be discussed in order and finally the piling process and its effects on the host soil will be considered.

5.2 Review of Observations Made of Soil from All Four Piles

5.2.1 Remoulded Zone – Thickness and Interface with Undisturbed Soil

In all four piles it was noted that a zone of remoulded soil of significantly different texture to the host material was present around the pile. In some samples this remoulded zone was observed to be split into two or three distinct layers, and the thickness of the remoulded zone differs to a large extent between samples. Table 4.1 shows that pile MR2 had on average the thinnest layer of remoulded soil, and that the soil around piles MR3 and MR4 had the greatest degree of layering within them.

A summary of the main properties of the remoulded zone is given in Table 4.2 – the finer details of how this remoulded material differed between piles and is discussed in more detail in subsequent sections. In general, there was a very distinct boundary between remoulded material and the surrounding undisturbed material. In all four piles localised examples of uplift of the bedding in the undisturbed soil surrounding the remoulded zone was observed at this boundary.

Where bedding was uplifted, it was typically at an angle of approximately 30^{o}, persisting for a few millimetres distance outwards from the boundary.

The boundary of the remoulded material with the surrounding undisturbed soil around all piles was undulating, meaning that it was often not at a constant horizontal distance from the pile. Around an arc length of approximately 40mm the thickness of the remoulded zone might vary by 20-30mm, with similar observations made in a vertical plane radial to the pile. This may be due to the direct action of the flights of the auger on the soil during installation of the pile when the auger is first introduced into the ground. When the auger first cuts into the host soil, the flights gouge material away leaving a rough surface at the pile shaft which is wider than the flights of the auger. When the auger is removed, as the flights are not as wide as the hole left by the augering process, the remaining space is infilled by apparently clay rich material on it's way back up the pile shaft. This process may occur because CFA auger design is standard for all soil types, and highlights a need for a specific design created for use within stiff clays.

While host material within the samples was highly variable in colour and grain size, the remoulded material did not show any clear correlation in appearance with the material directly adjacent to it (except for one instance around pile MR2, which may be put down to chance). I.e. remoulding within areas of host soil with a high instance of grey/green silt did not show a greater abundance of silt when viewed by the naked eye. However, from Figure 4.1 it can be seen that the greatest proportion of green silt rich material was at a depth of 1500mm and below, and at this depth it was also noted that the remoulded zone was split into layers in all cases.

Similarly, the remoulded zone was not significantly wider in areas where host material was noted to be softer or more fissile than the bulk properties of the surrounding soil, nor notably thinner in areas where host soil was harder or stiffer than the observed bulk properties. This is in contrast with what might have been expected if material was pushing outwards from the pile, where it might be expected to exploit softer, more fissile areas. Because in general this does not happen (except one example in the soil surrounding pile MR2 which may again be put down to chance, see Figure 4.25) it can be concluded that the remoulded material is residue left from direct interaction between the flights of the auger and the host soil, with the auger scooping out material and leaving this remoulded residue around the edge of the pile shaft before concreting.

5.2.2 Remoulded Zone – Composition and Fabric

In all four piles, there was a residue of red mudstone remaining on the pile after all remoulded material had fallen off or was removed. This residue was approximately 1mm thick and could be removed from the pile by scraping with a knife, where it would fall in centimetre scale hard flakes.

The remoulded zone around three of the four piles (with the exception of pile MR4) contained splinters, aggregates and/or cracked off small blocks of cement or aggregate in varying degrees of size and angularity. No such material was observed within undisturbed soil.

There are two possible ways in which these aggregates might have been introduced into the remoulded zone. Firstly, they may have been directly derived from concrete from the pile. This would suggest that while the action of the flights of the auger during installation contributes greatly to remoulding of the in situ mudrock, so may the removal of the auger and the addition of concrete, thus allowing some concrete to be mixed in to the remoulded area. This is supported by the presence of aggregates extruding from the pile shaft observed in pile MR2. Concrete is placed at high pressure as the auger is removed from the pile shaft, and as such presumably always flows above the cutting tool on the auger. The cutting tool protrudes further into the host soil than the flights of the auger and the mixture of this pressure, the already softened clay rising up the pile shaft, and the cutting tool allow the concrete and the remoulded soil to mix.

Layering within the remoulded zone is discussed on a pile by pile basis in sections 5.8-5.11.

5.3 Review of Observations from Axiocam, Thin Sections and Scanning Electron Microscope (SEM)

Summaries of the observations made using the axiocam and from thin sections are seen in tables 4.2 and 4.3. The axiocam was used to observe micro- and macro-textures that could not be seen by the naked eye. In all four piles, silt sized aggregations were observed under the axiocam and appeared very different from pile to pile. Around pile MR1, the aggregations were approximately 3mm in diameter and had a rough and irregular boundary. The aggregations had a clay rich appearance and contained some highly crystalline quartz. This is in direct contrast with pile MR2 where the edge of the aggregate is regular and distinct and a dark brown crust was seen along this boundary. In this case the aggregates themselves did not appear to contain clay but appeared to be primarily formed of very fine grained quartz. This was the only place where a direction of movement may be observed from the silt aggregations.

Within the remoulded zone around pile MR3, aggregations of very fine grained quartz were seen of sub-millimetre scale, with an irregular boundary. Green silt was also seen within the matrix of the remoulded zone. The aggregations of very fine grained quartz in the remoulded zone around pile MR4 were irregular in shape and predominantly crystalline quartz, with some red-brown clays.

The soil matrix of the remoulded zones around all piles showed differences under the axiocam. Pile MR1 showed two very different textures in the two samples taken, with sample 13A showing a massive and granular texture, and sample 14A showing a linear, highly fractured texture (see Figures 4.44 and 4.46).

Pile MR2 had a remoulded zone with a clay matrix containing two layers. This was not visible to the naked eye while unpacking the sample boxes (see section

4.3) except in the sample taken from 1457-1979mm below ground level. The matrix of pile MR3 showed a granular but fissured texture with a high silt content, while the remoulded zone of pile MR4 showed a grainy and only slightly fractured sample. These observations are in agreement with the hand lens observations reported in section 4.3. The remoulded soil observed around piles MR1, MR3 and MR4 had a granular texture, with fissures observed in the remoulded soil around piles MR1 and MR3. This observation is in direct contrast with the hand lens observations reported in section 4.3, where the remoulded zones from around all four piles were noted to contain fissures.

Thin sectioned samples for all four piles showed an amorphous clay matrix containing silt sized aggregations of very fine grained quartz. The proportion and abundance of these quartz grains was highly varied, and the proportion did not appear to be related to the host soil surrounding the pile from which they were taken.

The thin sections taken from around pile MR1 show a fabric running sub-vertically away from the pile, fanning outwards with a spacing of approximately 1mm. This indicates some upwards strain placed upon the remoulded soil after deposition, either due to upwards motion of the remoulded material during augering or caused by the removal of the auger.

Thin sections taken from around pile MR2 showed larger agglomerations of fine grained quartz than seen in the soil surrounding pile MR1, indicating a greater level of disturbance of the soil around pile MR1 than around pile MR2 since aggregates of silt sized particles would have been broken up to a greater extent by the over-rotation of the auger used to install pile MR1. The vertical fabric of the remoulded zone indicates some vertical movement of soil during installation of the pile, but less outwards movement than was observed around pile MR1.

The remoulded soil observed with the naked eye around pile MR3 was highly different to that seen surrounding the dry piles, and the thin sections taken from this pile validate these observations. Large areas of green, silt-sized quartz material and brown amorphous clays are seen, with brown clay rich crusts often seen surrounding the quartz material. As with the soil surrounding pile MR2, the vertically cut thin section shows a sub-vertical fabric with material appearing to be pushed up parallel to the pile. The orientation of sub angular blocks of the quartz material also indicates vertical movement.

The thin sections taken from the soil surrounding pile MR4 showed an alignment of the granular textures which, as with piles MR1 and MR3 indicates a vertical movement of the remoulded zone. As with other samples, aggregates of quartz were seen within a dark brown clay matrix.

Scanning electron microscope (SEM) photographs of samples taken from the remoulded zones surrounding the piles show very fine grained (silt and clay sized average grain size) material surrounding all four piles, with very poor organisation of crystals. A summary Table is given in Table 4.5.

The SEM photographs of the remoulded soil surrounding pile MR1 show a fine grained matrix containing frequent platy particles of between 1.5μm and 24μm diameter, with an average size of 10μm.

The remoulded soil from around pile MR2 shows a platy texture with individual particles of between 1.5μm and over 50μm diameter and an average size of 20μm.

The first, innermost, remoulded layer surrounding pile MR3 has a highly different texture from the two dry piles, with a smothered, cloaked effect presumed to have been created by the presence of clay particles. Blocky particles of up to 70μm in diameter are seen, surrounded by flaky particles of <2μm to 50μm in diameter, averaging approximately 10μm. The second remoulded layer shows a similar cloaking effect due to presence of clays, with very few discernable crystals within the matrix, and an average particle diameter of 5μm. One photograph (Figure 4.67) shows blocky particles of up to 25μm diameter with very little clay matrix. The third, outermost, remoulded layer shows a granular texture with few platy particles. Blocky particles range from a diameter of 5μm to 25μm, with an average size of 10μm.

The remoulded soil from around pile MR4 consists of flaky, platy particles ranging from 2µm to 30µm with an average of 25µm.

The pores observed in samples under the SEM were usually of approximately 5µm in diameter. In the dry augered piles, the remoulded material had a greater percentage of pores (up to 8%) with only 1-2% pores in the surrounding undisturbed soil. In the wet augered pile, MR3, it was observed that the percentage of pores within the remoulded zone increased away from the pile, rising from 2-3% in the inner layer, to 10% in the outer layer.

The undisturbed surrounding all the piles had a very granular texture, with sub angular blocky particles ranging from a diameter of 2µm to 10µm, with an average of 5µm. The texture was not very different in structure from the samples observed from the remoulded zones of the piles, although the cloaking effect of clays observed in the remoulded zone of pile MR3 is not observed here. A closer look at the undisturbed material reveals that the blocky material is composed mostly of platy flakes of clays. The absence of these blocks of clays from the remoulded zone surrounding each of the piles suggests that the bonds holding the blocks together have been broken, and the clays released as discussed by Atkinson *et al.* (2001) and Sherwood (1967).

5.4 ICP and XRD – Analysis of Chemistry and Mineralogy

Chemical analysis was performed to ascertain how the cement in the concrete interacts with the soil in remoulded zones around the pile. Due to the presence of cement fragments within the remoulded zone, it might be expected that the remoulded zone would have increased percentages of tricalcium silicate, dicalcium silicate, tricalcium aluminate, tetracalcium aluminoferrite and gypsum (Taylor, 1997).

Unsurprisingly, the highest concentration of any element in all samples was SiO_2, or quartz. The assertion by Sherwood (1967) that silica is an important aggregating agent suggests that there should be higher percentage of silica in undisturbed, more highly aggregated material, than in remoulded soil, as if bonds between clay crystals are made of SiO_2 then it might be expected that when these bonds are broken (as might be expected to be the case during the formation of the remoulded zone), the abundance of silica would be reduced or at least remain the same as seen within undisturbed material. An inspection of the results obtained by ICP analysis shows this not to be the case. Samples taken from the remoulded zone around each pile had an average of 46.1% of whole rock abundance SiO_2, as compared with 32.1% for the undisturbed material – i.e. samples taken from within the remoulded zone show an abundance of silica greater than that in the undisturbed areas. It might therefore be reasonably concluded that some mixing between the remoulded zone and cement from the concrete (which is high in silica) has occurred.

The greater abundance of SiO_2 within the remoulded zone was also seen within the whole rock X-Ray diffraction (XRD) results, whereas the percentage of SiO_2 in the form of native quartz within the remoulded zone was shown to be, on average, 4% lower than in the undisturbed material. This suggests that the excess SiO_2 observed within the remoulded zone was present not just as quartz, but held within other minerals such as clays or present as a cement. Where remoulded zones were split into layers, it was observed with XRD analysis that the abundance of quartz decreased away from the pile within these layers – another indication that the source of the excess SiO_2 is the cement in the concrete. This further indicates mixing between the remoulded zone and cement from the concrete as discussed in Section 5.2.2.

The abundance of calcite is low in all samples, at 0-15% of whole rock abundance. There is no overall difference seen between remoulded and undisturbed samples with respect to calcite, indicating that if calcite is the cement holding together the aggregations of clays within the host soil, once the aggregations are broken this cement remains within the soil and is not lost during the piling process. Averages for CaO as calculated by the ICP-AES method were generally higher than those generated by the XRD method by 5-6% indicating the presence of CaO other than in the form of calcite, presumably as a constituent part of some of the clay minerals discussed above.

The XRD results do not show a great abundance of the swelling minerals of the smectite group, but there is some presence of illite-smectite interlayered clay minerals. Work by Chandler *et al.* (2001) shows that in the Gunthorpe Member of the Mercia Mudstone Group illite predominates as the main clay mineral with, with some illite-smectite, illite-smectite-chlorite interlayers and approximately 15% chlorite. The results discussed in this study are consistent with this, showing the samples used to be fairly typical in mineralogical composition for this member. The clay assemblages presented by Jeans (1976) indicate that the soil tested during this study fall within assemblage 1 (see section 2.4).

Clay sized micas, haematite, pyrophyllite, K-feldspar, calcite and quartz were also seen within samples.

5.5 Particle Size Distribution Tests

If the hypothesis stated earlier within this dissertation that aggregates of clays are split during the piling process is correct, then it would be expected that the particle size distribution (PSD) curve for zones of remoulded soil would show a significantly greater percentage passing through the 63µm sieve than the curve for undisturbed soil for all piles. This hypothesis is supported for most piles, excluding pile MR1, and a greater percentage of clay is seen within remoulded zones than undisturbed areas.

The PSD curve for the soil around pile MR1 did not show an increase in abundance in silt and clay sized particles in the remoulded zone, in fact the opposite was seen, with 2% greater clay seen within the representative undisturbed soil sample (taken from around pile MR1). The PSD curve for the remoulded soil taken from around pile MR2 showed a similar abundance of clay to the representative undisturbed soil sample, and also showed that where the remoulded zone consisted of a single layer this contained a greater percentage of all particle sizes up to 0.063mm diameter than where the remoulded zone was split into two layers.

The samples taken from the remoulded soil around pile MR3 showed a higher abundance of clays than seen around the dry piles. Perhaps unsurprisingly, the second remoulded layer had the greatest proportion of silt sized particles. The first (inner) and second remoulded layers had approximately 2% less clay than the third (outer) remoulded layer.

The samples taken from around pile MR4 show a higher percentage of clays in the remoulded zone than in the undisturbed material around pile MR4 by approximately 4%. The remoulded zone also contained a lower percentage of silt sized particles.

5.6 Water Content Tests

Tests described by Meyerhof and Murdock (1953) showed a 4% increase in water content in the soil directly adjacent to the pile shaft, with experiments by O'Neil and Reese (1972) showing an increase in water content 19mm from the pile shaft, with the greatest increases 1.8m from the base of the pile shaft. The results of experiments recorded in this dissertation do not support these results, showing no strong trends of water content compared to horizontal distance from the pile. There could be many reasons for this. For example, results were not taken on site at the time of piling as with Meyerhof and Murdock (1953), but between 8 days and 3 months after initial installation of the pile from material stored away from the site. The time lag between installation and measurement taking may have been sufficient for water to drain away from the soil-pile interface (especially given the fissured nature of the remoulded zone) and hence to have equalised throughout the samples. It should also be noted that as only approximately the top 2m were excavated for this study, it could not be noted if water content increases dramatically 1.8m from the base of the pile as noted by O'Neil and Reese (1972).

Water contents may also have been affected by extremely wet weather conditions on site, especially during the first two days of the excavation of the piles and prior to installation of the piles.

5.7 Strength and Plastic Index Tests

Plastic index tests were performed on samples from remoulded and undisturbed soil from all four piles. Bulk samples of the Gunthorpe Member of the Mercia Mudstone Group were found to have a liquid limit of 26% and a plastic limit of 19%. All samples tested from around the piles had a higher liquid limit than the bulk sample from the red clay rich layers, but the plastic limit remained roughly constant at approximately 19-20%. An undisturbed sample removed from near the remoulded zone in MR1 had a liquid limit of 30%.

The highest liquid limits are seen within the remoulded soil around the dry piles, MR1 and MR2, at between 29-34%, with lower liquid limits seen in the wet piles, of between 27% and 32%. The average value of the remoulded soil around the dry piles was found to be approximately 5% above the average for the wet piles. However, while these differences are interesting, it is noted that they may be solely due to statistical variation.

Where more than one layer of remoulded soil was tested from within the remoulded zone around the wet piles, no more than 5% difference between the two layers was seen in the liquid limit, with no correlation observed between distance from the pile and the remoulded layer and liquid limit.

The liquid limit was observed to decrease with distance from the pile. This would fit with the hypothesis that a greater percentage of clay is present nearer the pile (in the remoulded zone) compared to within the undisturbed host soil. If clay is released by the remoulding process as theorised, then the greater percentage of clay would be expected to give a higher liquid limit, as observed.

Such an increase in clay content is consistent with results from the particle size distribution (PSD) tests. However, the increase in liquid limit with proximity to the pile observed during this study (a 5% increase, on average, between bulk samples and samples from the remoulded zone) does not fit with the observations by Atkinson *et al.* (2001). Atkinson *et al.* (2001) observed an increase in liquid limit of 30% between undisturbed and artificially remoulded soil (created by using a meat mincer to break down undisturbed soil samples) for one Member of the Mercia Mudstone Group, and 12% for another.

Triaxial tests indicate that the remoulded soil has a lower value of M, the critical state coefficient of friction than bulk samples or the undisturbed soil around the piles. This is consistent with both the release of clays within the remoulded zone suggested by the PSD tests and the plastic index tests, which showed an increase in liquid limit within the remoulded zone.

5.8 Discussion of Pile MR1 – Dry and Over-Rotated

Pile MR1 (the first to be installed after the trial pile) was installed on 26/06/07 and was installed during bad weather. The pile was installed without the addition of water and over-rotated. During installation there was a blockage in the auger. This pile was the only one to clog the auger, showing that the blockage in itself may be a symptom of over-rotation under dry conditions.

During the installation of pile MR1, the auger was rotated for 6 minutes and 21 seconds at the toe with 202 revolutions and used a significantly greater volume of concrete (1.19m^3 of concrete was used for the installation of this pile) than the other three piles despite being nominally the same length and diameter. After the auger became blocked, it was removed from the pile shaft, unblocked using spades and concrete was run through to remove the auger cap before the auger was placed back in the pile shaft, therefore the majority (if not all) of the extra concrete used can be accounted for by this process. However, it is also possible that over-rotation of the auger caused some caving of material deeper than the excavation limit of 1981mm below ground level (widening of piles in this manner was noted by Foley and Davis (1971) during a pile excavation), and the resulting wider diameter of pile required a greater volume of concrete. However, there is no evidence of this in the sections viewed, nor is it supported by observations from the other over-rotated pile (MR4) where the volume of concrete used was consistent with the other piles.

The problems with the blockage of the auger during installation are consistent with the observations in the laboratory. The remoulded zone showed an overall trend of increasing thickness with depth, with the remoulded zone reaching a maximum thickness of 50mm, thicker than noted by Leach *et al.* (1976) and Pellew (2002). There was a great variation in thickness both horizontally and vertically, with no apparent relationship to the strength of the host material. This indicates the flights of the auger struggling to cut through undisturbed material, not pushing through the soil in a smooth manner, but cutting through the soil unevenly, creating a rough surface and thus creating friction during the installation of the pile. It is also possible that when the auger was removed for unblocking, this disturbed the surface of the remoulded soil, causing some to be lost. However, the surface of this pile was no less smooth than the other three test piles, suggesting that remoulded material had not been lost during the gap between creating the hole and concreting the pile, when no confining stress was being applied.

The highly undulating boundary observed between the remoulded and undisturbed soil may have been a result of gouging of host soil during over-rotation, with the gouges having been filled with remoulded soil. However, as discussed in section 5.9, where remoulded zones are split into 2 layers, fissures run across the layers, indicating that the remoulding action is completed before fissuring occurs and suggesting that in this case the gouging and remoulding action occurred concurrently.

The remoulded material around MR1 showed fissures fanning from the pile in a clockwise direction at a 30^{o} angle upwards. The remoulded material had a mixture of massive, granular texture and a highly organised fissured texture with a disorganised texture seen at the grain scale, with poor alignment of minerals.

Thin sectioned samples indicate upwards and outwards movement of material within the remoulded zone due to the subvertical nature of the fabric.

The remoulded zone was a red brown colour and was rich in clay, supporting the hypothesis that silt sized aggregations of clay are split into their constituent clays during augering of the pile.

The presence of aggregate from the concrete within the remoulded zone indicates some mixing of concrete with remoulded material. The results of particle size distribution tests do not suggest that aggregates of clays are broken into their constituent clay particles around this pile, but rather suggest that when the soil is remoulded during the piling process it is merely a textural change.

The water content tests for pile MR1 show a slight decrease in water content with depth. Pile MR1 was installed dry, therefore this was not due to addition of water at the top of the pile during installation boosting the water content at shallow depths.

Chemical analysis of samples from this pile shows that material from the remoulded zone contains 15.4% more SiO_2 than undisturbed material, suggesting that silica is gained during the remoulding process. However, in the sample directly adjacent to the concrete pile (scraped from the pile surface) there was 55.9% silica, suggesting that the increased percentage of silica within the remoulded zone was generated by the presence of the concrete. It might therefore be assumed that some leaching of chemicals from the pile into the soil occurs at the soil-pile interface. However, this same layer also contained below average values for Al_2O_3 and CaO (two large components of cement), opposing the idea that there is mixing occurring between the cement and soil. In fact, conversely this might suggest that if – despite the particle size distribution results – it is assumed that piling splits aggregates of clay, any excess silica seen on the layer adhering to the outside of the pile has come from the cement holding together the aggregates of clays within the host soil, rather than originating from the concrete within the pile. It may therefore be suggested that when silica, used by the soil as a cementing agent to hold together aggregates of clay, becomes detached from clay minerals when they are disaggregated, it does not get leached from the remoulded zone of the pile but remains within the remoulded zone and becomes especially concentrated directly adjacent to the pile itself.

5.9 Discussion of Pile MR2 – Dry and Normally Augered

Pile MR2 was normally augered without the addition of water, and a total of 1979mm of pile was excavated. The soil surrounding this pile had the smallest thickness of remoulded material, never greater than 20mm in thickness, and occasionally non existent. The remoulded material around this pile also had the least undulating boundary with the surrounding undisturbed soil and therefore had the most consistent-thickness layer of remoulded material – usually around 10mm in thickness. This indicates that the auger gouged into the host soil less than was seen in pile MR1 (which was also augered dry but over-rotated), where the remoulded zone was up to 55mm and highly variable in thickness. Hird *et al.* (2008) noted in laboratory tests that when Continuous Flight Auger (CFA) piles are augered perfectly, very little disruption of the ground is seen, and this agrees with the observations made here for this pile, although stiff, layered mudrock may be expected to respond in different ways to the isotropic artificial soil used in the tests of Hird *et al.* (2008).

Some mixing between concrete and the remoulded zone (as discussed in Section 5.2.2) is suggested by the material surrounding pile MR2, as aggregates believed to originate from the pile were found within the remoulded zone. These were particularly abundant in the top 1000mm of this pile. Fragments of concrete were seen within a thin section taken from the top 1000mm of pile MR2, indicating extensive mixing of concrete and the remoulded material.

Uplift of bedding was seen in the undisturbed material directly adjacent to the remoulded soil. The beds were raised by just under a centimetre over a 2 centimetre distance from the boundary between remoulded and undisturbed soil. This is indicative of some form of upwards movement and might indicate that the auger either entered the ground or was removed at a speed which did not allow one full rotation of the auger to move the auger a vertical distance of one flight, thus creating an upwards motion against the surrounding soil and causing material to deform in a ductile manner, leaving the beds uplifted. However, if all failure were by this mechanism then it would be reasonable to expect uplift of bedded material all around the remoulded material, not just in localised areas. It is more likely that material gets broken during augering in a brittle manner and that this broken soil becomes remoulded with the remoulded material moving up the pile shaft during boring, causing the ductile deformation described above. This would account for uplift of some softer beds, and would also account for the sub-vertical textures seen in the remoulded zone within the thin section analysis (see section 4.5). It would also explain the lack of physical similarity between the remoulded and undisturbed material – it is a common feature of the soil surrounding all four piles that the remoulded material was more uniform in colour than the surrounding undisturbed soil. For instance, in areas where the undisturbed, bedded soil was predominantly a green silt, the remoulded material of the same depth against the same pile rarely reflected this, therefore vertical movement and mixing of the clay must have occurred. When observed under the axiocam microscope, the green silt aggregations in the remoulded zone showed tails indicating movement before final deposition, with the thin sectioned samples indicated a pure vertical movement of remoulding.

In the soil surrounding pile MR2, only in the soil surrounding the final excavated section of pile MR2 (1457-1979mm below ground level) was it observed that the remoulded zone was split into two vertical layers with a distinct boundary. The innermost layer was presumed to be of the same material as the rest of the remoulded zone for depths of 0-1457mm as it was the same colour and texture as that observed at other depths. The second, outer, layer was paler in colour but was structurally in continuum with the inner remoulded layer. Fissures were not displaced over the boundary between the two layers indicating that they were formed after the layering effect, so it can therefore be concluded that the two layers were produced at exactly the same time and in the same manner, rather than the outer layer being produced early on during boring and the inner layer subsequently being formed inside it – this would produce fissures which did not cross between the layers (assuming that fissures are produced after remoulding).

A zone of weakness was seen within the remoulded material, evidenced by the tendency of material to fall from the pile not at the soil-pile interface or the remoulded soil-undisturbed soil interface, but rather at approximately 5-22mm from the pile (still within the remoulded zone). In the upper 1000mm of the pile, the remoulded material that was still attached to the pile was very strongly stuck to the pile shaft and had to be removed from the surface of the pile using a sharp knife.

Chemical analysis from the soil surrounding pile MR2 showed little variation in SiO_2 between scraped, remoulded and undisturbed samples, but did show a great variation within each group. This is in direct contrast with chemical analysis taken from the soil surrounding pile MR1 where the percentage abundance of SiO_2 increased towards the pile. This homogeneity of SiO_2 abundance around pile MR2 suggests a smaller percentage of clay aggregates being split open and a lower degree of disturbance of the remoulded zone in comparison to the remoulded zone around MR1.

5.10 Discussion of Pile MR3 – Wet and Over-Rotated

Pile MR3 was installed with the addition of water and over-rotated at the toe for 7 minutes and 51 seconds (a total of 133 revolutions), exactly two thirds of the number of revolutions at the toe as in the other over-rotated pile, MR1. It is unclear why the revolutions at the toe were fewer than during the installation of pile MR1 despite the time taken being over one minute greater. This indicates that the auger, when over-rotating, was travelling at a slower pace during the installation of this pile than pile MR3.

A total of 1831mm of pile MR3 was excavated, with mostly well preserved soil surrounding it. As with the dry piles, pile MR3 had a remoulded zone surrounding the pile shaft, however, there were large difference between the remoulded zone surrounding this pile and the remoulded zone surrounding piles MR1 and MR2. The main difference between this and the other piles was the layering of the remoulded zone observed in samples taken from most depths – only two examples of layering within the remoulded zone were observed in the dry augered piles, as opposed to MR3 where layering was a common occurrence.

Where three layers were seen within the remoulded soil, the inner and outer layers had a dark brown clay rich texture and may be assumed to have been produced in the same manner as the remoulding found around piles MR1 and MR2, due to its similar appearance to the single remoulded zone observed in the dry piles. However, the results of the particle size distribution (PSD) tests show that the third, outer, layer had 2% more clay within it than the first, inner, layer. The middle layer was approximately 10mm thick and consisted of a pale brown clay rich matrix containing 1-2mm diameter round agglomerations of green quartz rich silt/sand sized particles, often with a dark brown sub-millimetre thick crust of clay. It may be assumed that these agglomerations result from the breaking down of the hard green silt beds in the bedded undisturbed host material. However, the vertical positioning of agglomeration rich bands within the remoulded zone does not match up to the locations of the green silt beds in the undisturbed host soil. This indicates that the remoulded zone, or at least this middle remoulded layer, is vertically mobile during installation of piles. The round shape of the silt aggregations also indicates movement of the silt prior to being deposited in its final position, otherwise an irregular shape would be expected. The observed uplift of the beds in the undisturbed soil surrounding the pile implies that the dominant direction of movement of the soil surrounding the pile is upwards during the remoulding process. However, although the fabric of the remoulded zone shows vertical fissures (note that this is weaker in this pile than in others), it does not indicates the direction of movement of the material.

When viewed using the scanning electron microscope, it was seen that the porosity of the remoulded layer increased with distance from the pile. Both the inner and outer remoulded layers contained blocky particles with an average diameter of 10μm while the second layer contained very few discernable particles.

It is clear that the addition of water during installation of piles contributes to remoulding of clay within the Mercia Mudstone Group and facilitates the separating of clays within the remoulded zone into layers. Given the addition of water, the clay may become more pliable and more easily moved around the pile shaft, however what is unclear is the mode by which the remoulding separates into three layers.

It is also unclear, especially if the above hypothesis is correct, why the section between 510 and 860mm below ground level did not show this separation into layers within the remoulded zone but showed remoulding more similar to that seen in the dry piles.

There was an observed decrease in water content with depth in the soil surrounding pile MR3, but the average water contents were similar to the piles that were installed dry. This shows that either water is immediately removed from the pile shaft during the piling process, that it dissipated in the week after piling, or that water was lost during the time taken for samples to be taken. It is not clear why this would have occurred to a greater extent for this pile than the other wet augered pile.

The presence of aggregates from the concrete observed in the remoulded zone indicate mixing of the concrete and remoulded soil during pile installation, although to a lesser degree than seen within the dry piles.

Chemical analysis of the material surrounding pile MR3 showed the highest variation in SiO_2 abundance of all four of the piles, varying between 57.9% and 30.8%, with an average of 44.1%. In all samples, the percentage of silica decreases away from the pile within the remoulded zone, with the outer layer containing approximately 8% less SiO_2 than the inner layer. This would suggest that if SiO_2 is an aggregating agent within the Mercia Mudstone Group, the most disaggregated material within the remoulded zone is found in the outer layer. Alternatively, if SiO_2 is derived from the cement, this would indicate the greatest mixing between remoulded material and the cement in the remoulded zone closest to the pile, which would show that mixing of the remoulded material does not make it completely homogenous.

The soil surrounding pile MR3 also showed the greatest variation in CaO abundance of the four piles, with the concentration varying from 10.2-17.8% and increasing with distance from the pile within the remoulded zone. If CaO is a cementing agent within aggregates in undisturbed Mercia Mudstone Group (as suggested by Davies, 1967), this would imply that the most disaggregated material was found directly adjacent to the pile, in line with the observations of SiO_2 abundance.

5.11 Discussion of Pile MR4 – Wet and Normally Augered

Pile MR4 was normally augered and installed with the addition of water. The pile took 165 revolutions of the auger to the toe, exactly the same as the other normally augered pile, MR2.

The remoulded zone around pile MR4 was split into one and two layers, with two zones only seen between depths of 951mm and 1342mm below ground level. Where one zone was observed, it was dark brown and clay rich and showed a granular texture with occasional silt aggregations. Thin sectioned samples showed a textureless, massive structure within the remoulded zone. Where two remoulded layers were observed, the inner layer was thin (at approximately 7mm in diameter), consisting of a pale brown clay, containing sub-vertical fissures with green tingeing within them. The outer layer was a red brown clay with some aggregates of green silt up to 10mm in diameter.

Like pile MR3, where remoulding was split into three layers, it is unclear why the remoulding around pile MR4 would be split into two distinct and different layers, but unlike the remoulding in MR3 it is possible that the two zones represent different levels of disaggregation of aggregates within the host material. The inner layer contained less aggregates of silt material, and therefore may represent an area where a greater percentage of aggregations within the

Mercia Mudstone Group had been fully broken down, while the outer layer of remoulding may represent an area where aggregations had only been partially broken down due to their distance from the auger during installation.

When viewed using the scanning electron microscope (SEM) the inner remoulded layer was seen to contain highly disoriented clays, with very low porosity and an average grain size of 15μm. Unlike the results from the particle size distribution (PSD) tests from the other four piles, it can clearly be seen from the material surrounding pile MR4 that there is a higher abundance of clays within the remoulded zone than in the undisturbed material, and that the abundance of silt sized particles is reduced within the remoulded zone. This directly fits with the theory of breaking down of silt sized aggregations to release clays during the piling process.

It was unfortunate that few sections of this pile had a well preserved boundary between remoulded material and undisturbed material visible – material around this pile tended to break away at the soil-pile interface or at plane approximately 8mm away from the pile. The material surrounding pile MR4 was the only example of a diffuse boundary observed between remoulded and bedded material found around all four piles.

The presence of uplifted beds in the undisturbed material again indicates upwards travel of remoulded material during the remoulding process as discussed in section 5.10.

Chemical analysis of samples removed from around pile MR4 showed the highest average abundance of SiO_2 at 50.5%, with the highest abundance seen in a sample removed from very fine layer adhering to the shaft of the pile (57.6%). This high presence of SiO_2 within the film of material on the shaft of the pile further suggests that SiO_2 abundance may be linked to leaching of the element from the cement within the pile as discussed in section 5.9.

Remoulded material surrounding the pile showed slightly raised plastic index compared to the undisturbed soil.

5.12 Discussion of All Four Piles

All four piles showed an obviously altered, remoulded fabric and colour in the few centimetres surrounding the pile shaft. This remoulded zone varied in thickness both with depth and around the pile shaft.

Particle size distribution (PSD) tests indicated that, in all piles except pile MR1, the remoulded zone had a higher clay content than the surrounding host material. This means that the clay minerals must either have been produced by the breakdown of other materials within the host soil as the result of the high pressures created during installation of the piles, or that clays were brought in during the piling process, or that non-clay material is lost. The most probable explanation is that clays are produced by the breakdown of larger particles within the host soil, although the difference in abundance of clays between the remoulded and undisturbed areas was approximately 10%, indicating that not all aggregates were broken down. It is interesting to note that while the percentage of clay sized minerals increased in the remoulded zone surrounding each of the piles, the relative abundances of each individual clay mineral does not appear to be affected. This vast increase in clay content at the soil-pile interface will have knock on effects for the shaft friction and settlement properties of the piled foundations.

To test the effect that this increase in clay content has, plastic index tests were performed. The remoulded zones around all four piles were shown to have an increased liquid limit compared with a representative bulk sample – again an indication of increased clay content. As discussed in section 5.7 this did not replicate the increase in index properties observed by Atkinson *et al.* (2001).

Textural and mineralogical changes were also observed in the soil around the piles. The dry piles, pile MR1 and pile MR2, both showed remoulding of soil around the pile shaft, with little to no splitting of the remoulded zone into layers. The remoulded zone around pile MR1 showed a sub-vertical fabric, indicating an upwards and outwards movement of material within the remoulded zone. This contrasted with the normally augered pile, MR2 which only showed a vertical fabric, which appeared to be fanning out clockwise from above but did not give an indication of outwards movement. While this still indicates disturbance of the surrounding soil by the auger, unlike the over-rotated pile MR1 where material appeared to be pushed away from the auger, material here appeared to only be pushed upwards. It is therefore likely that when a pile is over-rotated and the flights of the auger spin at the same vertical depth for a prolonged period of time, this gives time for the rotating flights to push material upwards, much like a badly screwed corkscrew. When the corkscrew is pushed into the cork of a wine bottle, if it is pushed too slowly, this disturbs the cork and pushes fragments upwards. When the corkscrew is screwed well, little cork is displaced – this may be the same with the auger.

The piles installed with the addition of water, piles MR3 and MR4, showed distinctly differing textures and fabrics to the dry augered piles. Pile MR4 (wet and normally augered) showed no obvious fabric within the remoulded zone, whereas pile MR3 (wet and over-rotated) showed a light outwardly fanning vertical fissured fabric. This was similar, but less strongly developed, than that which was observed in the other over-rotated pile, pile MR1.

At points, remoulded soil surrounding piles MR3 and MR4 showed two or three distinct layers that were rarely seen around the dry piles. The inner layer was often a brown clay rich soil, similar to the remoulded soil seen in the dry piles. The outer 1 or 2 layers were either a light brown clay rich soil, or a light brown clay rich soil with green tingeing, or containing green aggregates of quartz silt. Where three layers were observed the outermost layer was often of similar colour and texture to the inner layer. This indicates a similar mode of production for the inner and outer layers of remoulded material, with heavier and less clay rich material pushed into the middle of the remoulded zone. The separation of the layers within the remoulded zone also indicates vertical movement of material around the pile shaft.

The abundances of silica observed within the remoulded and undisturbed material do not at first glance support the splitting of aggregations theory if aggregations are cemented with silica as suggested by Sherwood (1967) – if aggregates are cemented together with SiO_2 then it would be reasonable to expect a higher abundance of SiO_2 in the host material than in the remoulded soil as cementing agents would have been lost. However, SiO_2 is a major component of concrete, so while it may be expected that disaggregated clays would have a lower abundance of silica than aggregated clays (see section 5.4), the high abundance of silica in the remoulded zones may be attributed to some leaching of the cement mixture from the concrete into the remoulded soil.

As the remoulded material has a smaller percentage of CaO than the undisturbed material, it would be reasonable to assume that calcium oxide is a contributing factor in the aggregations of clays in the Mercia Mudstone Group as suggested by Davies (1967). Pile MR3 showed a gradient in the percentage of CaO with the lowest at the contact at the soil-pile interface, and the highest percentage at the contact with the undisturbed material. If Davies (1967) is correct that CaO is a cementing agent (and hence would be found in lower abundance in disaggregated soil) this would suggest that the soil closest to the pile is the most disaggregated.

The collective evidence from all four piles would appear to show that some disaggregation of aggregated clays contributes to a remoulding effect of soil surrounding piled foundations. The over-rotated piles had a remoulded zone which appeared to show signs of outwards migration of soil within the remoulded zone, and all piles showed at least one example of uplifting of beds within otherwise undisturbed material, indicating that the dominant force exerted upon the remoulded zone is upwards.

5.13 Discussion of the Piling Process and Its Effects on the Surrounding Soil

5.13.1 Drilling of the Pile

As the auger is screwed into the soil, the flights come into contact with the soil and break up the soil. The majority of the broken soil is moved upwards through the auger and reaches the surface as a spoil heap. The flights of the auger exert a stress upon the soil and gouge soil from the host mudrock, which is shown by the undulating boundary between the remoulded and undisturbed soil indicating that soil is broken, rather than cut, away into the pile shaft.

The pressure and remoulding action of the flights of the auger cause silt sized, bound aggregations of clays to break apart, leaving a zone of remoulding around the pile, sometimes with more than one layer. Where 1-2mm aggregations of green silt were observed within the remoulded zone, incomplete breakdown of the host mudrock must have occurred, and these aggregations are the remains of broken pieces of green silt layers from within the undisturbed stratigraphy. It was noted that the abundance of these silt aggregations did not correspond with the stratigraphy directly adjacent to a given section of the remoulded soil, suggesting that remoulded material must have been transported before final deposition. Vertical textures observed within thin sectioned samples and sub-vertical textures noted using the naked eye also indicate a sub vertical transport of material before final deposition.

Uplift of beds within the undisturbed soil adjacent to the remoulded soil indicate that there is an upwards pressure exerted upon the soil surrounding the auger. This uplifting must have occurred either as a direct result of the flights of the auger during the initial drilling – possibly where the auger was not being pushed into the soil at sufficient speed for the flight to complete a full rotation within the correct depth – or that upwards movement of the remoulded zone created sufficient upwards pressure to bend the beds upwards as it moved.

5.13.2 Removal of the Auger/Infilling with Concrete

During this stage, it is reasonable to conclude that fissures were created, as it was noted that where fissures were present in samples with more than one layer, fissures crossed the layer boundary indicating that remoulding was complete before fissures were created.

The pressure of the concrete infilling the pile, along with the rotating auger tip will have allowed mixture between the concrete and the remoulded soil, as indicated by the presence of SiO_2 and aggregates within the remoulded zone.

5.13.3 Curing of Concrete

During the six days that the piles were cured, leaching of the SiO_2 must have occurred due to its heightened abundance in the remoulded zone surrounding all piles. Water may have drained down fissures in the remoulded zone, causing the water content tests to not show the predicted increase in water content at the soil-pile interface as observed by Skempton (1959). Heating of the concrete during curing may have contributed to a zone of weakness often observed at the soil-pile interface by causing clays to dessicate.

5.13.4 Presence of Water

It was noted that in the piles which were augered with the addition water there was a higher instance of the remoulded zone splitting into two or three layers. Where the zone was split into two layers it might be reasonable to assume that the layers represent two differing degrees of remoulding. However, in the remoulded soil around pile MR3, where three layers were observed, the middle layer had a much paler brown matrix than observed in the inner and outer layer, and had a much higher silt composition.

The lack of high swelling clays within the mineral assemblage means that the remoulded zone would not have swelled greatly with the addition of water.

6 Conclusions

The main aim of the work presented within this thesis was to discover the effects of Continuous Flight Auger (CFA) piling upon the Mercia Mudstone Group at the soil-pile interface, and to investigate the effects of over-rotation and the addition of water during installation of the pile on the soil-pile interface.

Previous work has shown that soil disturbance may be observed around piles installed in clay rich soils (Pellew, 2002; Leach *et al.* 1976). The paucity of literature surrounding the problems with piling in the Mercia Mudstone Group has provided a poor framework for engineering within this troublesome group in the past and it is hoped that this study will provide some insight and some building blocks for further research.

When installed in the Mercia Mudstone Group, piles using the Continuous Flight Auger (CFA) method exhibit a zone of remoulded soil surrounding the pile shaft. This remoulded soil is distinctly different from the host soil in colour and texture. The remoulded zone ranges in thickness from 0-50mm, with thicknesses varying greatly both laterally and vertically around all piles.

The pile which had the thinnest average remoulded zone of soil was pile MR2 with an average thickness of 12mm. This indicates that process of installing pile MR2 (normally augered and without the addition of water) caused the least disturbance within the soil out of all four piles. As pile MR2 was installed to replicate normal pile installation this is the expected result.

At least one sample from all four piles exhibited a remoulded zone which was split into layers. The pile with the most layers in the remoulded zone was pile MR3 (installed with the addition of water and over-rotated), where three layers were seen in all but one sample – 510-860mm below ground level. It is unclear why this has happened. However, with the other three piles, splitting of the remoulded zone occurred mainly at the greatest sampled depths. This may coincide with the harder, green silty beds seen within the stratigraphy.

The remoulded zone is potentially created by the breakdown of silt sized aggregations into their constituent clay minerals within the host mudrock. If this is the case it would be reasonable to expect it to be reflected within the particle size distribution (PSD) curves, with a greater percentage of clays being found within the remoulded zone than within the host soil. Three of the four piles (excluding pile MR1) do indeed show this trend. The host mudrock does not appear to have a particularly high clay content (approximately 7%), and the increase seen within the remoulded zone is only in the order of approximately 5% for each pile, suggesting that not all aggregates of clays present within the host soil are fully broken down by the piling process.

The boundary between undisturbed and remoulded material is sharp and undulating in all cases. At the boundary between remoulded and undisturbed material, beds within the undisturbed soil were seen to rise against the contact. This implies that the dominant movement of the soil directly surrounding the pile shaft is in an upwards direction. In the remoulded zone of all four piles vertical layering was seen, with a vertical texture (this is especially clear in thin section). Around pile MR1, silt aggregations were observed showing tails, also indicating vertical movement. This means that when the pile is augered, the dominant movement of the remoulded zone is vertically upwards, towards ground level.

The dominant texture found within the remoulded zone surrounding each of the piles was a series of fractures fanning vertically from the pile in a clockwise direction. It can be concluded that this texture has arisen directly from the action of the auger. As the fissures crossed layer boundaries within the remoulded zone, it can be concluded that fissures were created either during or after the removal of the auger. A greater degree of fissuring was observed around piles which were installed dry than those installed wet, indicating that the remoulded soil around the wet piles deforms in a ductile manner as opposed to the brittle failure observed by the fissuring around the dry piles.

Aggregations of green silt were seen in the remoulded zone around all four piles. The lowest percentage was seen around pile MR2 where very few aggregates were seen, and the highest percentage was seen in the second of three remoulded layers developed around pile MR3. To be formed, the aggregations of silt must presumably first be broken from the host soil, but not be broken to the extent where they no longer form competent aggregations. It is therefore likely that in the case of MR2 not enough green silt material was cut away from the host soil to give a large abundance of aggregations. In the case of piles MR1 and MR4, 2% of the remoulded zone in one section was formed of aggregates (sections at 0-495mm and 951-1342mm below ground level respectively), with none being present at other depths. In the remoulded zone surrounding pile MR3, silt aggregations were observed in the second layer of remoulding only, making up up to 50% of the total layer. It is unclear why the silt aggregations were concentrated within this layer in this manner, along with a paler brown matrix than was seen within the other remoulded layers.

Over-rotation of the auger during pile installation did not appear to cause any specific features in the remoulded zone.

When the dry and over-rotated pile was installed the auger became blocked, this was not the case in the wet and over-rotated pile. Although this only occurred once, it may still suggest that over-rotated piles are more likely to experience blocking of the auger.

Chemical and mineralogical analysis of the remoulded and undisturbed soil did not provide conclusive evidence that the aggregates of clay were cemented using either calcite or silica. The most probable explanation for the increase in abundances of silica in the remoulded zone as compared to the undisturbed material was that silica was leached from the concrete into the remoulded material during the piling process.

The presence of angular aggregates of concrete within the remoulded zone of all piles except MR4 indicates that concrete stuck to the auger from previous piling jobs becomes incorporated within the remoulded soil. It was initially thought that these aggregates were a result of mixing between the fresh concrete and the remoulded zone, but textures within the remoulded zone indicate this not to be the case.

Preliminary triaxial testing indicated that the remoulded zone may have a greater undrained strength and a lower critical state friction coefficient than undisturbed samples by approximately 0.24. While the triaxial tests carried out within this study were by no means exhaustive, these may be considered as a guide to behaviour of the soil. The decrease in value of M within the remoulded zone may be considered congruent with the release of clays within the remoulded zone as it shows behaviour tending towards clay behaviour.

Due to the gouging action caused by the auger within this stiff clay, some consideration should be given to auger design for specific ground conditions.

6.1 Suggestions for Further Work

As with most research, this project has generated many questions which could be addressed by further work. The following section lists suggestions for further work.

The triaxial and particle size distribution (PSD) tests presented within this dissertation give a valid indication of trends but are not exhaustive – further testing will show how representative these results were.

While it has been ascertained that in the Mercia Mudstone Group remoulding occurs in the area surrounding the piles, little has been achieved in this project to understand the actual effect this has upon the load settlement behaviour of the piles. One could gain important insights into the nature of the remoulded zone by performing load tests on piles subjected to over-rotation and the addition of water.

The work outlined in this dissertation has given a good insight into the effects of water and over-rotation of the auger on the physical appearance of the remoulded zone, however due to physical and time constraints the deepest section studied was taken from only 1981mm below ground level. Further studies may wish to observe the soil-pile interface at a greater depth to give an indication of the effects of depth.

Further work should seek to test the findings of this dissertation in other dominant clay lithologies, such as the London Clay. While some work has been done on the soil-pile interface in the London Clay, this work has mainly concentrated on strength properties, and less on physical properties like those discussed in this dissertation. While work on strength is obviously very valuable, understanding the processes active at the soil-pile interface is very important in minimising the potential loss of shaft capacity in piles.

It would also be interesting to test the Edwarlton Member of the Mercia Mudstone Group, due to the past observations of difficult engineering behaviour (Atkinson *et al.*, 2001). It would also be valuable to identify the effects of gypsum veining on remoulded soil around piles, as these are common within the Mercia Mudstone Group, but not present at the test site.

Attempts should be made to replicate the remoulding seen in the field within the laboratory, to better understand the processes occurring during remoulding around piles.

Little is known about the cementing agent of aggregates within the Mercia Mudstone Group, therefore further experiments should attempt to characterise this cement.

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1.1 Maps

BGS map, Leicestershire XXIII, S.E.

1.2 Websites

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http://www.geoforum.com/info/pileinfo/images/fond6.jpg (December, 2008)

	11S	13A	13B	14A	24A	24B	23C	23S	21A	33A	33B	33C	33D	24BA
SiO2	55.9	35.9	51.3	44.0	51.0	43.6	41.9	51.1	44.0	48.1	44.2	30.8	41.6	38.7
Al2O3	10.9	11.1	11.1	10.6	10.3	12.1	13.9	10.4	11.1	11.8	10.2	9.15	9.75	8.26
CaO	8.04	12.0	8.11	10.5	8.69	10.7	8.98	8.84	10.3	8.56	11.2	17.8	12.6	7.66
Fe2O3	4.74	5.41	4.83	4.74	4.21	3.52	7.04	4.42	5.06	5.29	4.04	4.33	3.78	3.42
K2O	4.36	4.78	4.64	4.64	4.21	4.68	5.59	4.36	4.88	4.65	4.21	4.25	4.12	3.35
MgO	4.89	11.6	7.77	9.93	6.35	7.85	7.17	6.10	9.68	6.57	7.86	10.96	8.40	5.71
MnO	0.155	0.362	0.192	0.266	0.224	0.318	0.216	0.211	0.261	0.225	0.302	0.425	0.321	0.195
Na2O	0.187	0.112	0.150	0.124	0.133	0.132	0.132	0.183	0.129	0.138	0.114	0.087	0.132	0.114
TiO_2	0.113	0.147	0.172	0.156	0.116	0.114	0.110	0.105	0.156	0.121	0.115	0.089	0.111	0.085

	24BS	32S	31A	31B	31C	31S	44A	41S	44C	44S
SiO2	54.7	36.3	57.9	46.8	39.7	46.5	55.0	57.6	42.2	47.2
Al2O3	11.4	8.89	13.4	9.5	10.6	10.5	11.8	10.7	11.0	11.9
CaO	7.07	11.9	4.58	10.3	10.9	9.76	6.73	6.58	11.8	8.88
Fe2O3	4.83	3.85	5.93	3.43	4.85	4.45	5.34	4.66	5.41	5.30
K2O	4.85	3.80	5.54	4.23	4.80	4.62	4.77	4.50	4.65	4.66
MgO	5.02	7.86	5.40	8.86	10.0	8.47	5.31	5.19	7.26	8.22
MnO	0.160	0.269	0.124	0.248	0.254	0.210	0.163	0.129	0.156	0.210
Na2O	0.187	0.112	0.181	0.135	0.120	0.183	0.159	0.222	0.127	0.159
TiO_2	0.112	0.088	0.199	0.156	0.150	0.159	0.112	0.169	0.163	0.163

Appendix 1: Raw data from major element analysis of samples

Numbers given are percentages of the whole rock

	11S	13A	13B	14A	24A	24B	23C	23S	21A	33A	33B	33C	33D	24BA
As	5.17	5.34	5.26	4.59	1.99	5.56	6.91	4.61	5.75	5.32	4.63	4.29	4.75	5.04
Ba	408	384	406	332	354	391	390	392	342	426	353	232	336	501
Be	2.64	2.34	2.35	2.14	1.10	2.73	3.17	2.38	2.26	2.59	2.27	2.20	2.21	2.24
Bi	<	0.309	0.581	0.287	<	<	<	<	0.28	<	<	<	<	<
Cd	0.188	0.146	0.16	0.145	0.057	0.160	0.136	0.126	0.146	0.137	0.115	0.103	0.114	0.108
Co	14.2	14.7	14.3	13.7	6.50	19.9	17.2	14.1	13.7	16.6	14.0	12.6	15.0	14.3
Cr	68.0	78.6	83.7	74.5	29.5	54.9	69.8	56.4	73.9	61.4	48.2	45.1	56.9	53.8
Cs	8.16	9.35	8.98	8.35	3.81	9.21	10.3	7.69	9.14	8.82	7.52	6.90	7.17	7.50
Cu	39.1	23.1	39.3	21.4	64.3	81.6	13.2	38.0	18.1	35.5	64.6	8.10	55.9	39.3
Ga	17.2	15.6	15.3	14.1	7.477	18.2	22.0	16.4	15.4	18.0	15.6	14.4	15.5	16.3
Ge	1.75	1.17	1.41	1.16	<	1.28	1.55	1.39	1.26	1.37	1.18	1.01	1.10	1.32
Hf	2.85	2.77	3.53	3.00	1.46	2.29	2.31	2.68	3.22	2.89	2.57	1.70	2.43	2.57
Li	61.3	45.4	45.7	42.2	47.0	53.8	60.7	52.2	43.6	54.5	45.1	39.6	45.4	46.4
Mo	1.34	1.27	1.00	0.945	0.382	0.542	1.40	0.936	1.35	0.892	0.788	0.882	0.783	0.827
Nb	12.7	11.0	12.2	11.1	5.96	12.1	14.1	12.1	12.0	13.4	11.9	10.0	11.7	12.3
Ni	32.5	39.6	37.7	34.9	29.7	38.6	38.1	28.9	36.4	32.8	28.5	25.0	27.6	28.1
Pb	12.0	4.77	6.47	6.26	4.01	5.51	11.1	9.07	5.79	9.07	7.05	6.35	6.75	8.78
Rb	141	116	110	101	118	137	160	133	117	137	121	112	123	127
S	923	174	220	106	<	138	164	266	133	143	143	147	131	156
Sb	1.17	1.08	1.02	0.873	<	<	1.73	<	0.997	1.08	<	<	<	<
Sc	10.3	9.87	9.60	9.15	9.57	10.9	12.7	9.54	9.38	11.0	9.47	8.33	8.94	9.37
Sn	3.593	2.60	2.99	2.57	1.018	2.426	2.652	2.364	2.65	2.415	2.154	1.895	2.09	2.114
Sr	104	53.0	59.5	55.1	59.8	58.0	57.4	88.3	53.2	63.7	54.1	48.4	73.3	65.1
Ta	0.829	0.903	0.962	0.878	0.451	0.888	0.873	0.779	1.07	0.895	0.806	0.706	0.817	0.792
Th	7.33	8.33	9.14	8.27	3.97	7.53	7.73	6.92	8.94	7.73	7.13	5.62	6.61	6.86
Tl	0.538	0.532	0.525	0.489	0.241	0.574	0.604	0.482	0.525	0.559	0.474	0.410	0.448	0.465
U	2.25	2.63	2.72	2.39	1.17	3.31	2.51	2.08	2.66	2.23	2.22	1.75	2.09	1.98
V	76.7	76.0	69.9	61.3	68.8	83.2	108	68.3	67.2	79.5	72.1	58.8	68.1	64.9
W	1.35	1.51	1.60	1.45	0.703	1.27	1.60	1.28	1.61	1.59	1.26	1.08	1.25	1.24
Y	22.5	21.8	24.5	23.8	22.6	22.2	21.2	22.2	24.0	25.3	22.0	18.2	22.3	18.3
Yb	1.86	59.7	55.5	52.0	1.72	1.70	1.99	1.74	55.1	1.89	1.69	1.42	1.62	1.68
Zn	57.5	147	230	174	50.1	61.3	66.4	49.9	200	57.2	50.5	45.2	48.5	48.2
Zr	210	5.34	5.26	4.59	216	130	130	205	5.75	222	185	93.3	166	161

Appendix 2: Raw data from trace element analysis of samples

Numbers given are percentages of the whole rock

	24BS	32S	31A	31B	31C	31S	44A	41S	44C	44S
As	4.21	4.69	5.03	4.07	5.86	4.51	6.91	5.00	5.59	4.94
Ba	433	288	473	475	305	420	390	447	362	449
Be	2.54	2.20	2.85	1.93	2.29	2.13	3.17	2.34	2.35	2.44
Bi	<	<	0.335	0.304	0.297	0.253	<	0.314	0.317	0.305
Cd	0.129	0.343	0.166	0.144	0.155	0.15	0.136	0.195	0.365	0.164
Co	16.4	19.9	16.3	13.4	13.7	13.9	17.2	13.9	14.5	15.1
Cr	63.9	49.8	86.4	71.6	76.5	75.6	69.8	90.3	80.0	78.8
Cs	8.55	7.35	10.6	7.81	9.26	8.97	10.3	9.07	9.86	9.79
Cu	50.5	17.6	37.8	65.6	19.9	37.5	13.2	39.5	19.2	29.3
Ga	18.4	15.7	18.8	13.8	15.9	15.4	22.0	15.9	15.8	16.7
Ge	1.48	1.18	1.64	1.19	1.26	1.32	1.55	1.65	1.40	1.39
Hf	2.92	2.24	4.17	3.25	2.98	3.25	2.31	3.12	3.13	3.10
Li	60.6	47.6	56.6	39.0	44.1	48.1	60.7	53.0	45.8	52.5
Mo	1.046	0.978	1.02	0.853	1.09	1.01	1.40	1.13	1.12	1.03
Nb	13.8	11.8	14.7	11.4	11.9	12.0	14.1	11.8	12.3	12.2
Ni	32.2	27.2	45.8	32.6	36.8	34.7	38.1	37.4	37.5	40.3
Pb	9.70	7.49	7.46	4.26	5.83	5.46	11.1	8.34	7.27	6.32
Rb	148	126	130	98	115	123	160	121	121	127
S	429	363	114	144	150	290	164	430	174	447
Sb	1.08	1.02	1.19	0.647	0.982	0.876	1.73	0.989	1.28	0.978
Sc	10.6	8.85	11.7	8.45	9.61	9.15	12.7	9.39	11.0	10.5
Sn	2.384	2.116	3.15	2.45	2.68	2.57	2.652	3.48	3.10	2.77
Sr	79.5	76.5	60.1	51.4	50.6	88.6	57.4	107	51.3	72.4
Ta	0.861	0.722	1.13	0.897	0.921	0.926	0.873	0.886	1.07	0.917
Th	7.55	6.18	10.7	8.82	8.75	8.92	7.73	8.52	8.78	8.58
Tl	0.543	0.450	0.627	0.462	0.51	0.51	0.604	0.532	0.609	0.542
U	2.16	1.89	3.06	2.66	2.62	2.61	2.51	2.48	3.00	2.48
V	79.0	68.1	85.9	62.0	69.8	67.9	108	68.4	85.2	73.9
W	1.42	1.30	1.87	1.38	1.53	1.53	1.60	1.54	1.64	1.58
Y	24.8	18.3	27.7	24.2	22.2	22.9	21.2	23.2	24.9	24.1
Yb	1.94	1.58	66.9	48.4	57.4	53.7	1.99	56.4	60.4	60.2
Zn	56.5	49.5	292	221	184	202	66.4	221	202	191
Zr	246	139	5.03	4.07	5.86	4.51	130	5.00	5.59	4.94

Appendix 2 (Continued)

	11S	13A	13B	14A	24A	24B	23C	23S	21A	33A	33B	33C	33D	24BA
La	29.8	26.3	27.9	26.5	14.6	27.9	30.8	28.0	27.4	30.1	26.4	24.5	26.0	28.3
Ce	58.1	55.1	57.9	54.7	28.6	55.2	61.4	55.1	56.6	59.8	52.6	49.0	52.0	55.6
Pr	6.70	7.05	7.45	7.01	3.40	6.50	6.90	6.40	7.23	6.86	6.20	5.59	6.02	6.50
Nd	23.7	24.7	26.2	24.6	12.1	23.3	24.2	22.7	25.5	24.7	22.3	19.8	21.5	23.1
Sm	5.20	4.76	5.04	4.75	2.65	5.10	5.20	4.98	4.91	5.45	4.86	4.31	4.81	5.00
Eu	1.03	1.14	1.19	1.11	<	1.05	1.01	<	1.14	1.06	<	<	<	1.01
Gd	4.41	5.20	5.47	5.27	2.27	4.42	4.32	4.24	5.32	4.58	4.25	3.75	4.14	4.30
Tb	0.64	0.668	0.708	0.661	0.33	0.653	0.622	0.622	0.684	0.676	0.621	0.549	0.607	0.622
Dy	2.95	3.19	3.44	3.15	1.52	3.07	2.82	2.91	3.26	3.06	2.91	2.54	2.85	2.84
Ho	0.648	0.745	0.789	0.729	0.338	0.675	0.648	0.682	0.753	0.757	0.637	0.575	0.63	0.616
Er	1.68	2.13	2.18	2.08	<	1.72	1.60	1.61	2.15	1.72	1.65	1.43	1.60	1.59
Tm	0.258	0.296	0.312	0.295	0.134	0.271	0.255	0.252	0.306	0.273	0.256	0.217	0.254	0.246
Yb	1.66	1.75	1.84	1.72	0.836	1.69	1.63	1.58	1.79	1.72	1.61	1.37	1.56	1.54
Lu	0.266	0.267	0.288	0.269	0.13	0.261	0.26	0.254	0.278	0.275	0.256	0.211	0.247	0.247

	24BS	32S	31A	31B	31C	31S	44A	41S	44C	44S
La	30.1	25.3	31.7	26.8	27.6	27.6	30.1	27.9	28.2	28.1
Ce	59.2	50.0	64.9	55.4	56.8	57.0	59.4	56.1	56.9	57.7
Pr	6.95	5.81	8.50	7.22	7.29	7.34	6.94	7.17	7.64	7.42
Nd	24.7	20.7	30.0	25.3	25.5	26.0	25.0	25.2	26.8	25.9
Sm	5.38	4.59	5.83	4.95	4.89	5.05	5.32	4.88	5.27	4.99
Eu	1.06	<	1.34	1.17	1.14	1.18	1.07	1.16	1.21	1.21
Gd	4.60	3.98	6.13	5.38	5.32	5.47	4.63	5.21	5.53	5.38
Tb	0.66	0.576	0.764	0.696	0.672	0.696	0.647	0.656	0.736	0.692
Dy	3.06	2.66	3.59	3.31	3.20	3.37	2.94	3.10	3.30	3.23
Ho	0.697	0.593	0.814	0.751	0.74	0.753	0.679	0.699	0.742	0.741
Er	1.69	1.49	2.35	2.10	2.10	2.16	1.65	1.99	2.01	2.08
Tm	0.267	0.234	0.333	0.301	0.295	0.314	0.258	0.281	0.318	0.300
Yb	1.71	1.46	2.04	1.80	1.78	1.81	1.63	1.72	1.82	1.77
Lu	0.275	0.229	0.321	0.275	0.275	0.284	0.26	0.271	0.321	0.282

Appendix 3: Raw data from rare earth element analysis

Shown as parts per million

	13A	13B	14A	24B	23E	24A	23C	23B	23A	21A	33C	33B	33A	31A
Illite	80	97	88	0	98	12	21	62	88	87	93	0	85	94
Illite-smectite	18	0	8	82	0	75	64	0	6	8	0	87	0	0
Illite-smectite-chlorite	0	0	4	0	0	0	0	38	0	0	0	0	0	0
Chlorite	1	3	0	18	2	4	6	0	1	1	1	4	9	2
Kaolinite	1	0	0	0	0	8	9	0	5	5	6	9	6	4
Muscovite/ Phlogopite		X	X	X	X	X	X	X	X	X	X	X	X	X
Gypsum	X	X	X	X	X	X		X	X	X			X	X
Feldspar	X	X		X	X	X	X	X	X		X	X	X	X
Haematite	X			X				X		X	X	X		
Quartz						X				X	X			
Pyrophyllite		X		X	X	X		X	X	X			X	X
Magnetite														

Appendix 4: The <2µm fraction recorded for all samples

Numbers denote the percentage of a given mineral making up a given sample. X denotes where a mineral was found to be present but the abundance not achieved

	31B	31C	24BA	44A	43C	41A	43B	43A
Illite	0	95	0	90	97	0	93	0
Illite-smectite	97	0	97	0	0	74	0	93
Illite-smectite-chlorite	0	0	0	0	0	24	0	0
Chlorite	3	1	3	1	1	2	2	2
Kaolinite	0	4	0	9	2	0	4	5
Muscovite/ Phlogopite	X	X	X	X	X	X	X	X
Gypsum	X	X	X	X			X	
Feldspar	X	X		X	X	X	X	X
Haematite				X	X	X		
Quartz			X		X	X		X
Pyrophyllite	X	X						
Magnetite			X					

Appendix 4 (Continued)

	13A	13B	14A	24B	23E	24A	23C	23D	23A	21A	33C	31C	31B	31A
K Feldspar	18	0	0	31	36	43	37	32	31	25	41	30	19	16
Illite & mica	28	5	16	0	13	0	5	0	24	11	6	15	12	22
Kaolinite	0	3	0	0	0	0	0	16	0	0	0	0	0	0
Chlorite	14	2	6	5	6	1	2	4	8	4	3	6	4	12
Quartz	28	23	33	21	18	9	16	22	19	36	8	23	38	50
Plagioclase	2	0	0	5	2	0	6	0	0	0	0	2	0	0
Calcite	0	4	9	7	3	7	5	2	3	9	7	6	1	0
Haematite	9	61	16	31	23	40	29	24	14	16	36	18	26	0

	23BA	24BE	41A	43A	43B	43C	44A	44C
K Feldspar	25	29	19	24	32	1	36	32
Illite & mica	16	18	0	0	0	0	0	0
Kaolinite	0	0	0	0	0	0	0	0
Chlorite	7	6	0	6	5	1	0	4
Quartz	28	15	44	56	17	87	25	34
Plagioclase	0	1	3	4	4	1	0	0
Calcite	3	4	15	10	8	1	13	3
Haematite	21	26	20	0	21	4	26	17

Appendix 5 shows the whole rock XRD analysis for all samples

Numbers denote the percentage of a given mineral making up a given sample.

	Zone	Description	Notes
Fully weathered	IVb	Matrix only	Can be confused with solifluction or drift deposits, but contains no pebbles. Plastic, slightly silty clay. May be fissured
Partially weathered	IVa	Matrix with occasional clay–stone pellets, less than $\frac{1}{8}$ in. dia. but more usually coarse sand size	Little or no trace of original (zone I) structure, although clay may be fissured Lower permeability than underlying layers
	III	Matrix with frequent lithorelicts up to 1 in. As weathering progresses lithorelicts become less angular	Water content of matrix greater than that of lithorelicts
	II	Angular blocks of unweathered marl with virtually no matrix	Spheroidal weathering. Matrix starting to encroach along joints; first indications of chemical weathering
Unweathered	I	Mudstone (often fissured)	Water content varies due to depositional variations

Table 2.1 shows the weathering profile of the Mercia Mudstone Group (Chandler, 1969)

Authors	Location	Weathering Grade	α	β
Chandler and Davis (1973)	Various sites	IV–III	0.45 (a)	–
Foley and Davis (1971)	Leicester	IV–II	0.45 (a)	>0.6 (b)
Leach *et al* (1976)	Kilroot, Co.	II	0.3 (a)	1.71 (b)
Leach and Thompson (1979)	Antrim	IV–III	0.3 (a)	0.86 (b)
Leach and Mallard (1979)	Berkeley, Avonmouth	Layered profile	0.33	0.82
Dauncey and Woodland (1984)	Birmingham	III	0.31–0.44	0.82–1.06
Houston (1995)	Burnaston, Derby,	IV–II	0.45	–
Kilbourn *et al* (1989)	Cardiff	IV–II	0.375	–

Table 2.2 shows the effect of weathering on the strength of the Mercia Mudstone Group (Chandler *et al.*, 2001)

Authors	Site	Grade	Foundation type	Gross bearing pressure (kPa)	Total settlement (mm)
	(a) under-bridge	III	(a) Strip: 41×2.75×1.5 m	241	10.2
	(b) over-bridge	I	(b) 11.6×6.1×2.45 m	290	13.7
	(c) overbridge M1 bridges Leicestershire	I	(c) 116×6.1×1.45 m	290	15.2
Davis (1970)	20 storey block of flats, Highgate Birmingham	III at founding level grading to II–I at about 3 m below founding level	Pads and strips below a basement 3.7 m below ground level.	235 based on a plan area of 35×17 m and gross load of 140 MN	55
Kitchener and Ellison (1997)	Second Severn Crossing cable-stayed bridge and viaduct, Avonmouth	Varies : II–IVb	Large spread caissons Piers N37–N46 27×6 m with extension to 10 m width. Mass concrete added where sandstone was very thin over mudstone	600	<25
Lord and Nash (1975)	Loughborough University Chemical Engineering Building	II–III	3.05 m square pads at depths of 2–5 m below ground level	300	7 mm max. by end of construction. Very little creep
Marsland (1977) and Marsland *et al* (1983)	Bridge abutment foundation M56/M6, Appleton, Cheshire	IV with III	Re slab 25×5×1.1 m; 1.6 m below original ground level	120	10
Meigh (1976)	Oldbury Nuclear Power Station Gloucestershire	Interbedded profile of siltstones, mudstones and sandstones	Concrete plugs, 2.59 m dia. 11.5 m below ground level	1265	105–125 (extensive creep; differential 10–13)

Table 2.3 shows the strength properties of the Mercia Mudstone Group from the literature (Chandler *et al.*, 2001)

Author	Method of preparation	Member	Liquid Limit	Plastic Limit
Atkinson et al. (2001)	Pass 20 times through a meat mincer at the plastic limit	Edwarlton	66	27
Atkinson et al. (2001)	10 minutes working	Edwarlton	33	23
Atkinson et al. (2001)	Pass 20 times through a meat mincer at the plastic limit	Unknown	42	21
Atkinson et al. (2001)	10 minutes working	Unknown	30	21
Chandler et al. (2001)	10 minutes working	N/A	N/A	N/A
Sherwood (1967)	10 minutes working			

Table 2.4 shows plastic indexes recorded for the Mercia Mudstone Group in the literature

Weathering Zone	Undisturbed Samples					Recompacted Samples				
	No. of Results	c' (kN/m^2)		φ' (degrees)		No. of Results	c' (kN/m^2)		φ' (degrees)	
		mean	range	mean	range		mean	range	mean	range
Zone 11	2	47	14 - 80	28	26 - 30	0	-	-	-	-
Zone 111 & 1Va	9	14	2 - 25	27	25 - 31	5	7	4 - 12	27	25 - 28
Zone 1Vb	1	0	-	23	-	0	-	-	-	-

Table 2.5 Effective stress parameters for Keuper Marl at Kilroot (after Leach *et al.*., 1976)

Start date	25/06/07
Site Address	Ibstock Brick Leicester Road Ibstock LE67 6HS
Total Volume required	$35m^3$
Target supply rate	$20+m^3$/day
Method of placing	Pump
Site Agitator	No
Concrete Ref.	CFA piling
Specification	N/A
Compressive strength class	C28/35
Design Chemical Class	DC1
Max wc ratio	0.55
Min Cement/combination content, kg/m^3	$340Kg/m^3$
Cement types	Blended acceptable
Max aggregate size, mm	20mm graded down to 10mm
Minimum Fines content	47%
Consistence	Target slump 175mm
Add mixtures	Plasticiser to be used
Slump tests (user testing)	Every load
Slump tests (supplier testing)	Every load

Table 3.1 shows the concrete specification for concrete used in field tests

Pile Number	Time to Bore	Number of revolutions of the auger to the toe	Time for over rotation	Number of revolutions at the toe	Time to concrete	Concrete Volume (m^3)	Other comments
MR1	6 minutes 48 seconds	121	6 minutes 21 seconds	202	30 minutes 54 seconds	1.19	Delayed due to blockage
MR2	7 minutes 35 seconds	165	N/A	N/A	2 minutes 0 seconds	0.76	
MR3	7 minutes 30 seconds	160	7 minutes 51 seconds	133	1 minute 15 seconds	0.76	
MR4	7 minutes 26 seconds	165	N/A	N/A	2 minutes 17 seconds	0.69	

Table 3.2 shows a summary of piles installed during field tests. Table courtesy of Tony Suckling (Stent Foundations)

Sample Number	Pile Number	Depth below ground level (mm)	Horizontal distance from the surface of pile (mm)	Obviously remoulded? (Y/N)	Tests done								
					W/C	PSD	AX	XRD	PI	SEM	TS	TRI	ICP
11	MR1	0-495	0-100	Both remoulded and undisturbed					X	X	X		
11S	MR1	0-495	Scraped*	Scraped*									X
13A	MR1	1177-1277	50	N				X		X			X
13B	MR1	1177-1277	0	Y			X	X		X			X
13C	MR1	1177-1277	<50	Y		X			X				
13D	MR1	1177-1277	>50	N		X			X				
14A	MR1	1581	0-11	Y			X	X					X
	MR1	774	0	Y	X								
	MR1	774	10	Y	X								
	MR1	774	20	Y	X								
	MR1	774	30	Y	X								

Table 4.1 shows the samples used for all tests

Sample Number	Pile Number	Depth below ground level (mm)	Horizontal distance from the surface of pile (mm)	Obviously remoulded? (Y/N)	Tests Done								
					W/C	PSD	AX	XRD	PI	SEM	TS	TRI	ICP
	MR1	774	50	N	**X**								
	MR1	774	70	N	**X**								
	MR1	977	18	Y	**X**								
	MR1	1077	18	Y	**X**								
	MR1	1077	50	N	**X**								
	MR1	1077	100	N	**X**								
	MR1	1077	150	N	**X**								
	MR1	1077	Scraped*	Scraped*	**X**								
	MR1	1481	0-11	Y-layer1	X								
	MR1	1481	11-25	Y-layer2	X								
	MR1	1581	0-11	Y-layer1	X								
	MR1	1581	11-25	Y-layer2	X								
	MR1	1681	0-11	Y-layer1	X								

Table 4.1 (Continued)

Sample Number	Pile Number	Depth below ground level (mm)	Horizontal distance from the surface of pile (mm)	Obviously remoulded? (Y/N)	Tests done								
					W/C	PSD	AX	XRD	PI	SEM	TS	TRI	ICP
	MR1	1681	11-25	Y-layer2	X								
	MR1	1751	0-11	Y-layer1	X								
	MR1	1751	11-25	Y-layer2	X								
21	MR2	690-1000	0-20	Y			X		X		X		X
21S	MR2	690-1000	Scraped*	Scraped*									X
21A	MR2	800-1000	0-10	Y		X							
23S	MR2	1000-1457	Scraped*	Scraped*									X
23A	MR2	1337	0	Y			X	X					X
23B	MR2	1337	0	Y						X			
23C	MR2	1337	50-100	N				X					X
23E	MR2	1337	10-50	Y				X		X			X
24A	MR2	1779	0-20	Y			X	X					X
24B	MR2	1779	20-70	N				X					X

Table 4.1 (Continued)

Sample Number	Pile Number	Depth below ground level (mm)	Horizontal distance from the surface of pile (mm)	Obviously remoulded? (Y/N)	Tests done								
					W/C	PSD	AX	XRD	PI	SEM	TS	TRI	ICP
24L2	MR2	1979	10-20	Y – layer 2		X							
	MR2	1437	0-3	Y	X								
	MR2	1437	50	N	X								
	MR2	1437	100	N	X								
	MR2	1337	0	Y	X								
	MR2	1337	50	N	X								
	MR2	1337	100	N	X								
	MR2	1237	0-3	Y	X								
	MR2	1237	50	N	X								
	MR2	1237	100	N	X								
	MR2	1829	0	Y	**X**								
	MR2	1829	50	N	**X**								

Table 4.1 (Continued)

Sample Number	Pile Number	Depth below ground level (mm)	Horizontal distance from the surface of pile (mm)	Obviously remoulded? (Y/N)	Tests done								
					W/C	PSD	AX	XRD	PI	SEM	TS	TRI	ICP
31	MR3	0-510	0-50	Y/N			X				X		
31S	MR3	0-510	Scraped*	Scraped*									X
31A	MR3	100-170	0-9	Y-layer1		X		X					X
31B	MR3	100-170	9-29	Y-layer2		X		X					X
31C	MR3	100-170	29-39	Y-layer3		X		X					X
32S	MR3	510-860	Scraped*	Scraped*									X
33A	MR3	860-960	0-2	Y-layer1				X		**X**			X
33B	MR3	860-960	2-22	Y-layer2				X		**X**			X
33C	MR3	860-960	22-70	Y-layer3				X		**X**			X
33S	MR3	860-1210	Scraped*	Scraped*									X
34S	MR3	1210-1831	Scraped*	Scraped*									X
34A	MR3	1210-1831	0	Y				X					X

Table 4.1 (Continued)

Sample Number	Pile Number	Depth below ground level (mm)	Horizontal distance from the surface of pile (mm)	Obviously remoulded? (Y/N)	Tests done								
					W/C	PSD	AX	XRD	PI	SEM	TS	TRI	ICP
33	MR3	1110	<22	Y					X				
34	MR3	1210	<20	Y					X				
31	MR3	1010-1210	0-100	Y/N								X	
	MR3	100	0-9	Y-layer 1	X								
	MR3	100	9-29	Y-layer2	X								
	MR3	100	29-49	Y-layer3	X								
	MR3	510	0-7	Y-layer1	X								
	MR3	410	0-7	Y-layer1	X								
	MR3	310	0-7	Y-layer1	X								
	MR3	510	7-14	Y-layer2	X								
	MR3	410	7-14	Y-layer2	X								

Table 4.1 (Continued)

Sample Number	Pile Number	Depth below ground level (mm)	Horizontal distance from the surface of pile (mm)	Obviously remoulded? (Y/N)	Tests done								
					W/C	PSD	AX	XRD	PI	SEM	TS	TRI	ICP
	MR3	310	7-14	Y-layer2	X								
	MR3	510	14-39	Y-layer3	X								
	MR3	410	14-39	Y-layer3	X								
	MR3	410	39-45	N	X								
	MR3	410	70	N	X								
	MR3	860	0	Y	X								
	MR3	760	0	Y	X								
	MR3	660	0	Y	X								
	MR3	760	50	N	X								
	MR3	1210	0	Y	X								
	MR3	1110	0	Y	X								
	MR3	1010	0	Y	X								

Table 4.1 (Continued)

Sample Number	Pile Number	Depth below ground level (mm)	Horizontal distance from the surface of pile (mm)	Obviously remoulded? (Y/N)	Tests done								
					W/C	PSD	AX	XRD	PI	SEM	TS	TRI	ICP
	MR3	910	0	Y	X								
	MR3	1210	30	Y	X								
	MR3	1210	50	N	X								
	MR3	1110	50	N	X								
	MR3	1010	50	N	X								
	MR3	910	50	N	X								
41	MR4	0-451	0-50	Y/N			X		X		X		
41A	MR4	0-451	0-18	Y				X					X
41B	MR4	0-451	Scraped*	Scraped*									X
41C	MR4	0-451	0-18	Y									X
41D	MR4	0-451	>18	N		X							
43S	MR4	951-1342	Scraped*	Scraped*									X

Table 4.1 (Continued)

Sample Number	Pile Number	Depth below ground level (mm)	Horizontal distance from the surface of pile (mm)	Obviously remoulded? (Y/N)	Tests done								
					W/C	PSD	AX	XRD	PI	SEM	TS	TRI	ICP
43A	MR4	1222	0	Y				X					X
43B	MR4	1222	50	N				X					X
43C	MR4	1222	100	N				X					X
44A	MR4	922	0	Y-layer1				X		**X**			X
44B	MR4	922	30	Y-layer2				X					X
44C	MR4	922	80	N				X					X
44	MR4	1542	0-30	Y			X		X				
	MR4	1222	20	Y	**X**								
	MR4	1222	50	N	**X**								
	MR4	1222	100	N	**X**								
	MR4	1322	0	Y	X								
	MR4	1222	0	Y	**X**								

Table 4.1 (Continued)

Sample Number	Pile Number	Depth below ground level (mm)	Horizontal distance from the surface of pile (mm)	Obviously remoulded? (Y/N)	Tests done								
					W/C	PSD	AX	XRD	PI	SEM	TS	TRI	ICP
	MR4	1932	0	Y	X								
	MR4	1842	0	Y	X								
	MR4	1742	0	Y	X								
	MR4	1642	0	Y	X								
	MR4	1542	0	Y	X								
	MR4	1642	50	N	X								
	MR4	1642	100	N	X								
	MR4	1642	150	N	X								
	MR4	1542	30	Y	X								
	MR4	1542	80	N	X								
	MR4	1542	130	N	X								
	Bulk red	N/A	N/A	N/A					X			X	
	Bulk green	N/A	N/A	N/A					X			X	

Table 4.1 (Continued)

*Scraped samples were removed from the pile shaft using a sharp knife and consist of a fine layer of material often seen on the pile shaft

W/C: Water Content

Ax: Axiocam

XRD: X-Ray Diffraction

PI: Plastic Index

PSD: Particle Size Distribution

SEM: Scanning electron Microscope

TS: Thin Section

TRI: Triaxial

ICP: Inductively Coupled Plasma

Table 4.1 (Key)

Pile	Thickness of remoulded zone	Approx. % of concrete/aggregate	No. of layers	Silt aggregations?	Fabric
MR1 (over-rotated)	22mm average. Maximum 50mm Minimum 0mm	2% in 0-495mm and 1277mm bgl sections	1: 0-1277mm bgl 2: 1277-1981mm bgl	0-495mm bgl – 2%	Clockwise fissures at all depths
MR2	12mm average Maximum 22mm Minimum 0mm	Up to 10% at 0-1000mm bgl	1: 0-1457mm bgl 2: 1457-1979mm bgl	Very few noted 0-1000mm bgl	Clockwise fissures at all depths
MR3 (over-rotated and water added)	35mm average Maximum 48mm Minimum 19mm	Up to 20% in layer 1 Approximately 2% of total remoulded soil	1: 510-860mm bgl 2: N/A 3: 0-510mm bgl 860-1210mm bgl	In layer 2 where remoulded zone layered. Up to 50%.	Weak fissuring, generally a granular, massive texture
MR4	28mm average Maximum 55mm Minimum 7mm	None seen	1: 0-951mm bgl 1342-1962mm bgl 2: 951-1342mm bgl	Only in section 951-1342mm bgl. Up to 2%	Weakly seen at 451-951mm bgl. Generally a massive texture

Table 4.2 summarises the main observations from the four piles (bgl = below ground level)

	depth	**Fissures**	**Green silt clasts**	**Layering of clays**
MR1 (over-rotated)	1177 - 1861mm below ground level	Strong fissuring fanning clockwise from the pile	Sub rounded, up to 4mm in diameter	No
MR2	1337-1779mm below ground level	Granular, massive texture	3mm, sub angular in shape	Dark and light bands of clays run parallel to the pile
MR3 (over-rotated and water added)	0-510mm below ground level	Weak fissuring fanning clockwise from the pile	1mm in diameter	No
MR4 (water added)	1342-1962mm below ground level	Weak fissuring	Up to 2mm in diameter	Dark and light bands of clays run parallel to the pile

Table 4.3 summarises the main observations using the axiocam

Pile sample taken from	Depth of sample	Fissures?	Grey silt clasts?	Layering of clays
MR1 (over-rotated)	0-100mm below ground level	30^{o} angle, 1mm spacing	Ranging from 0.4µm to 5mm. Sub angular.	On a sub mm scale, banding between dark and light clays, not visible in scanned sections
MR2	690-1000mm below ground level	Randomly orientated	Typically below 2mm in diameter	Disturbed layering of dark and light clays, visible at all magnifications
MR3 (over-rotated and water added)	0-510mm below ground level	Slides show layering of clays but a granular, unfissured texture	Sub-angular, all less than 2mm in diameter	Visible on all scales, layered fabric of dark and light clays
MR4 (water added)	0-451mm below ground level	No	Smallest average size of all the slides, sub mm scale	4 main layers seen, with smaller layers seen under the microscope

Table 4.4 summarises the main observations from the thin sections

Pile	Depth	Pores	Average grain size	Overall texture
MR1 (over-rotated)	1177-1277mm below ground level	2% of volume, 5µm in diameter	10µm	Varying between a smooth texture and a platy, flaky texture.
MR2	1000-1457mm below ground level	5% of volume, 5µm diameter	Averages from under 5µm to 20µm	Varying from granular to platy
MR3 (over-rotated and water added)	0-510mm below ground level	Layer 1 – N Layer 2 – 7-8% of volume, 6µm in diameter Layer 3 – 10% of volume, 5µm in diameter	Layer 1 - 10µm Layer 2 - 5µm Layer 3 - 25µm	Layer 1 – structureless Layer 2 – predominantly flaky with some smooth areas Layer 3 – granular
MR4 (water added)	922mm below ground level	<1% of volume, 5µm in diameter	25µm	Granular to platy, very little matrix seen

Table 4.5 summarises the main observations from the scanning electron microscope

Figure 2.1 The process of installation of a typical CFA pile
(http://www.geoforum.com/info/pileinfo/images/fond6.jpg, 2008)

Figure 2.2 Outcropping of the Mercia Mudstone Group, including the major basins
(Chandler *et al.*, 2001)

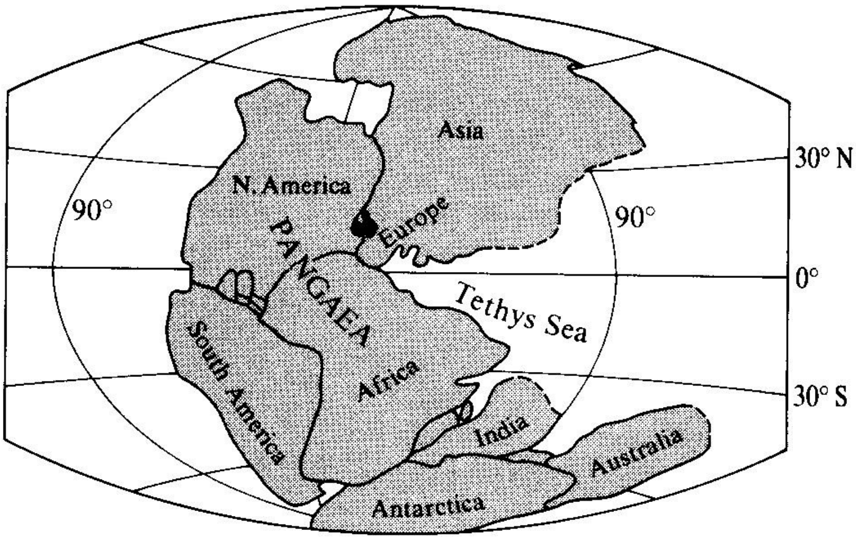


Figure 2.3 The position of the continents during the Permo-Triassic (after Open University S236 Geology)

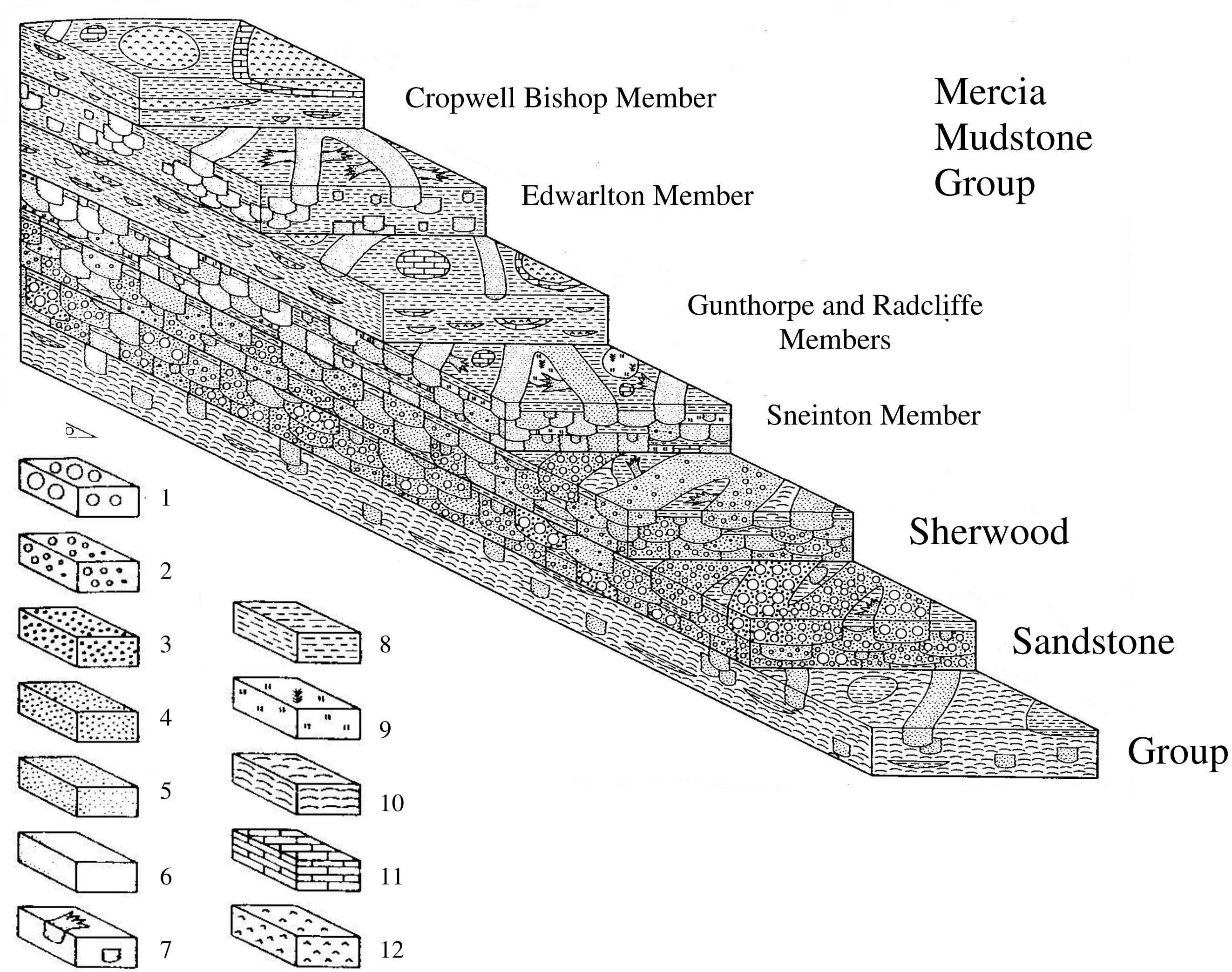


Figure 2.4 The progressive stratigraphy of the Mercia Mudstone Group and the Sherwood Sandstone Group, adapted from Madler (2002) Legend: 1-6 = fluvial channel deposits, 1 = coarse conglomerate, 2 = fine conglomerate, 3 = very coarse sand, 4 = coarse sand, 5 = medium sand, 6 = fine sand; 7 = crevasse-splay sand, 8 = floodplain and playa-lake mud, 9 = calcrete palaeosol, 10 = Aeolian dune and sheet sand, 11 = lacustrine playa and sabkha carbonate, 12 = playa to sabkha and lagoonal gypsum

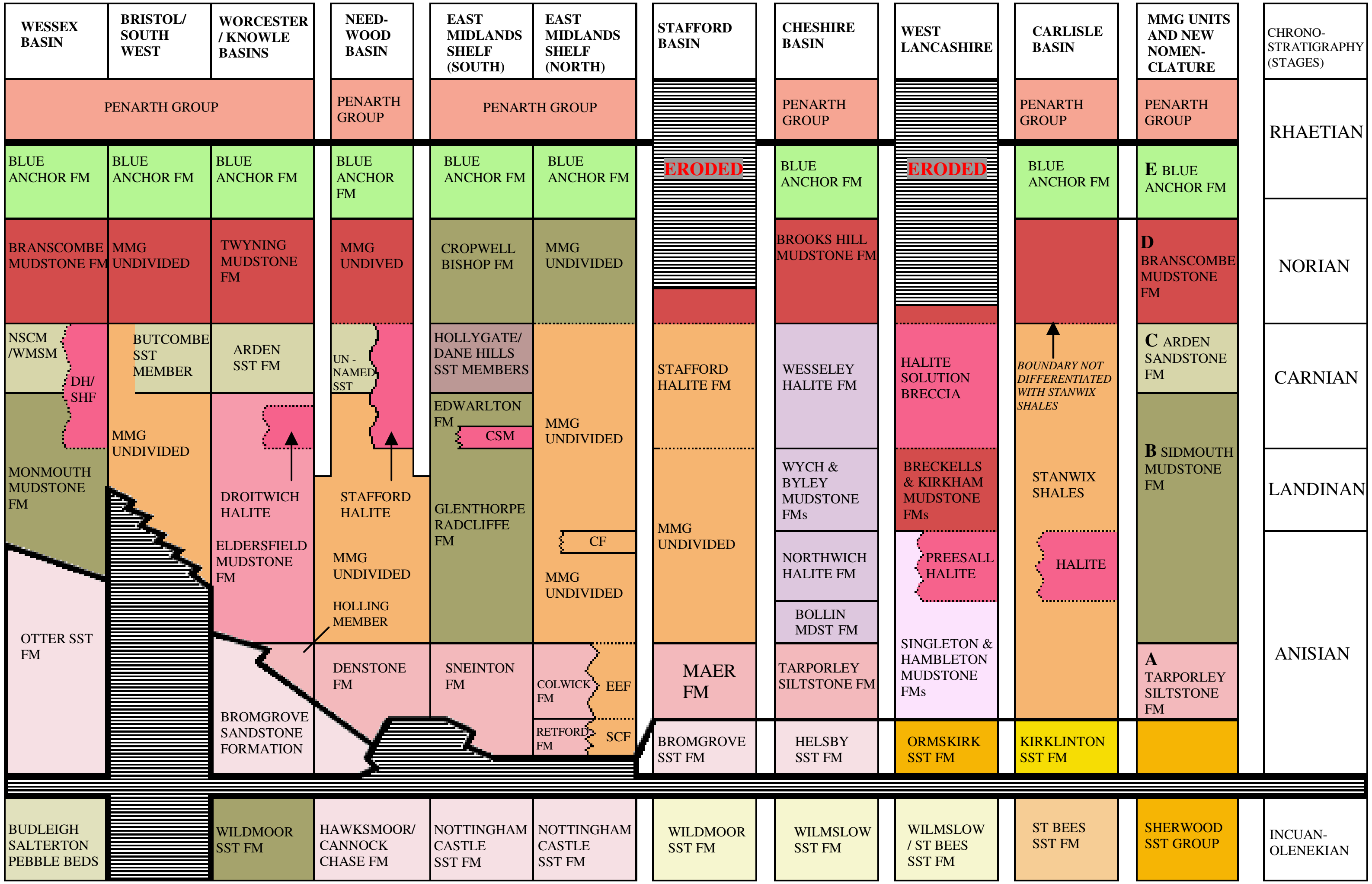


Figure 2.5 UK stratigraphy for the Mercia Mudstone Group comparing the old and new nomenclature (after Howard *et al.*, 2008). Gaps between columns indicate geographical separation of basins. Broken lines are boundaries seen only in boreholes. CF: Clarborough Formation; CSM: Cotgrave Sandstone Member; DH: Dorset Halite; MMG: Mercia Mudstone Group; NCSM: North Curry Sandstone Member; SCF: Seaton Carew Formation; SHF: Somerset Halite Formation; WMSM: Weston Mouth Sandstone Member; FM: Formation; SST: Sandstone; MDST: Mudstone

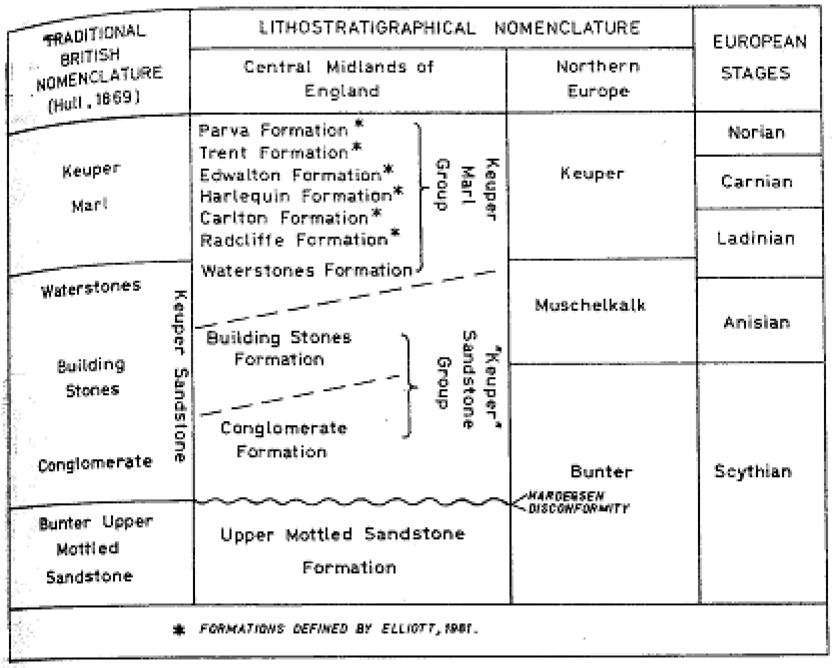


Figure 2.6 The stratigraphy of the Keuper Marl (Warrington, 1970)

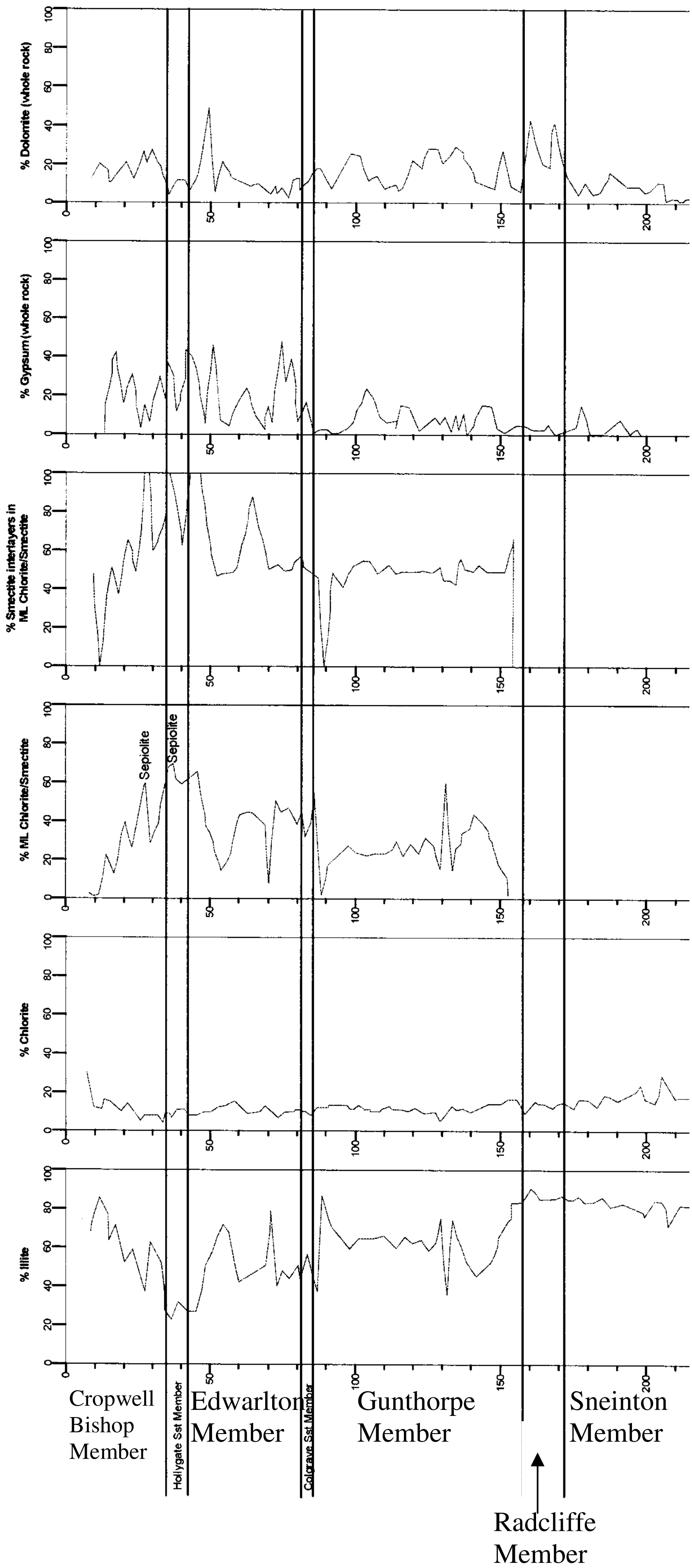


Figure 2.7 The composition of the clay fraction (<2µm) and the whole rock content of gypsum and dolomite of the Mercia Mudstone Group (after Chandler *et al.*, 2001)

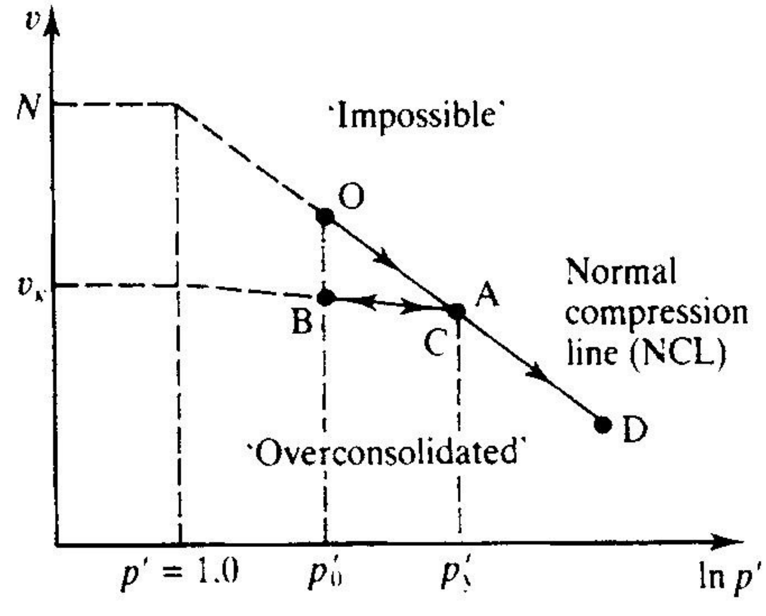


Figure 2.8 The relationship between specific volume and p' of an overconsolidated soil (Atkinson, 1993)

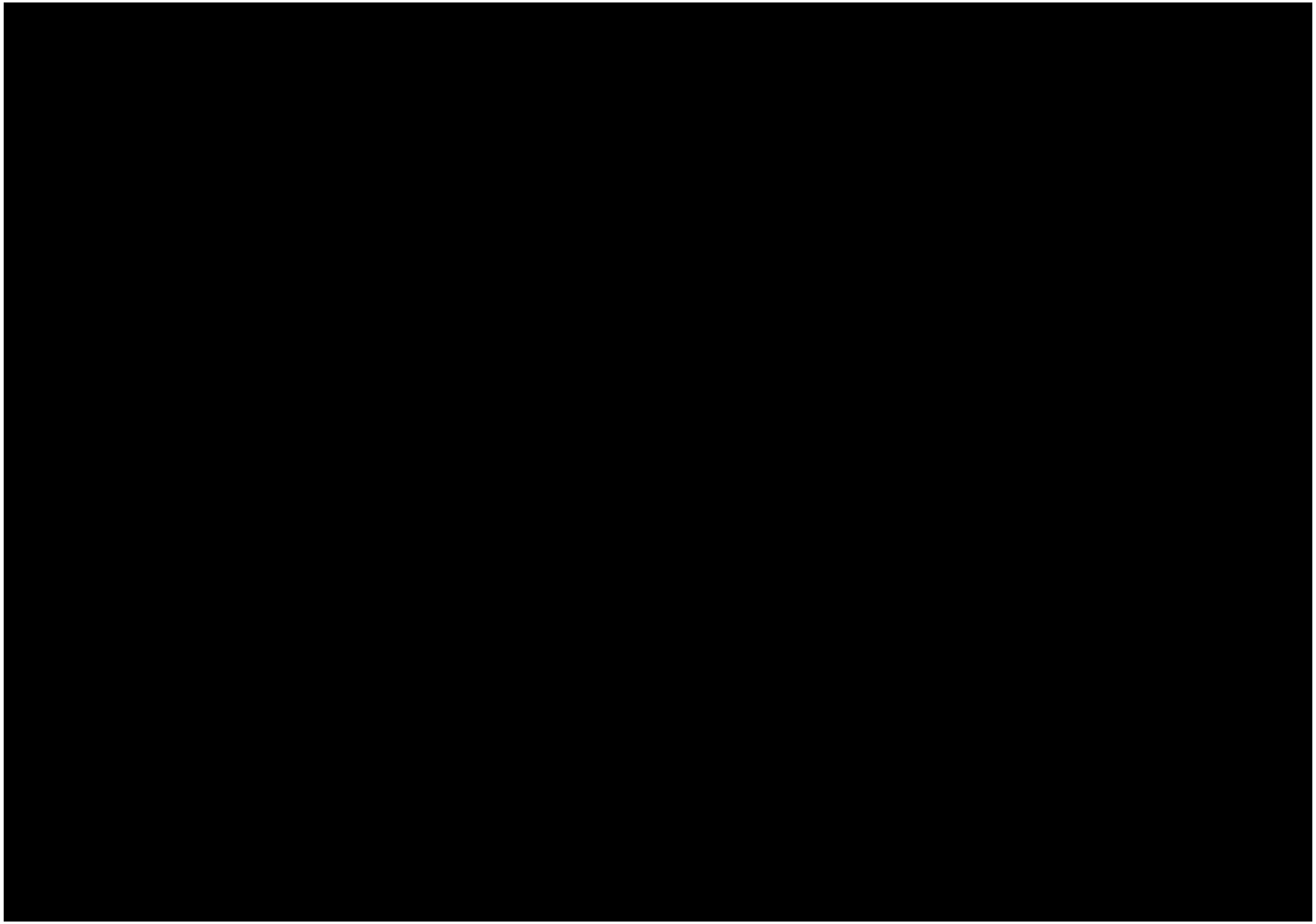


Figure 2.9 The geological map for the study area, blue circle indicates location of Ibstock brick Pit, blue square indicates location of enlarged map shown in Figure 2.10. Map adapted from BGS sheet XXIIIS.E. Leicestershire

Figure 2.10 shows an enlarged map of the Ibstock area, with the brick works marked on the map and indicated by blue circle. Legend is shown in Figure 2.9. Map adapted from BGS sheet XXIIIS.E. Leicestershire.

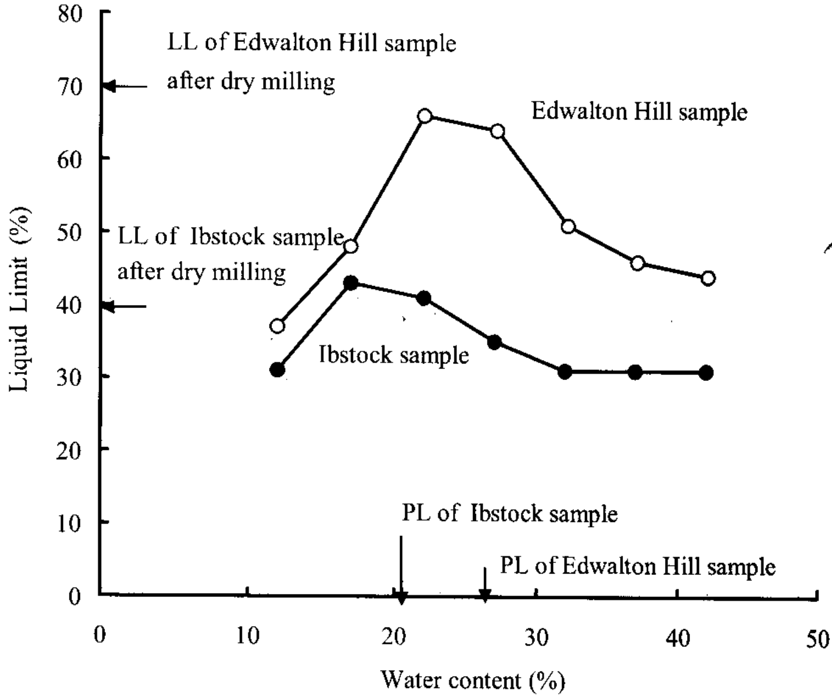


Figure 2.11 The variation in liquid limit with increasing water content when passed through a meat mincer (Atkinson *et al.*, 2001)

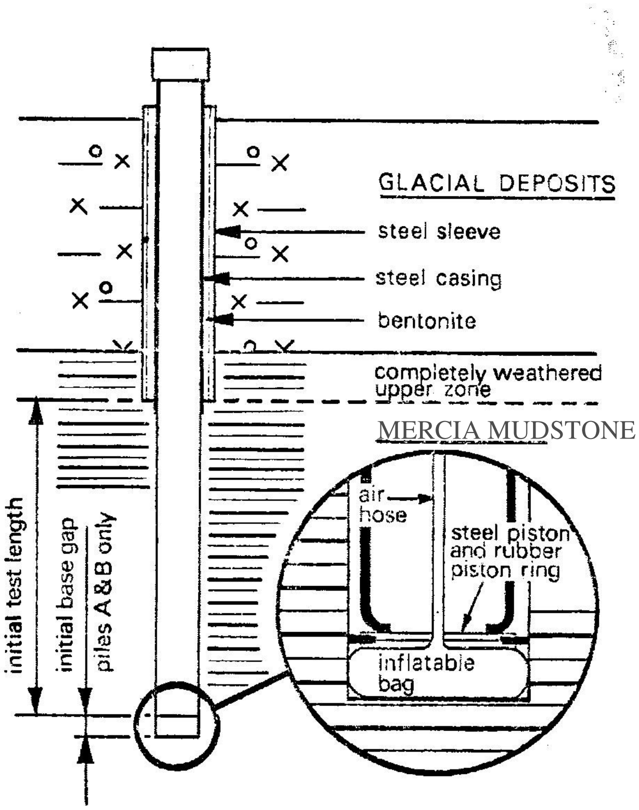


Figure 2.12 The field apparatus used to create a soft toe in piles, adapted from Leach *et al.* (1976)

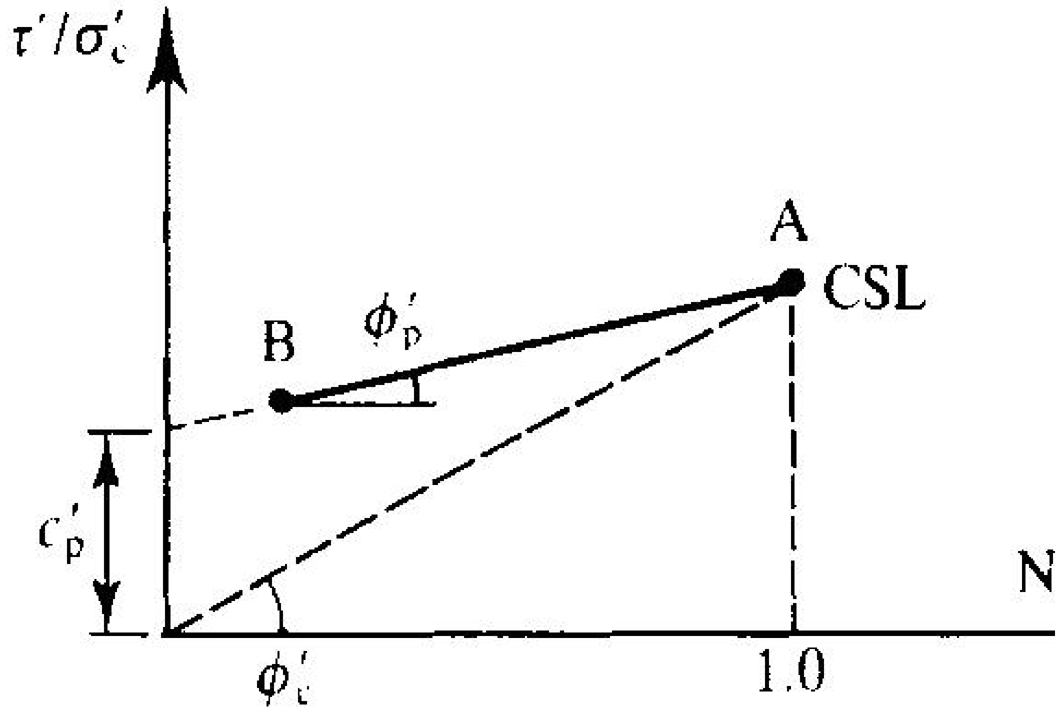
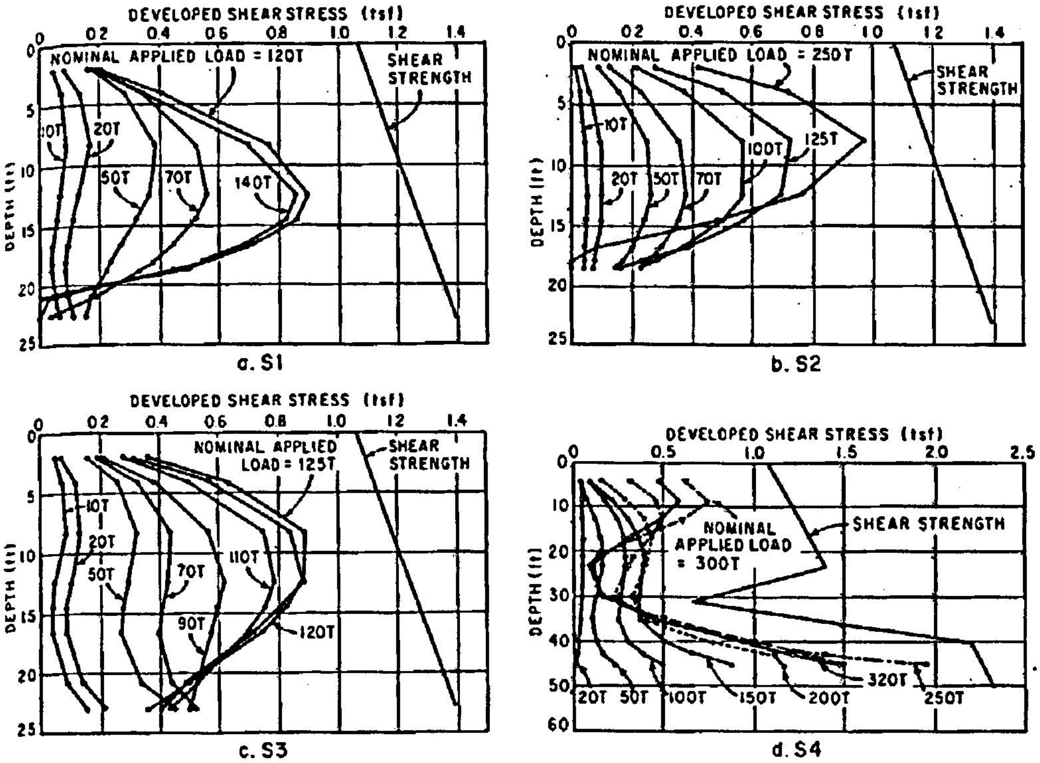


Figure 2.13 Graph showing the relationship between c' and ϕ' (Atkinson, 1993)



NOTE: Conversion to SI Units are as follows:
Tons per square foot to kilonewtons per square meter – Multiply by 95.8
Feet to meters – Multiply by 0.305
Tons to kilonewtons – Multiply by 8.9

Figure 2.14 The stress profile for four piles (after O'Neil and Reese, 1972)

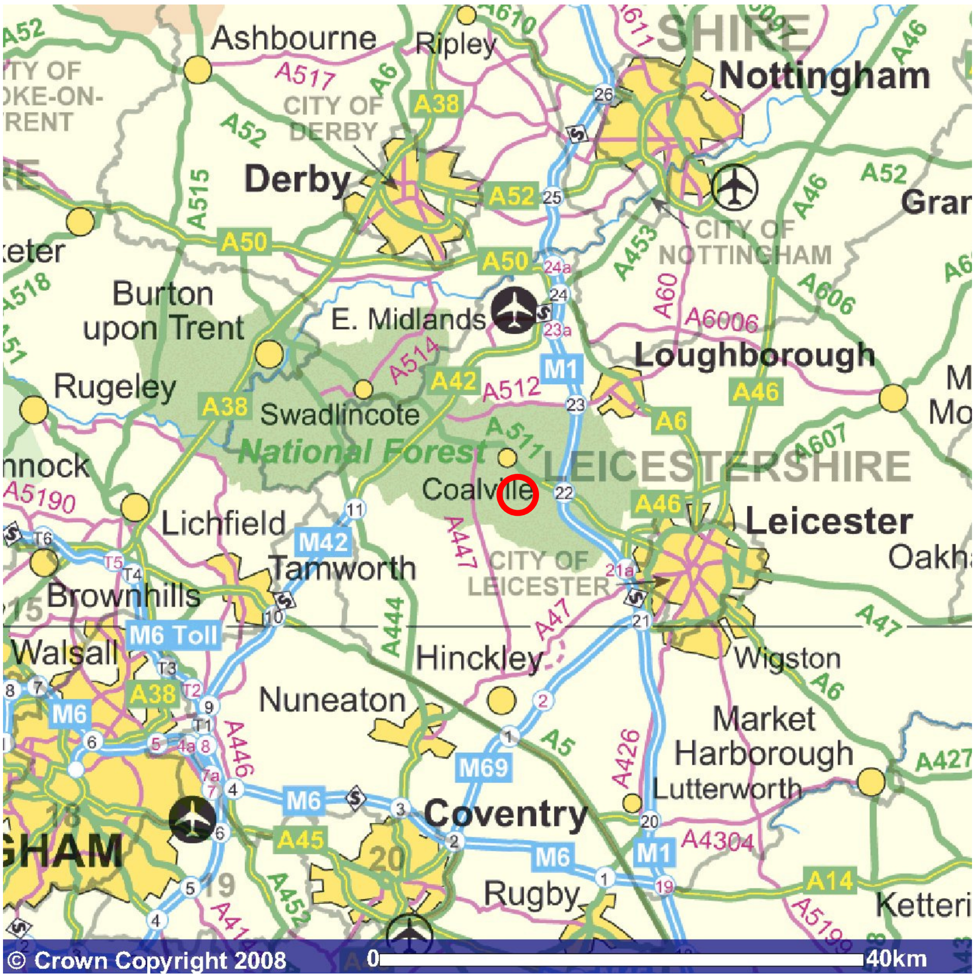


Figure 3.1 OS map showing the location of Ibstock Brick Pit (circled in red). Reproduced from (2008) **Ordnance Survey map with the permission of the Controller of Her Majesty's Stationery Office, © Crown Copyright NC/**11**/2008.**

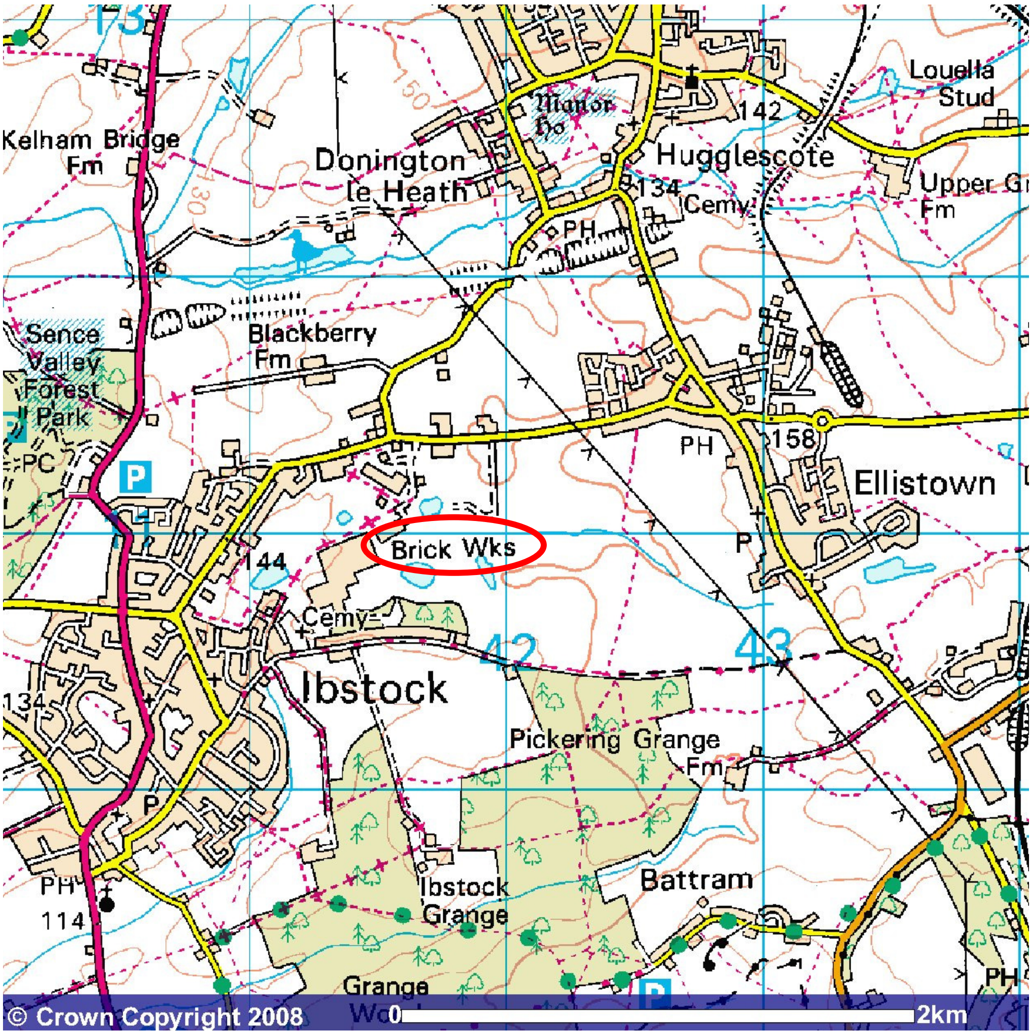


Figure 3.2 OS map showing the location of Ibstock Brick Pit (circled in red). Reproduced from (2008) Ordnance Survey map with the permission of the Controller of Her Majesty's Stationery Office, © Crown Copyright NC/11/2008.

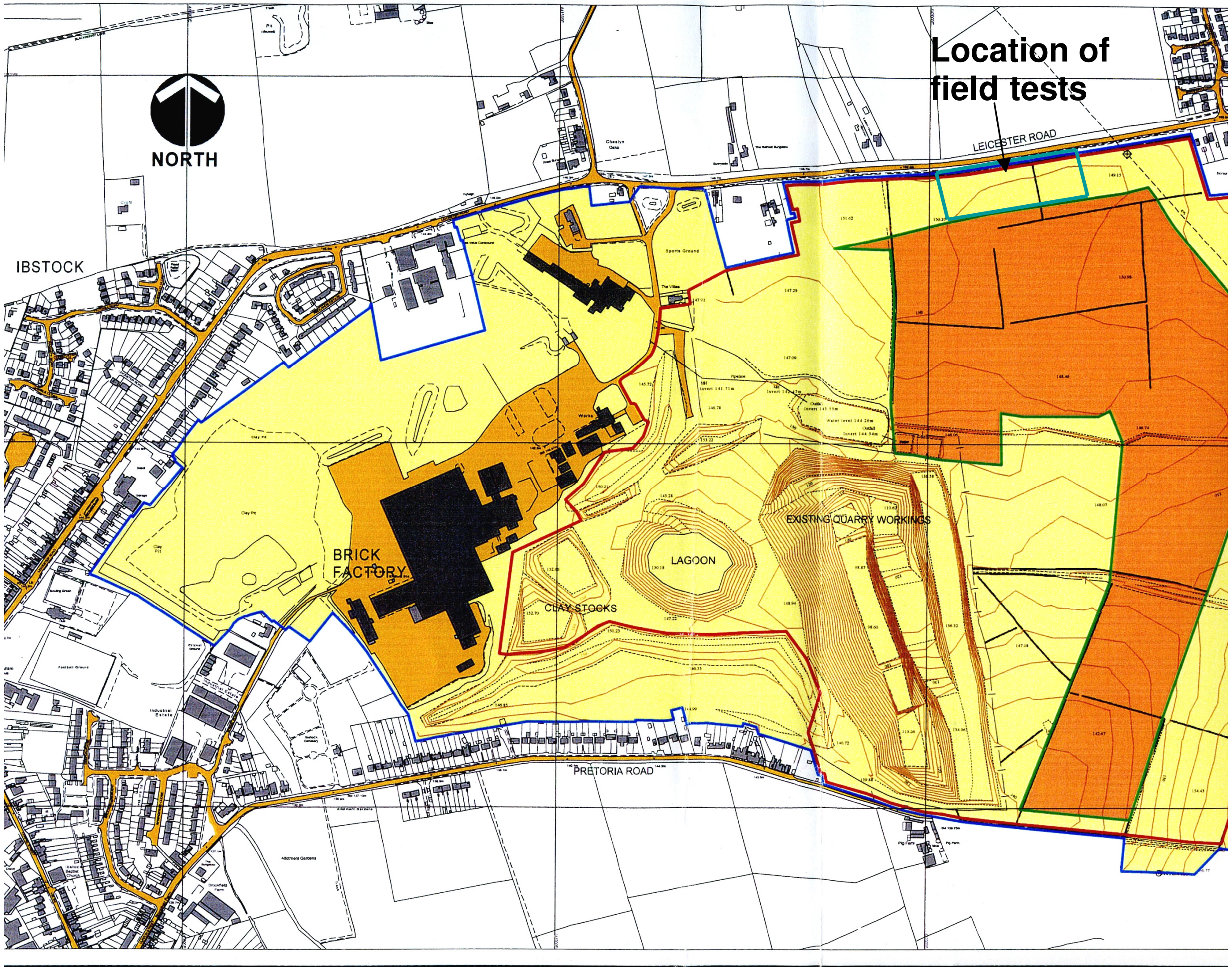


Figure 3.3 A plan of Ibstock Brick Pit including the location of field tests (map courtesy of Ibstock Brick Pit)

Figure 3.4 The rig used to install test piles

Figure 3.5 The auger used to install test piles

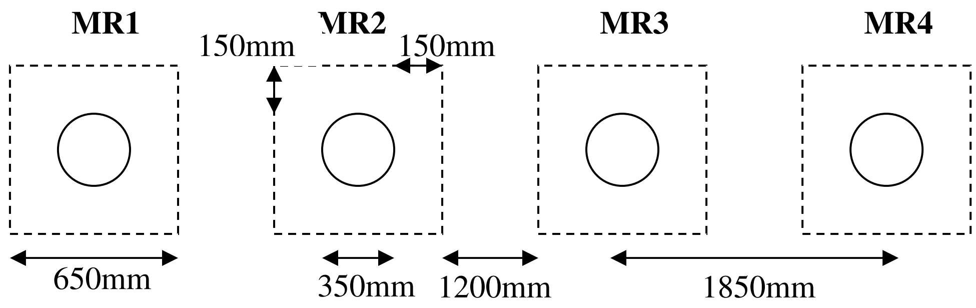


Figure 3.6 A schematic diagram of the order of piles and excavation geometries

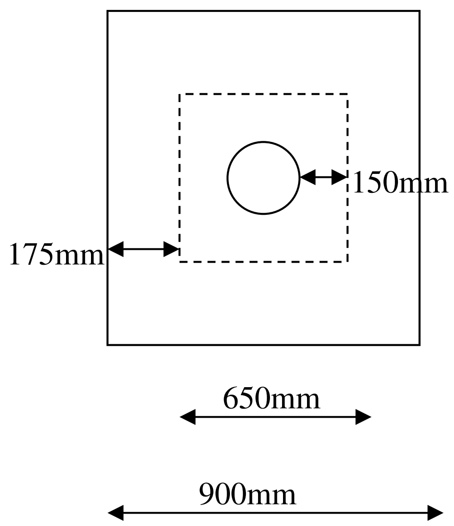


Figure 3.7 A schematic diagram of the position of the pile and soil in the box from above

Figure 3.8 Four piles and the surrounding soil, with 2 piles covered in stretchwrap and ready to be cut using the diamond saw

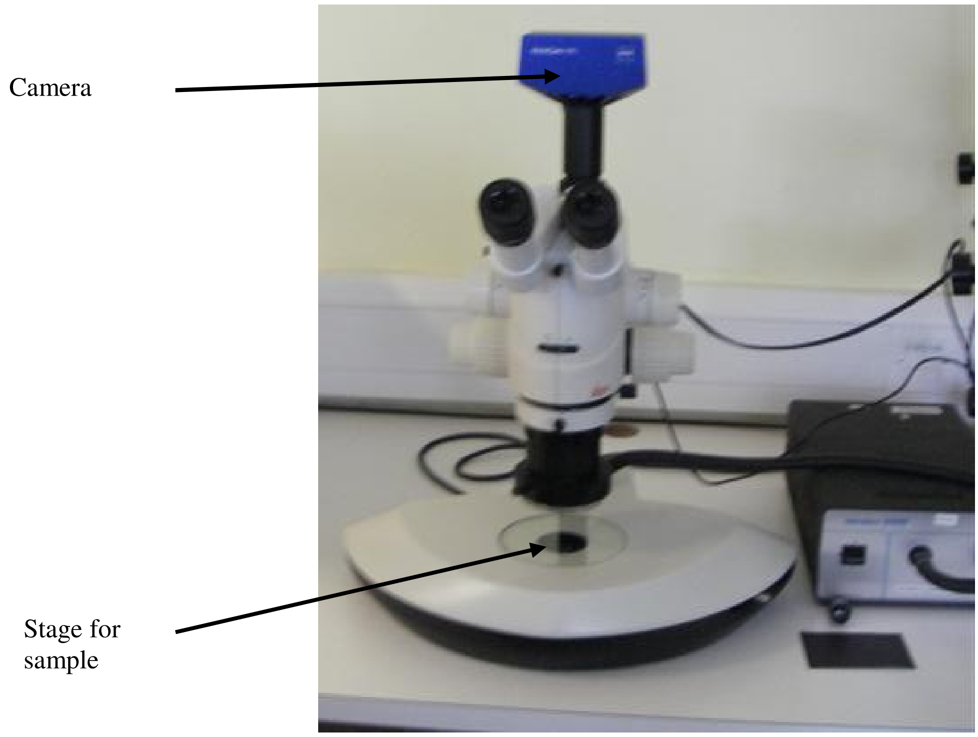


Figure 3.9 The testing apparatus used for the axiocam

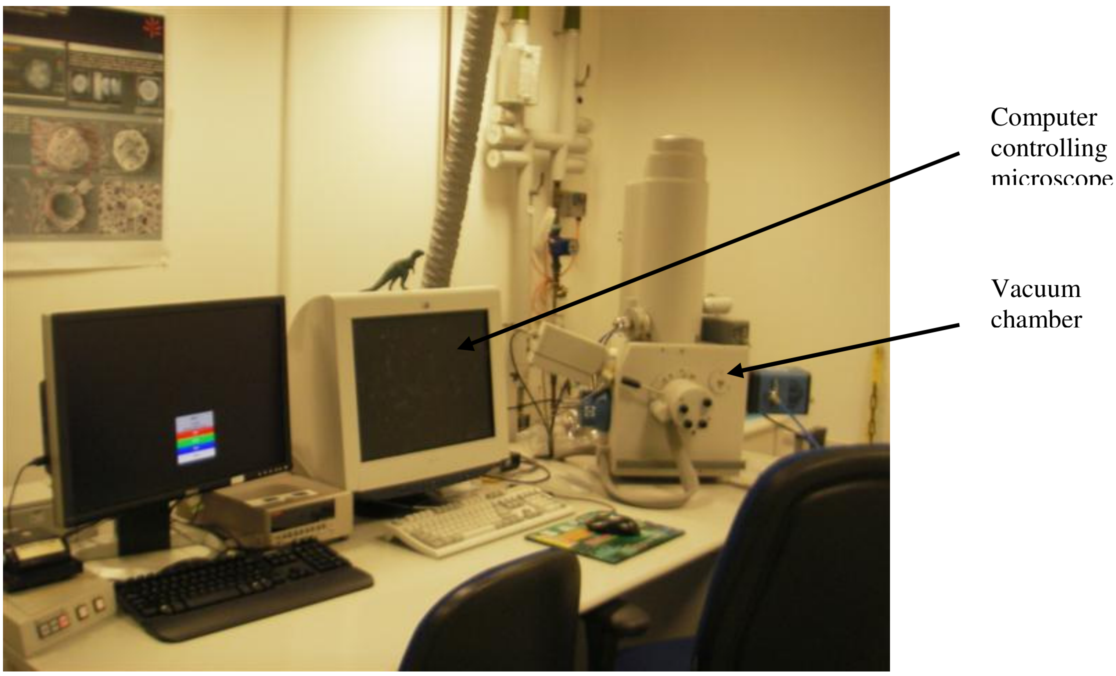


Figure 3.10 The apparatus used for SEM imaging

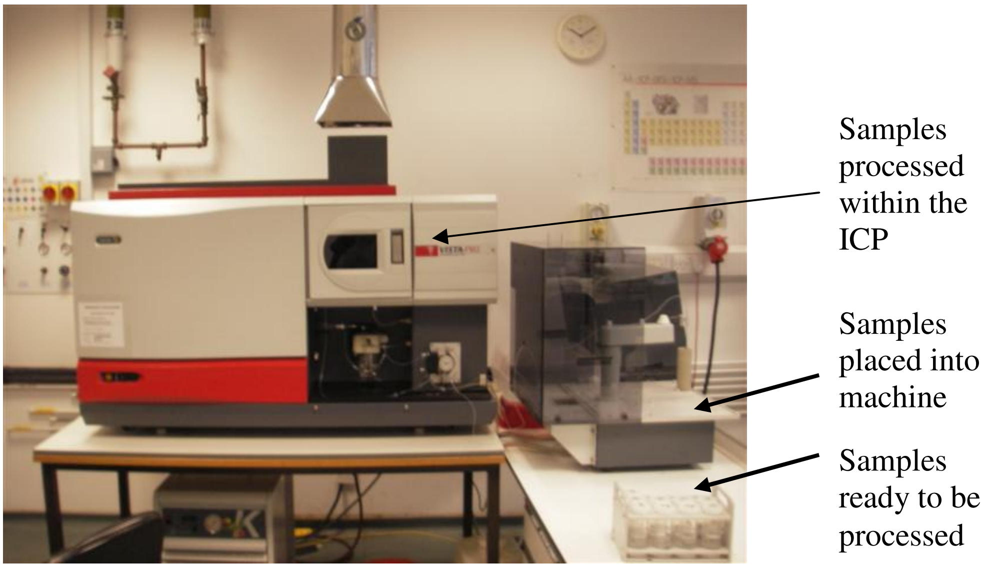


Figure 3.11 The ICP-AES

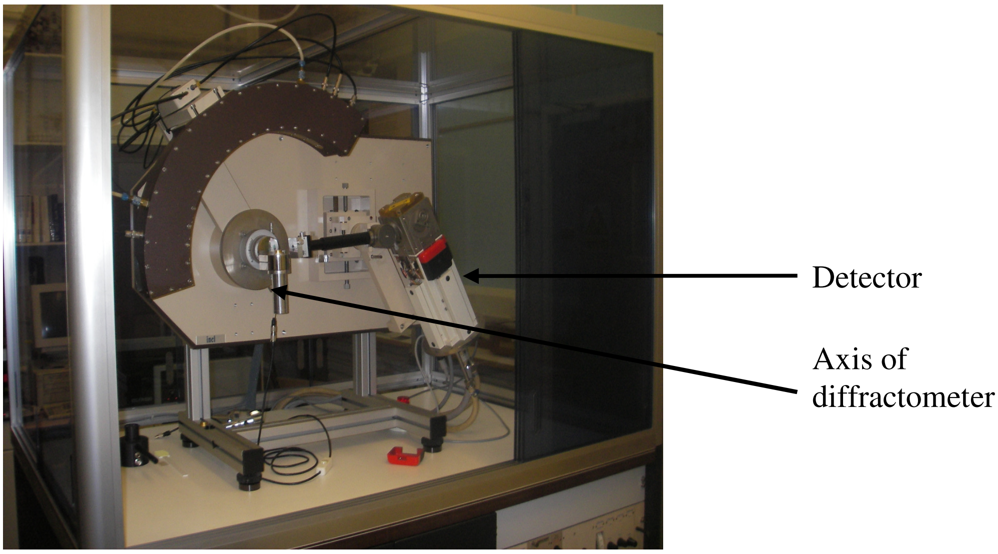


Figure 3.12 shows the XRD machine used for tests

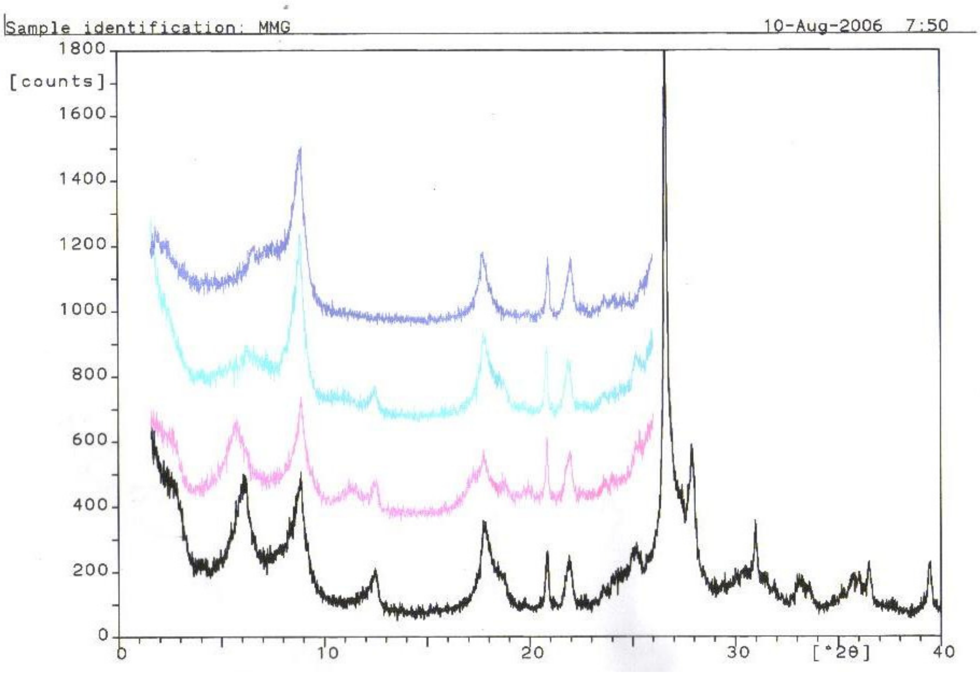


Figure 3.13 A typical XRD trace. The black line indicates the untreated trace, the pink line the glycolated trace, pale blue the first heated trace and the dark blue the second heated trace. The peaks present within each trace indicate the presence of a particular mineral species. The area below each peak gives an indication of the abundance of that mineral.

Figure 3.14 The standard set of sieves used for PSD tests

Figure 3.15 The cone penetrometer equipment used in liquid limit experiments

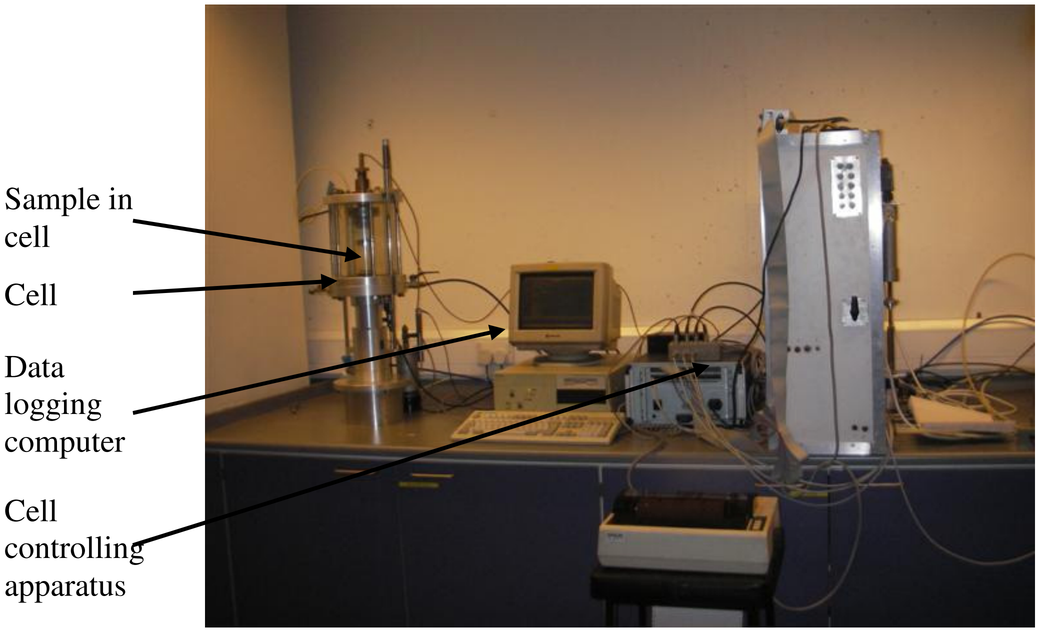


Figure 3.16 The equipment used for triaxial experiments

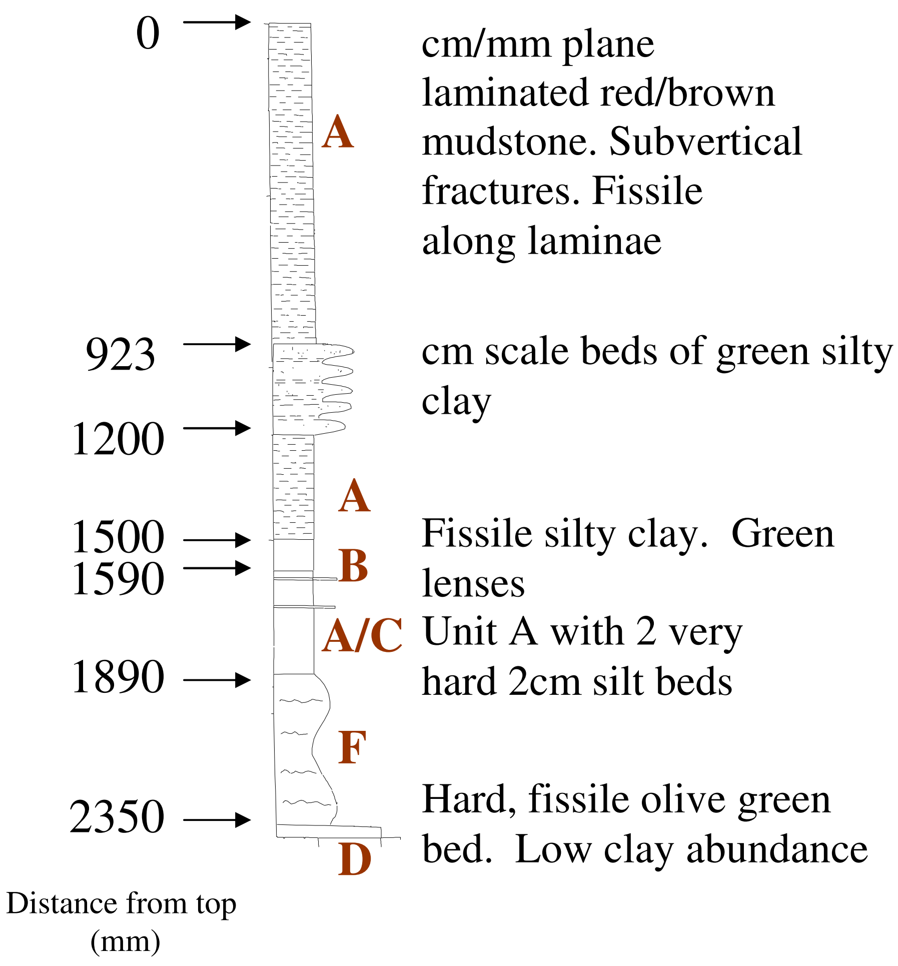


Figure 4.1 Stratigraphy of Ibstock Brick Pit, logged in the south wall of the excavation pit

Figure 4.2 Risings during augering of pile MR1 and shows sharp angular blocks of hard material mixed with fine, red/brown powder, as seen while the auger was screwing into the soil

Figure 4.3 The spoil heap for MR1 as the auger was removed.

Figure 4.4 The spoil heap produced by the installation of MR2. The spoil heap was a fine powder with some material sticking to the flights of the auger.

Figure 4.5 The spoil heap produced during installation of pile MR3 and shows a red soup overlying a fine red powder

Figure 4.6 The relationship between the auger and the wet soil around pile MR3. Clear markings can be seen on the inner surface of the shaft, along with the hose used to pour water down the shaft

Figure 4.7 The removal of the auger from pile MR3

Figure 4.8 The spoil heap produced by the installation of pile MR4

Figure 4.9 The section from pile MR1 0-495mm below ground level

Figure 4.10 The section from pile MR1 495-819mm below ground level

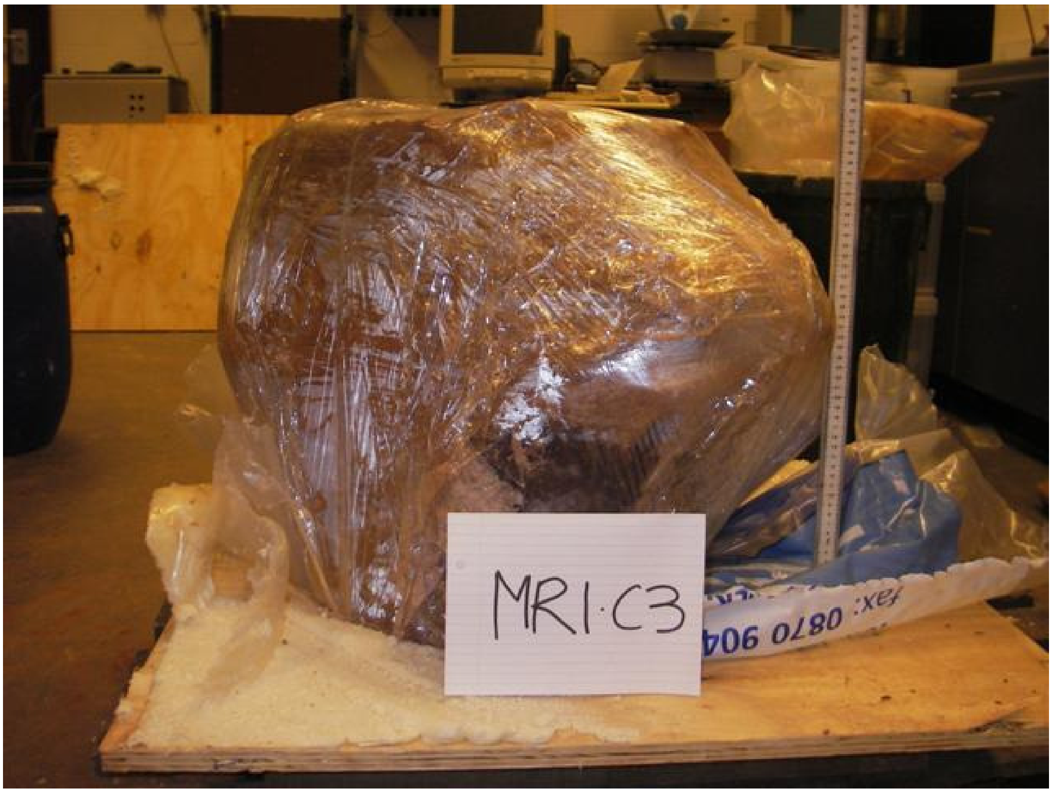


Figure 4.11 The section from pile MR1 819-1277mm below ground level

Figure 4.12 Shows the section from pile MR1 1277-1981mm below ground level

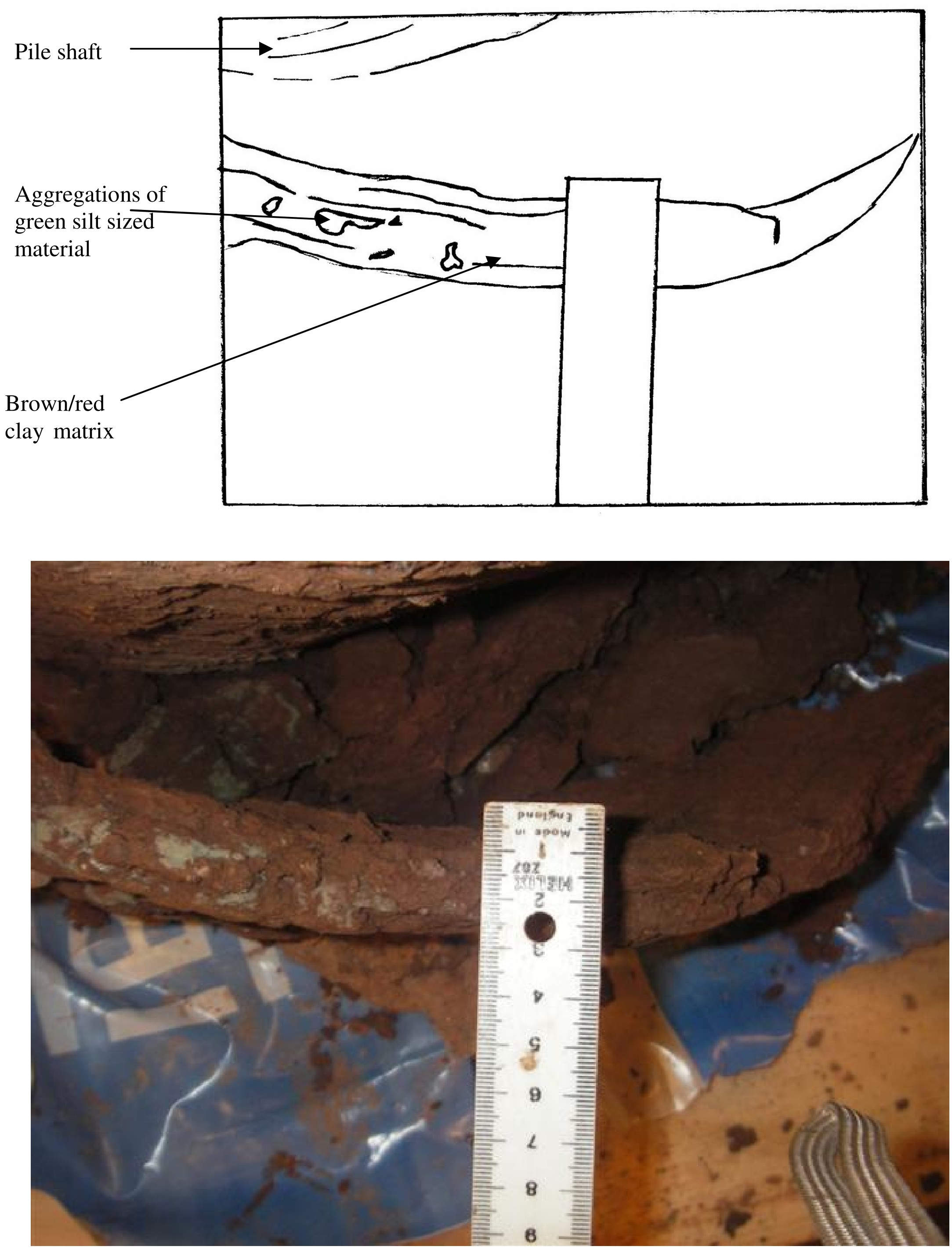


Figure 4.13 Sketch drawing and photograph of remoulded material around pile MR1, 0-495mm below ground level. The photograph is taken looking downwards, with the pile at the top of the picture

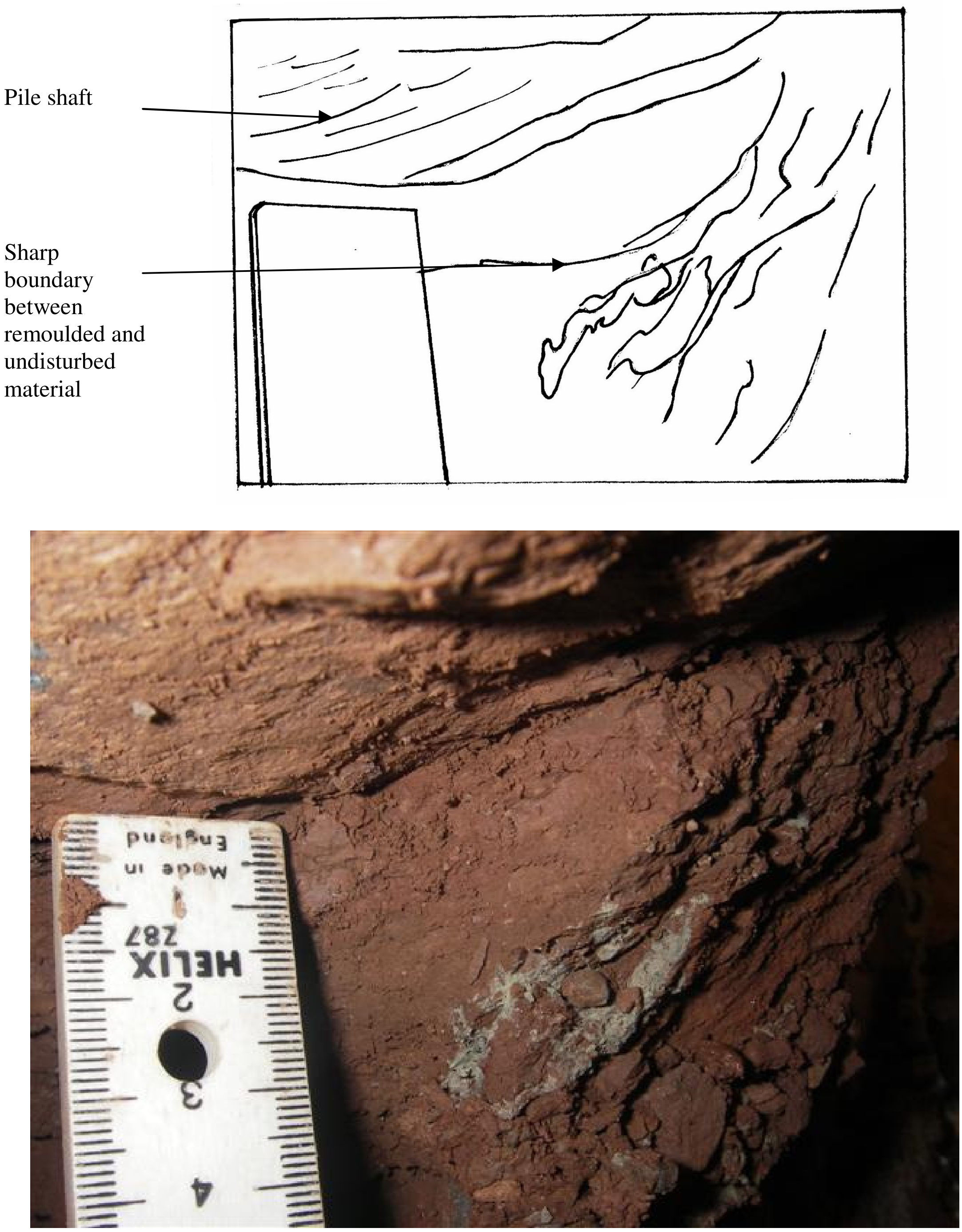


Figure 4.14 The contact between the remoulded and undisturbed material around pile MR1, 0-495mm below ground level, with remoulded material being of inconsistent width

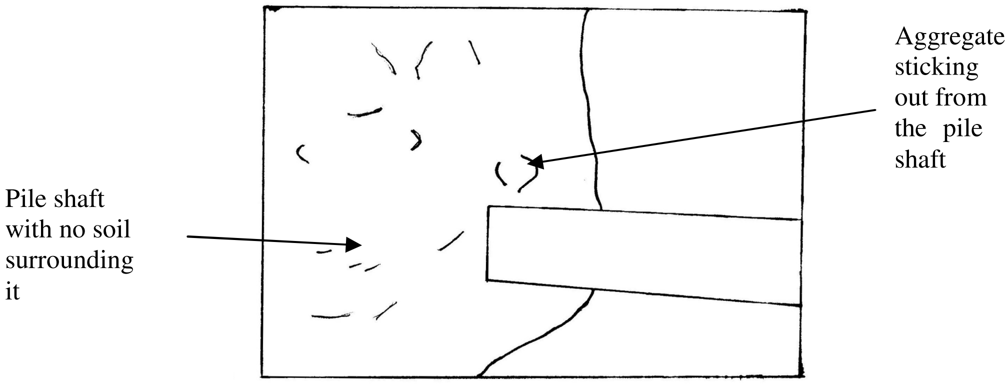


Figure 4.15 Aggregates from concrete of the pile coming out from the surface of the pile shaft. Pile MR1, 0-495mm below ground level.

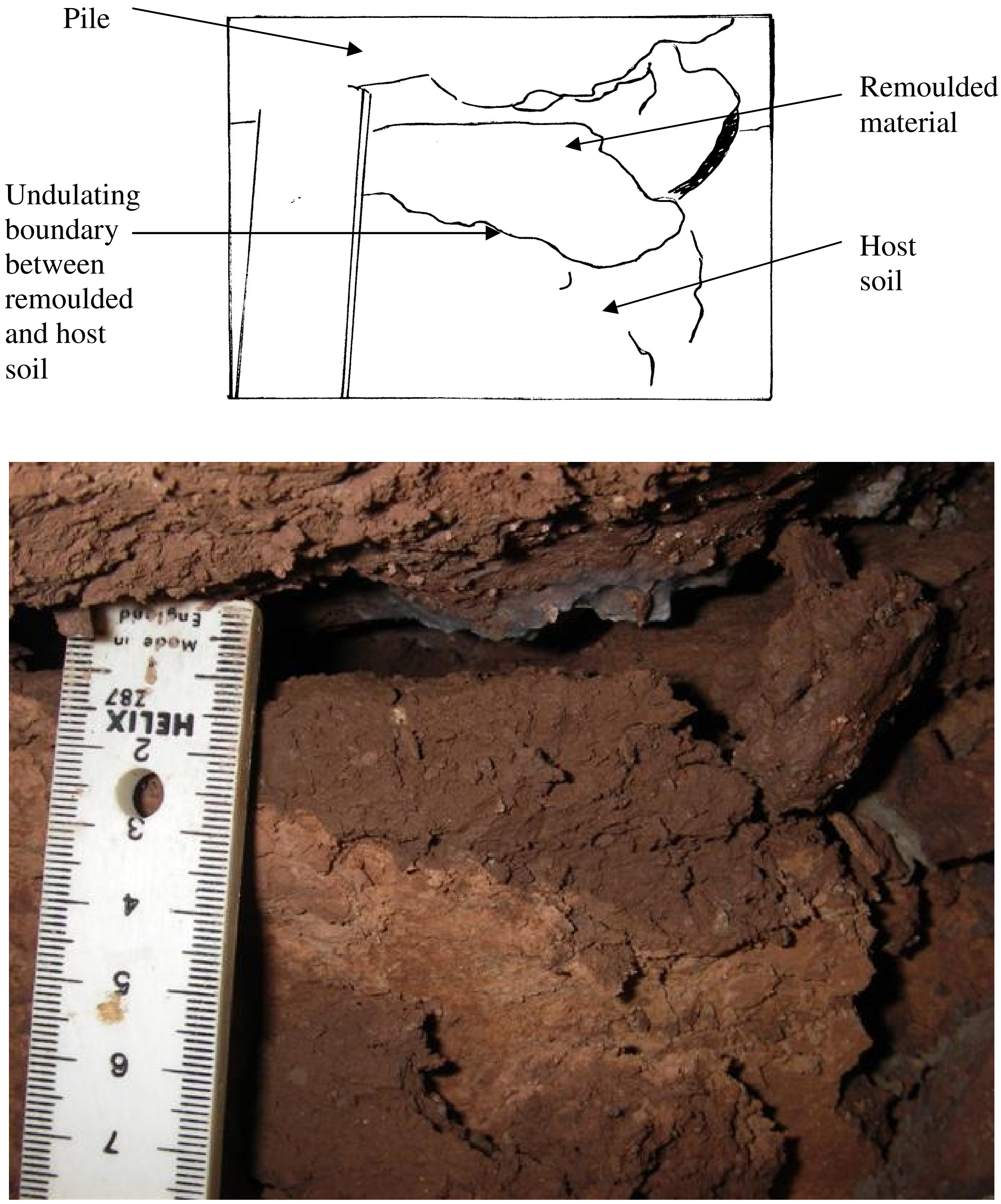


Figure 4.16 The boundary between the host soil and remoulded soil around pile MR1, 819-1277mm below ground level

Figure 4.17 The first section taken from pile MR2 0-1000mm below ground level

Figure 4.18 The second section taken from pile MR2 1000-1457mm below ground level

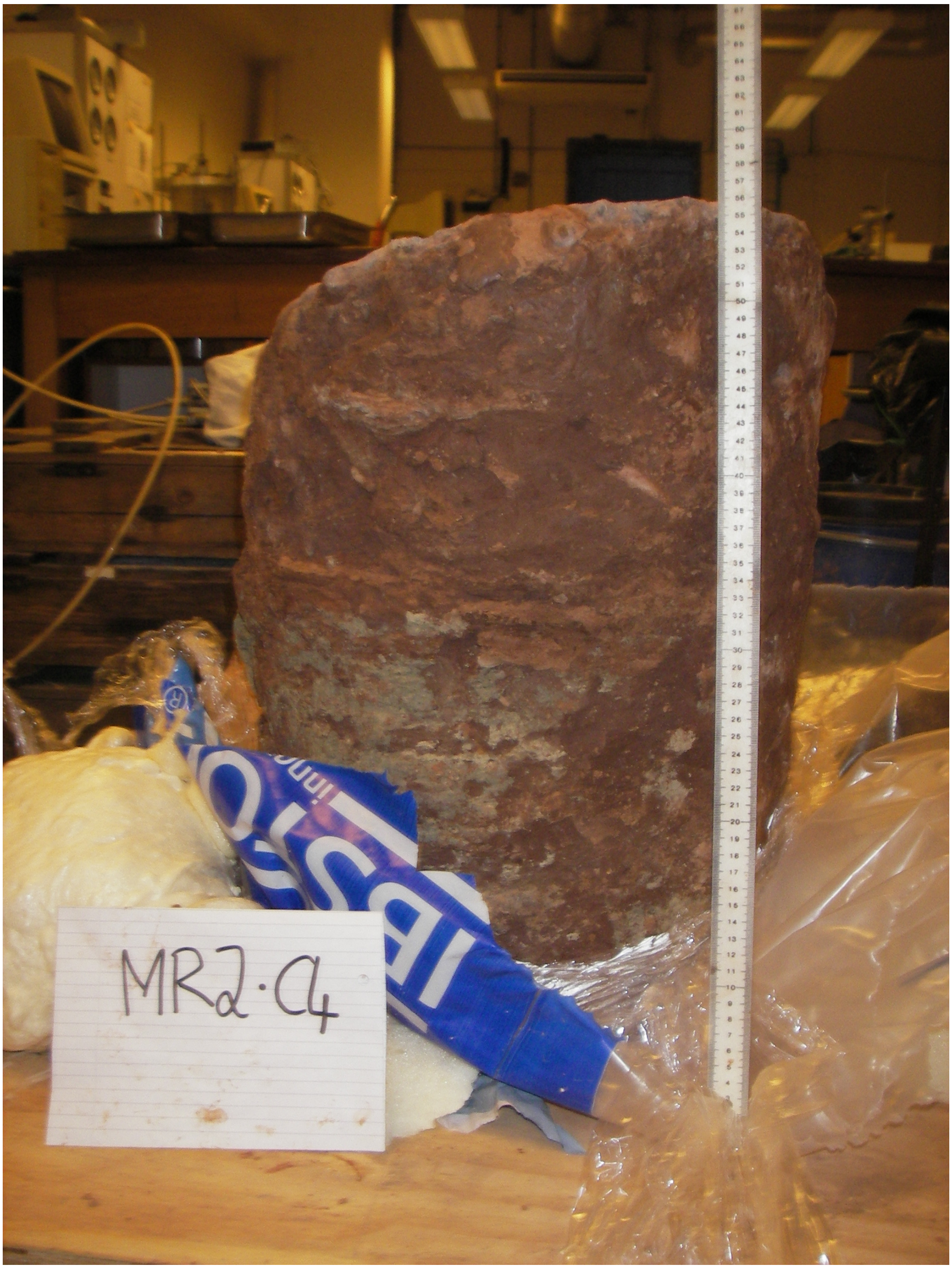
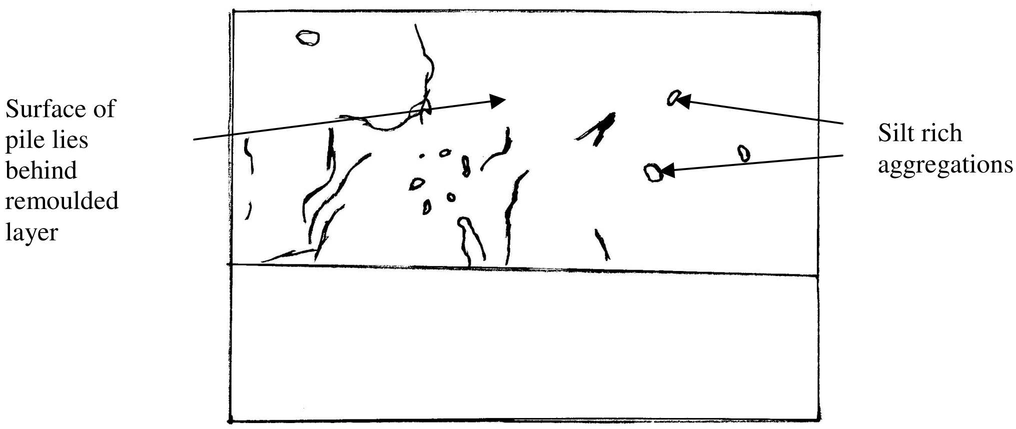


Figure 4.19 The third section removed from pile MR2 1457-1979mm below ground level



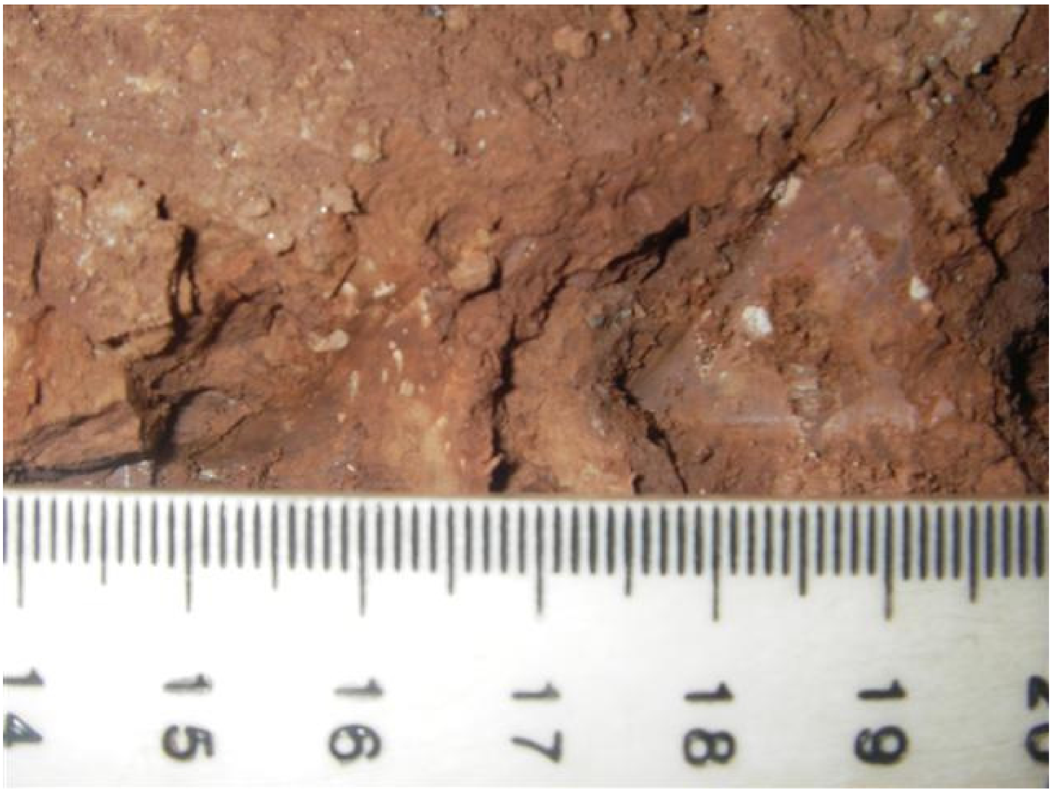


Figure 4.20 The remoulded zone of pile MR2 at 0-1000mm below ground level. Shows silt aggregations within the remoulded layer. Photo was taken horizontally against the vertical pile shaft

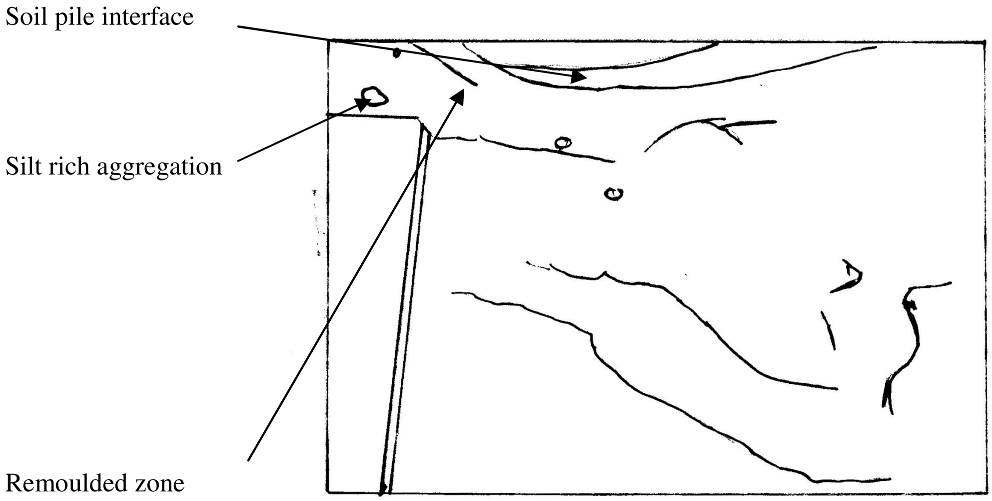


Figure 4.21The remoulded zone from around pile MR2 at 1000-1457mm below ground level

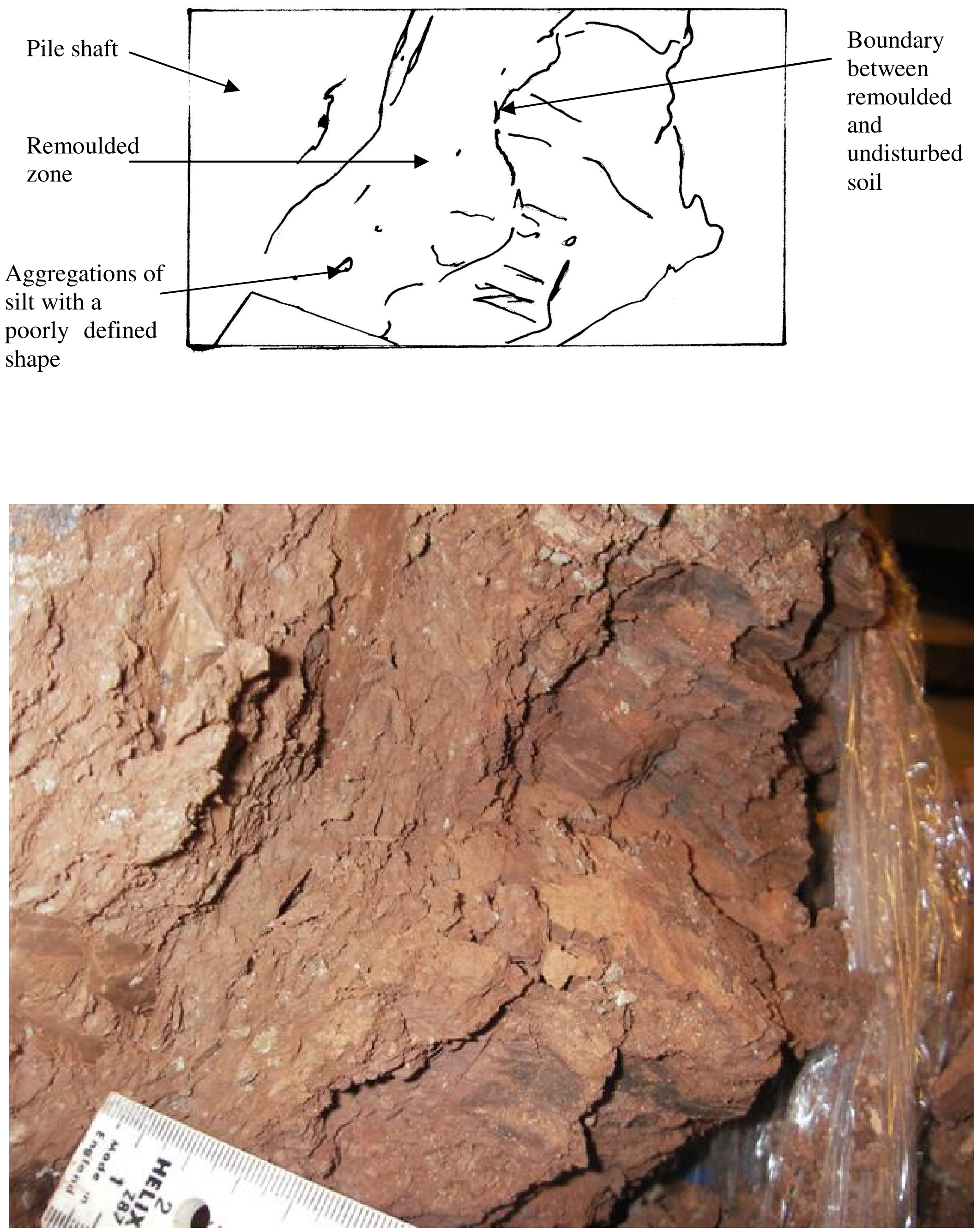


Figure 4.22 A vertical section through the remoulded zone of pile MR2 1000-1457mm below ground level. Photograph shows remoulded and undisturbed material

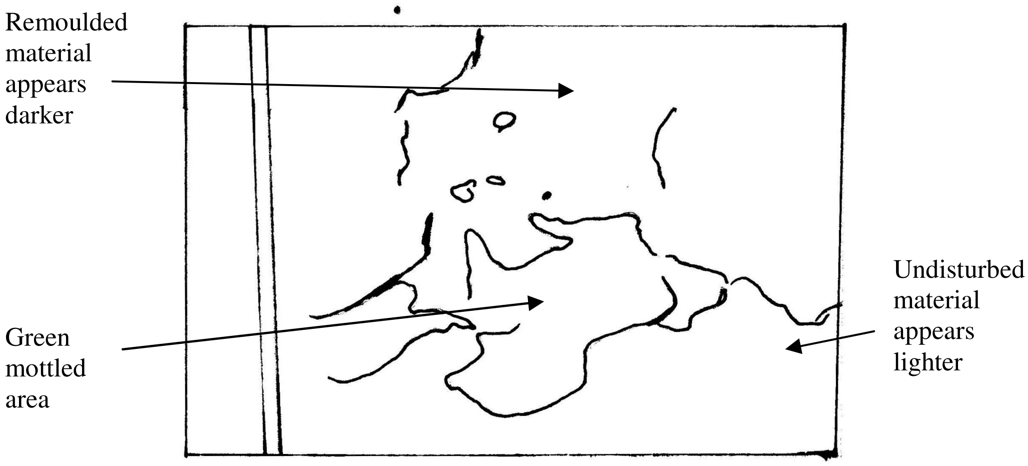


Figure 4.23 Vertical section with green mottling within the remoulded zone around pile MR2, at a depth of 1547mm below ground level

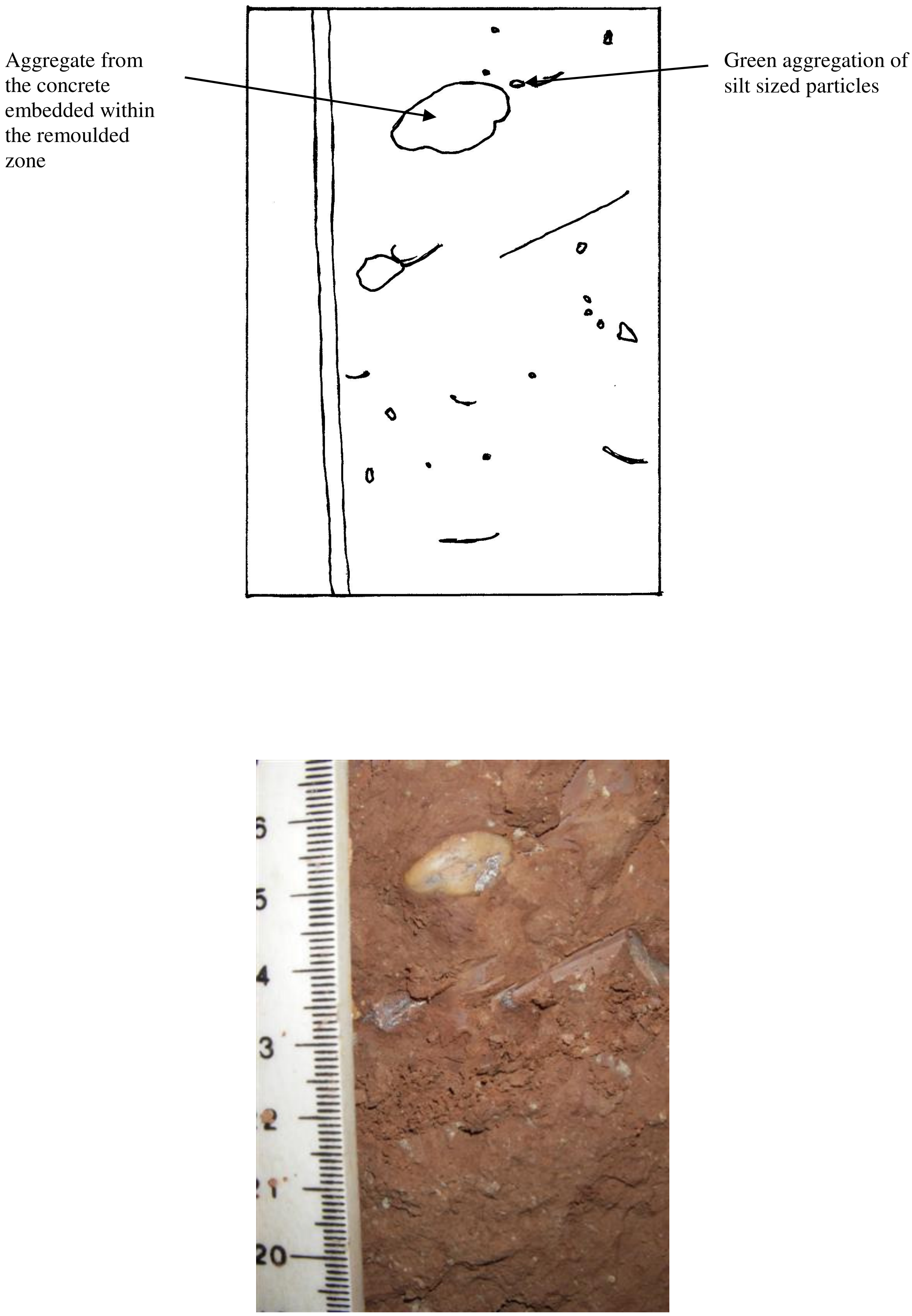
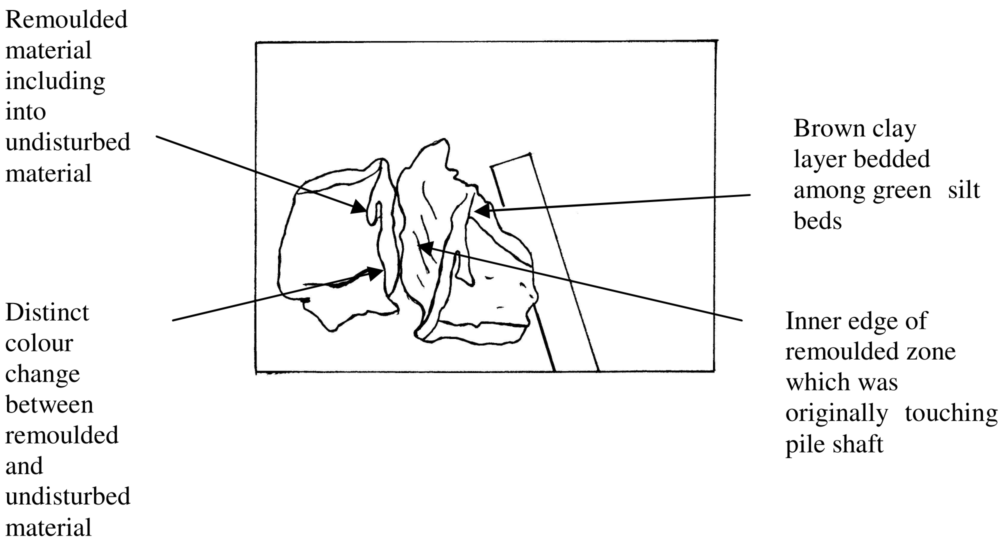


Figure 4.24 The vertical elevation of the remoulded surface of pile MR2 showing free aggregates within the remoulded layers. 1000-1457mm below ground level



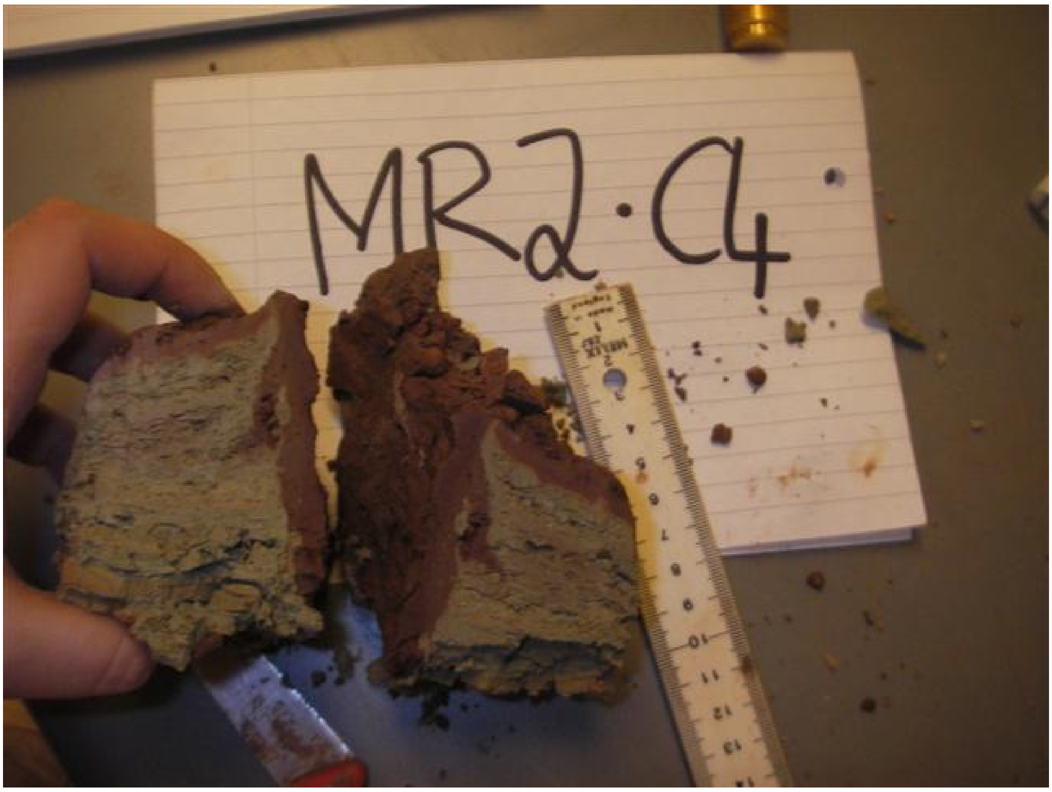


Figure 4.25 The colour change between remoulded and undisturbed material from around pile MR2 at a depth of 1457-1979mm below ground level

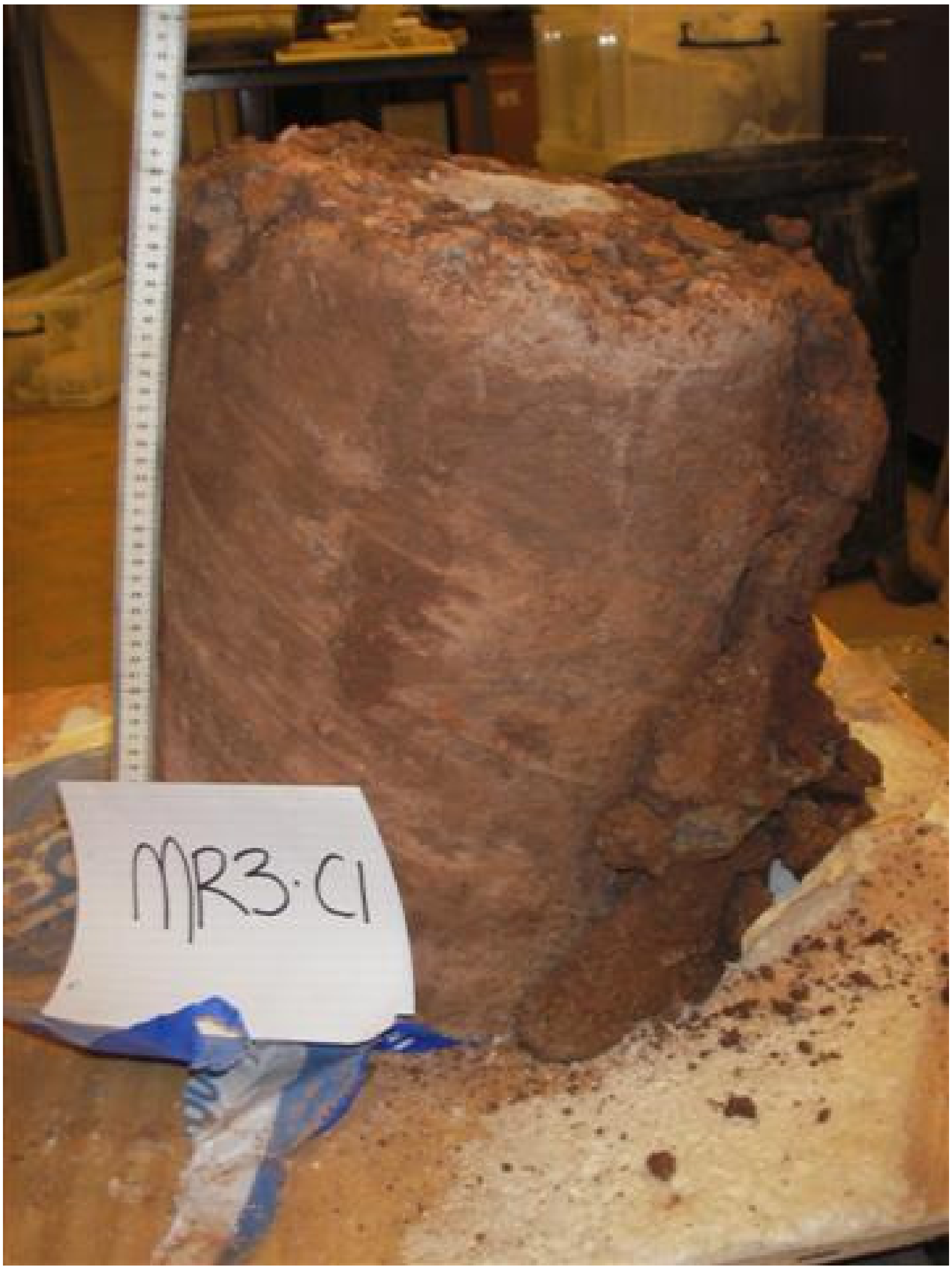


Figure 4.26 The first section from pile MR3 0-510mm below ground level

Figure 4.27 The second section from pile MR3 510-860mm below ground level

Figure 4.28 The third section from pile MR3 860-1210mm below ground level

Figure 4.29 The fourth section from pile MR3 1210-1831mm below ground level

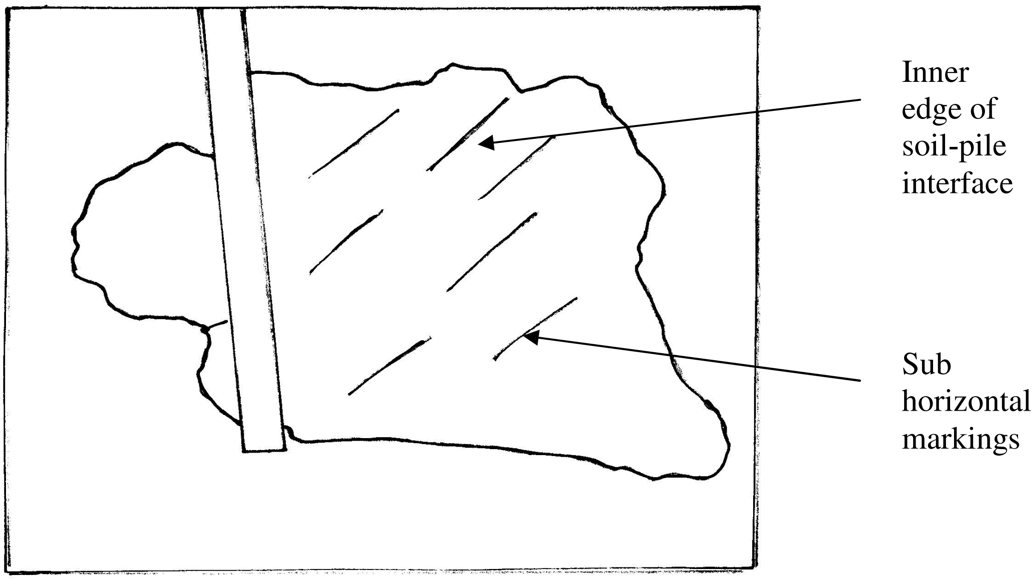


Figure 4.30 The inner edge of the soil-pile interface in the remoulded soil surrounding pile MR3, base of sample is from 860mm below ground level

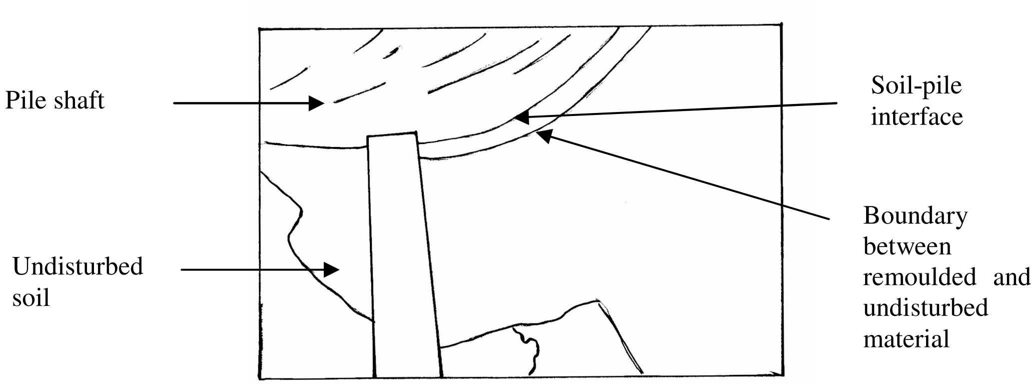


Figure 4.31 The boundary between remoulded and undisturbed material from the soil surrounding pile MR3 510-860mm below ground level

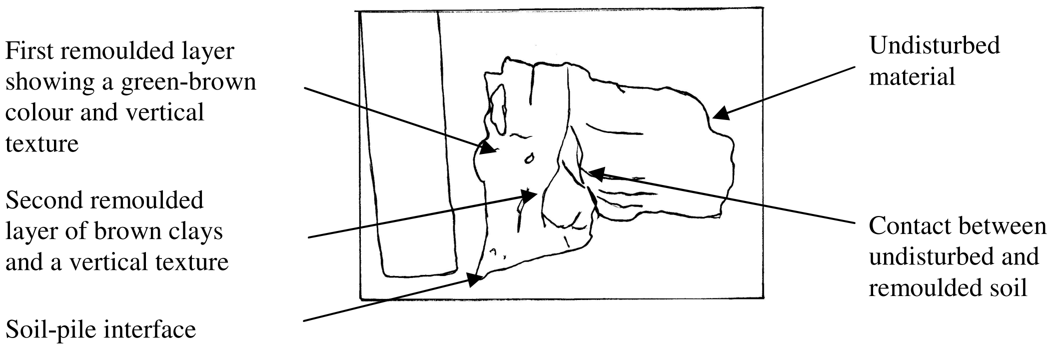


Figure 4.32 Zoning within the remoulded zone of pile MR3 510-860mm below ground level

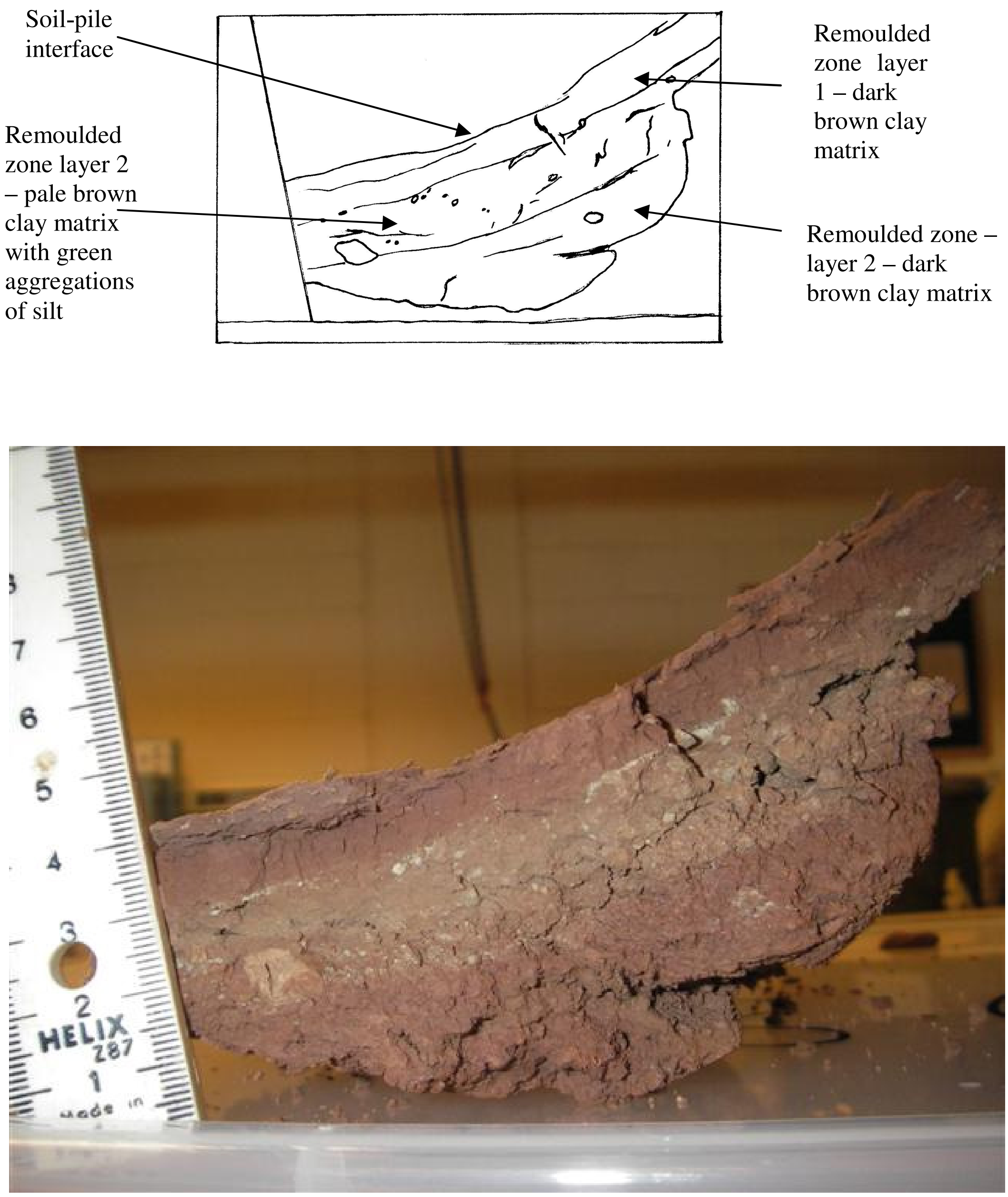


Figure 4.33 Zoning of remoulding with the soil surrounding pile MR3 860-1210mm below ground level. Then soils is viewed from above, and the pile would have been at the top of this picture

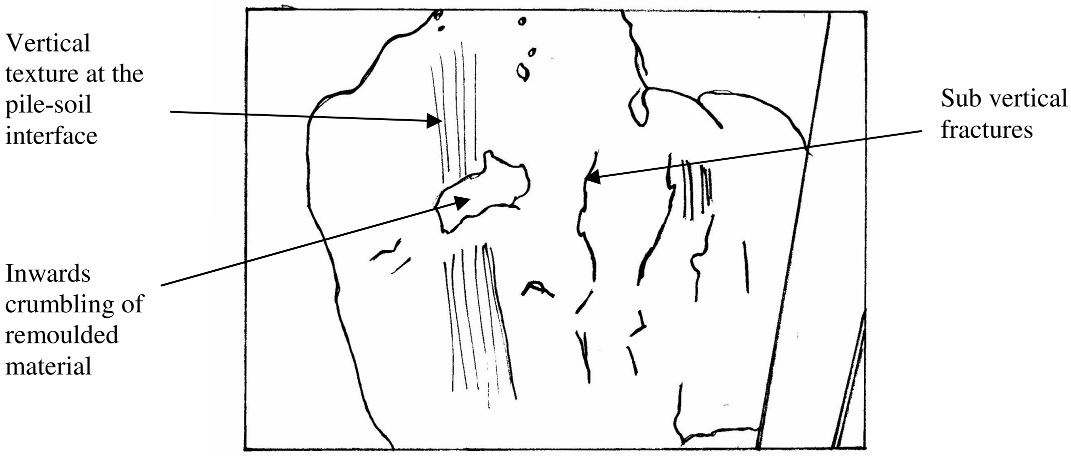


Figure 4.34 Te inner surface of the remoulded zone from around pile MR3, 860-1210mm below ground level. Pile would have been to the front of the picture

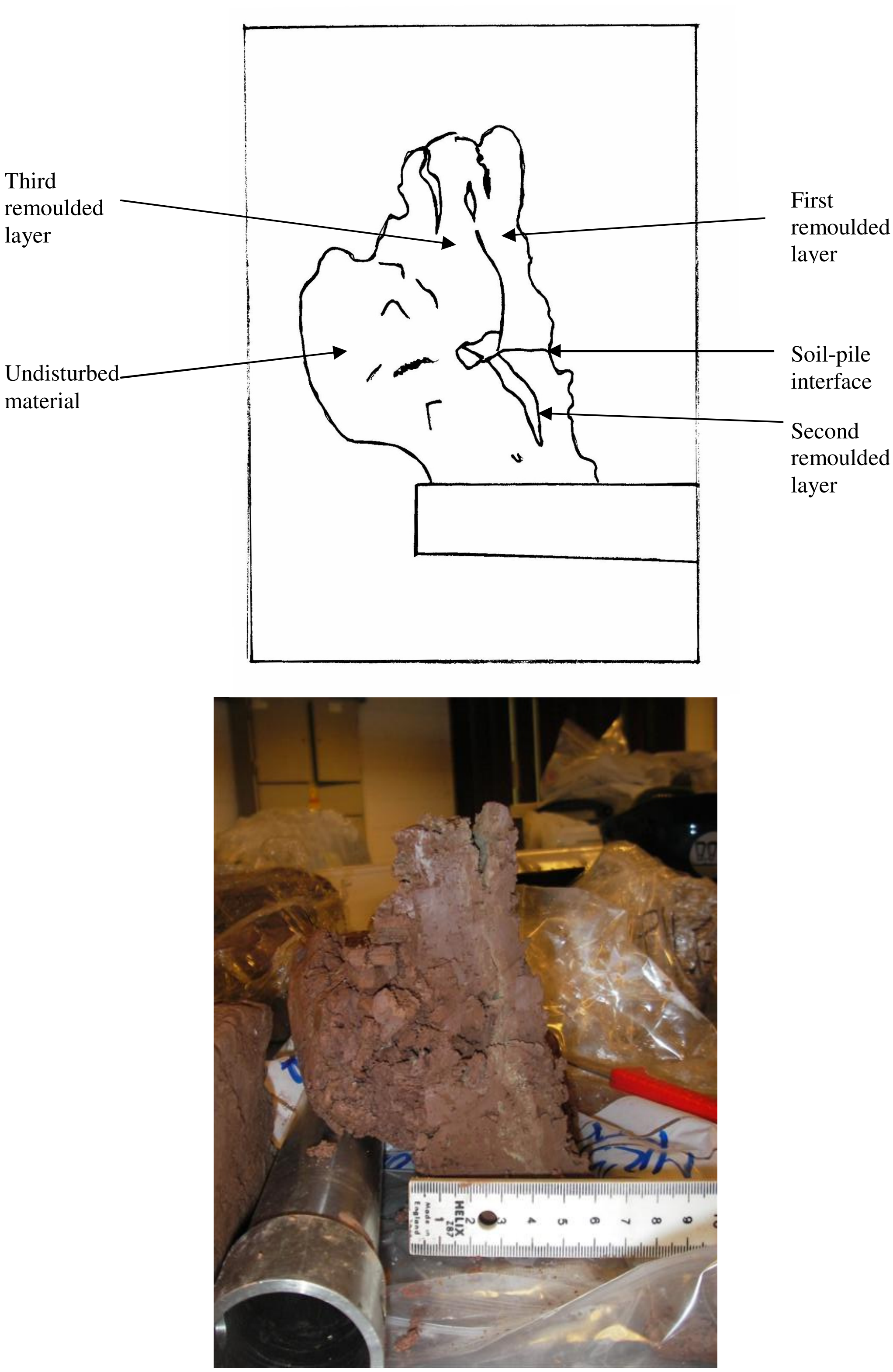


Figure 4.35 Zoning within the remoulded zone of pile MR3 at 860-1210mm below ground level, pile would have been at the right of this photograph

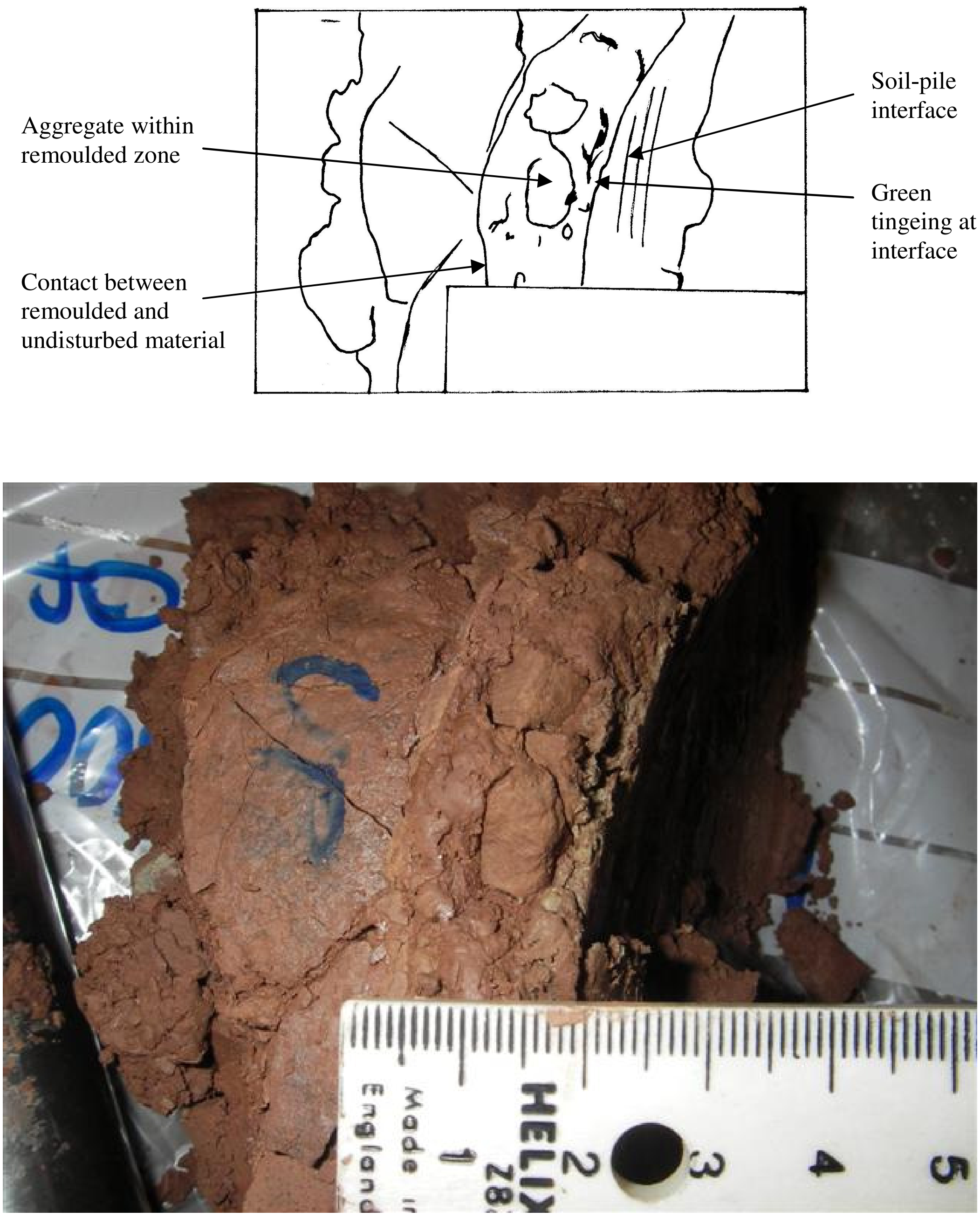


Figure 4.36 The remoulded and undisturbed material from pile MR3 860-1210mm below ground level looking down from above

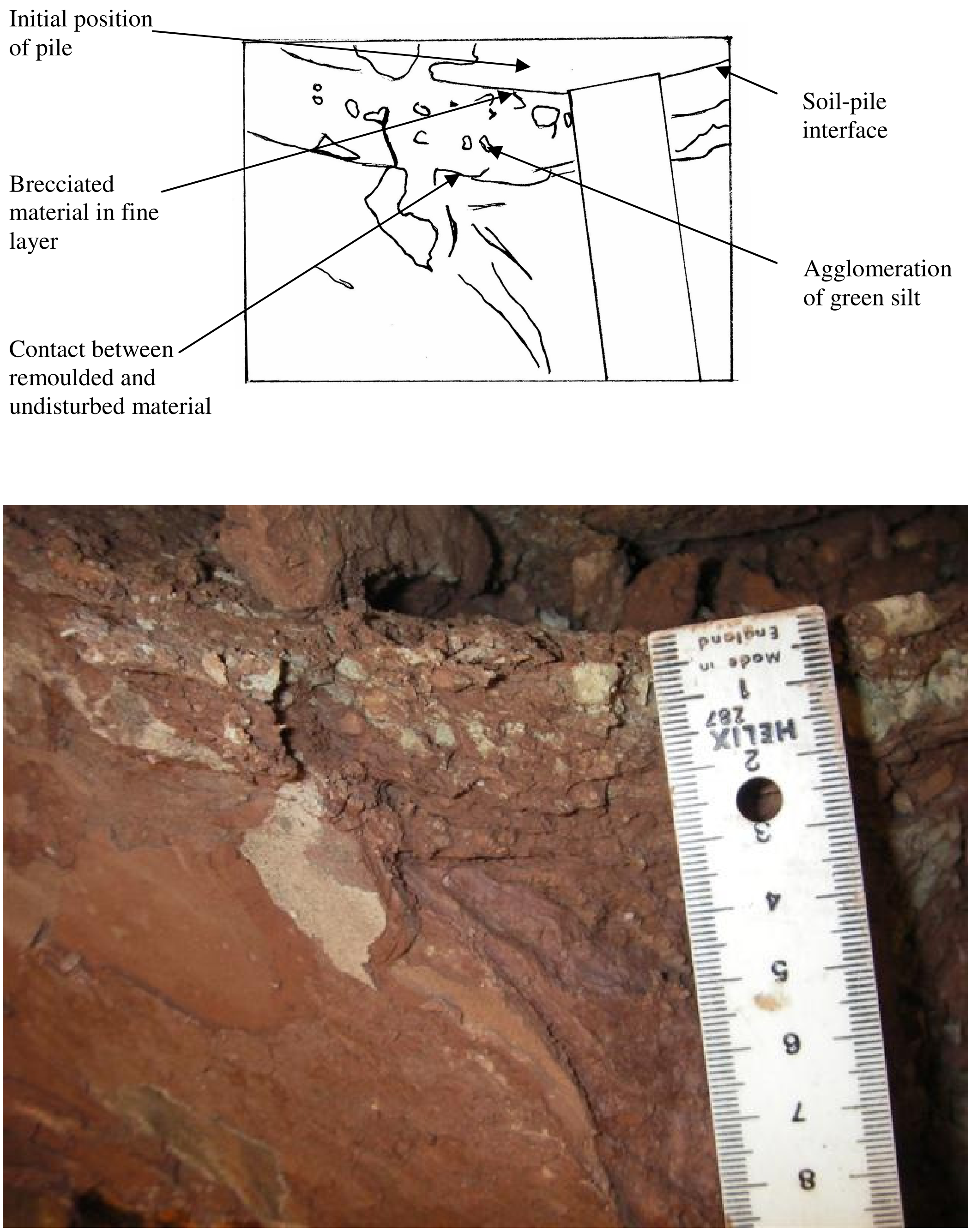


Figure 4.37 The remoulded zone from around pile MR3 860-1210mm below ground level taken from above

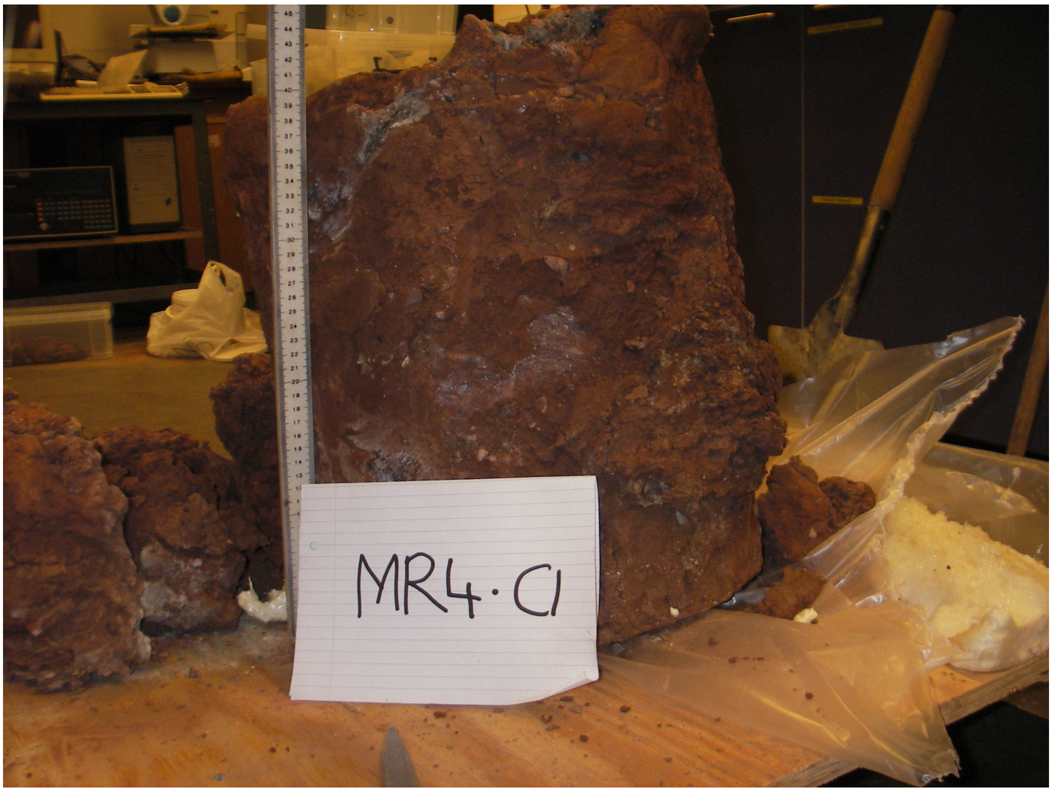
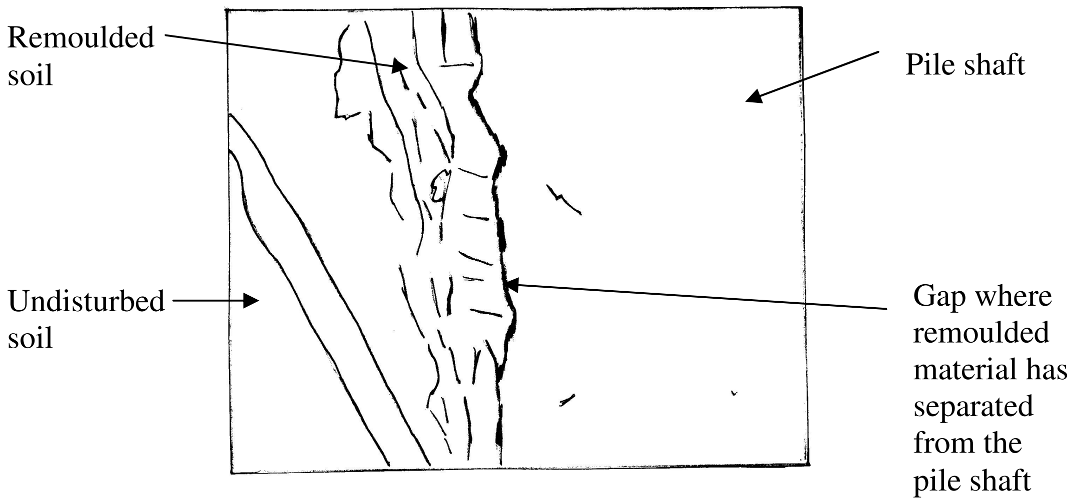


Figure 4.38 The first section taken from pile MR4 0-451mm below ground level

Figure 4.39 The third section taken from pile MR4 951-1342mm below ground level

Figure 4.40 The final section taken from pile MR4 1342-1962mm below ground level



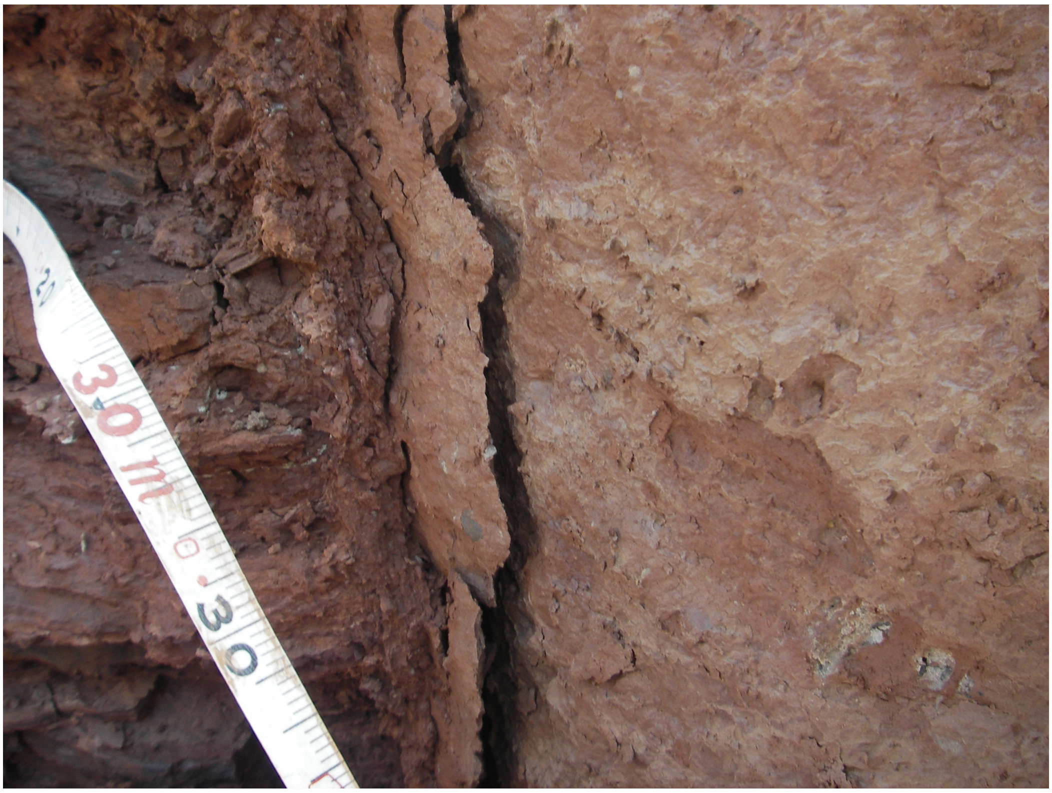
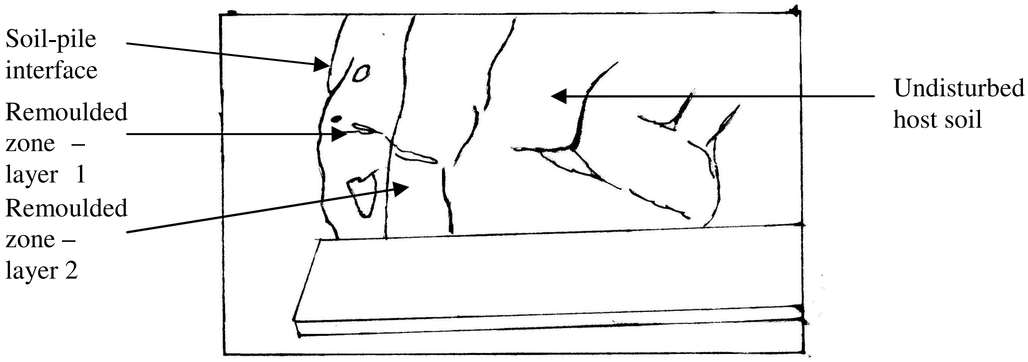


Figure 4.41 The soil pile interface of pile MR4 at a depth of 451-951mm below ground level



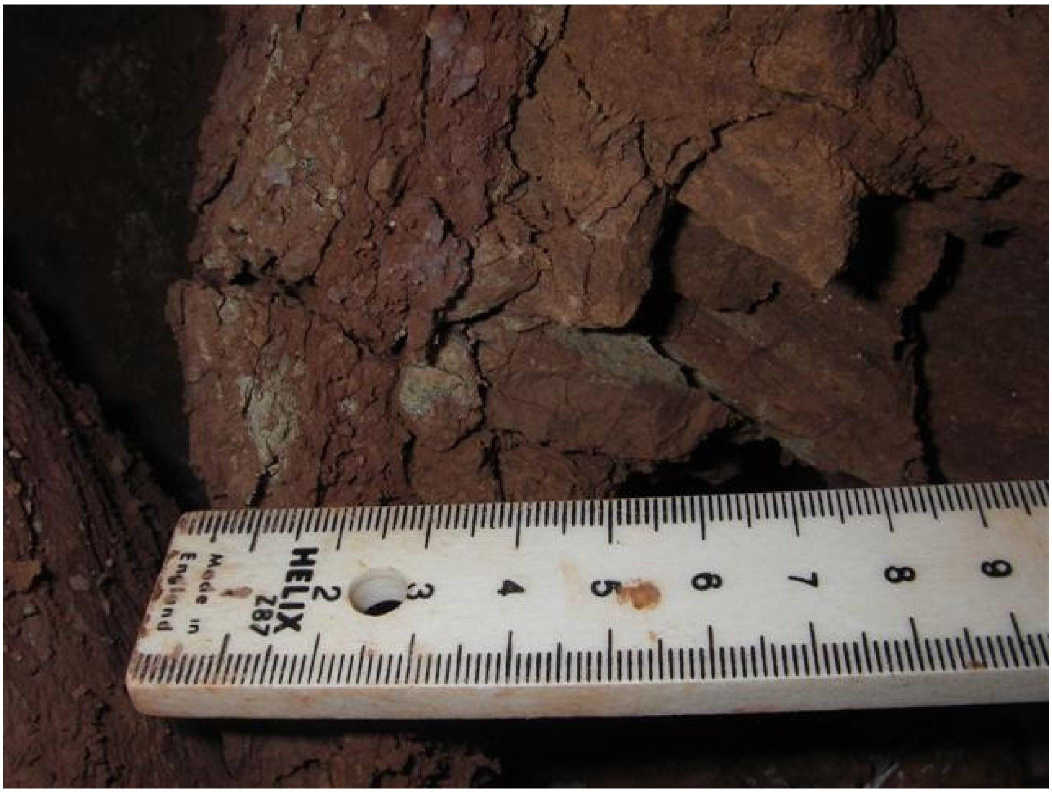
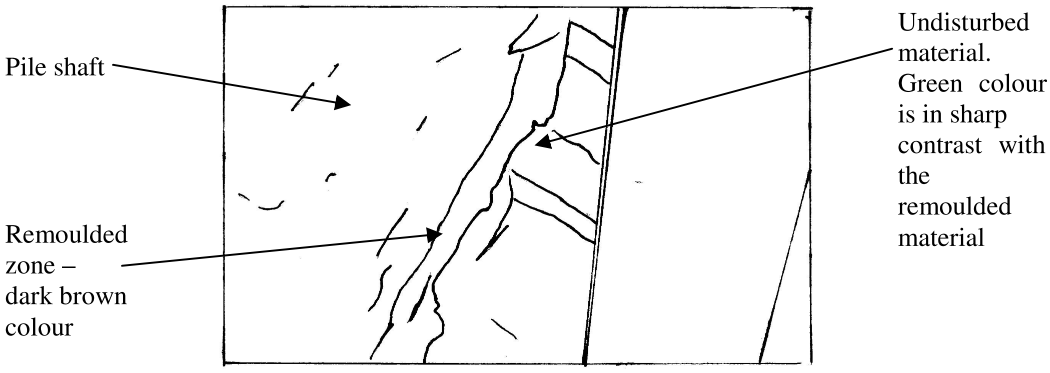


Figure 4.42 2 layers of remoulded material and their boundary with undisturbed host soil. Samples taken from 1342mm below ground level



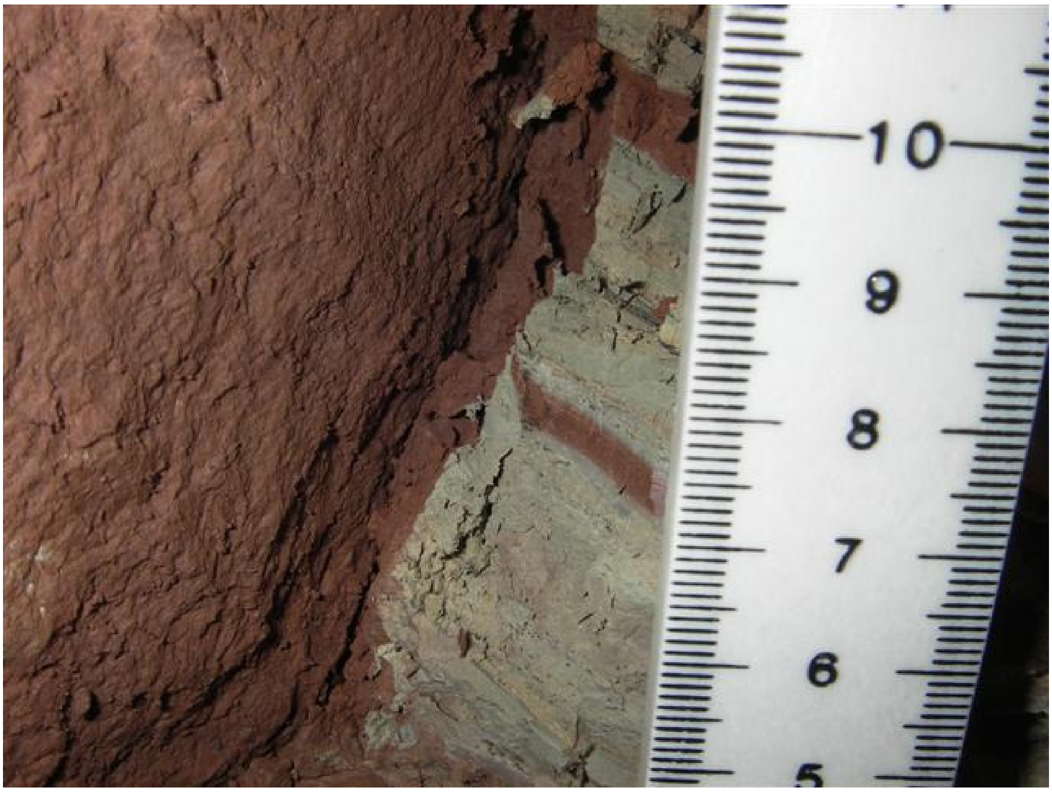


Figure 4.43 The remoulded material from 1600mm below ground level showing the distinct colour and texture differences between the remoulded and host soils

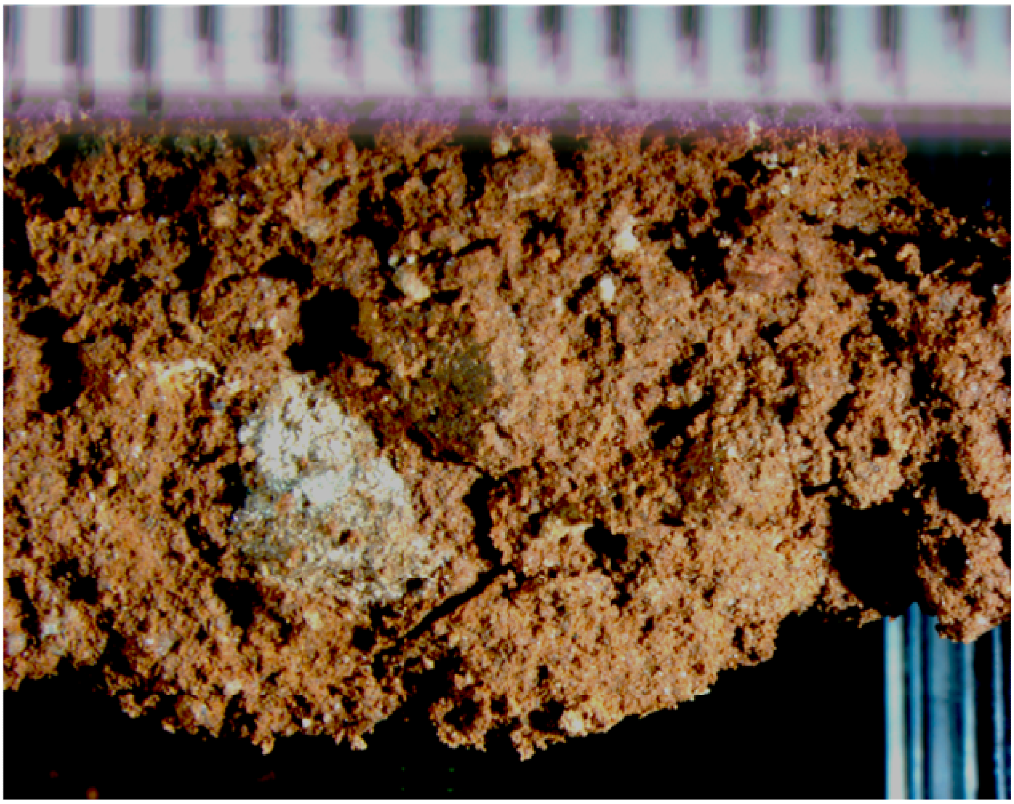


Figure 4.44 An enlarged photograph of the remoulded zone of pile MR1, 1177-1277mm below ground level. The increments on the ruler indicate 1mm lengths, and the pile was originally where the ruler is in the photograph. Photograph is taken from above

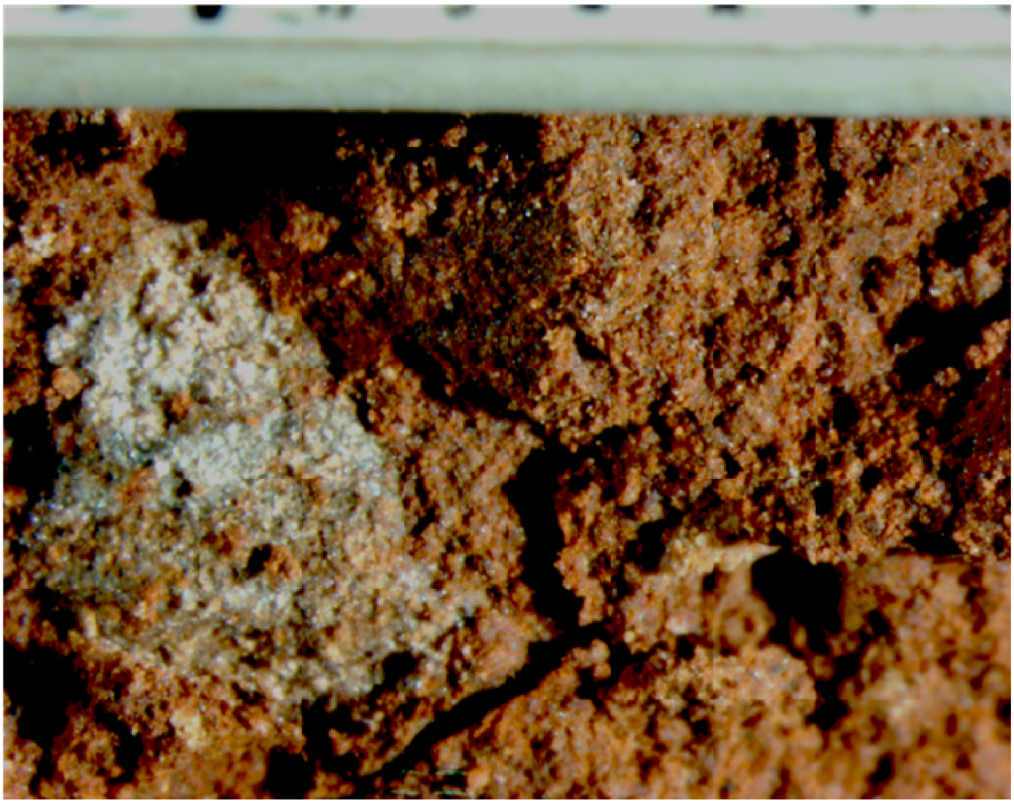


Figure 4.45 Closer view of figure 4.44, the remoulded zone of pile MR1, 1177-1277mm below ground level. The increments on the ruler indicate 1mm lengths, and the pile was originally where the ruler is in the photograph. Photograph is taken from above

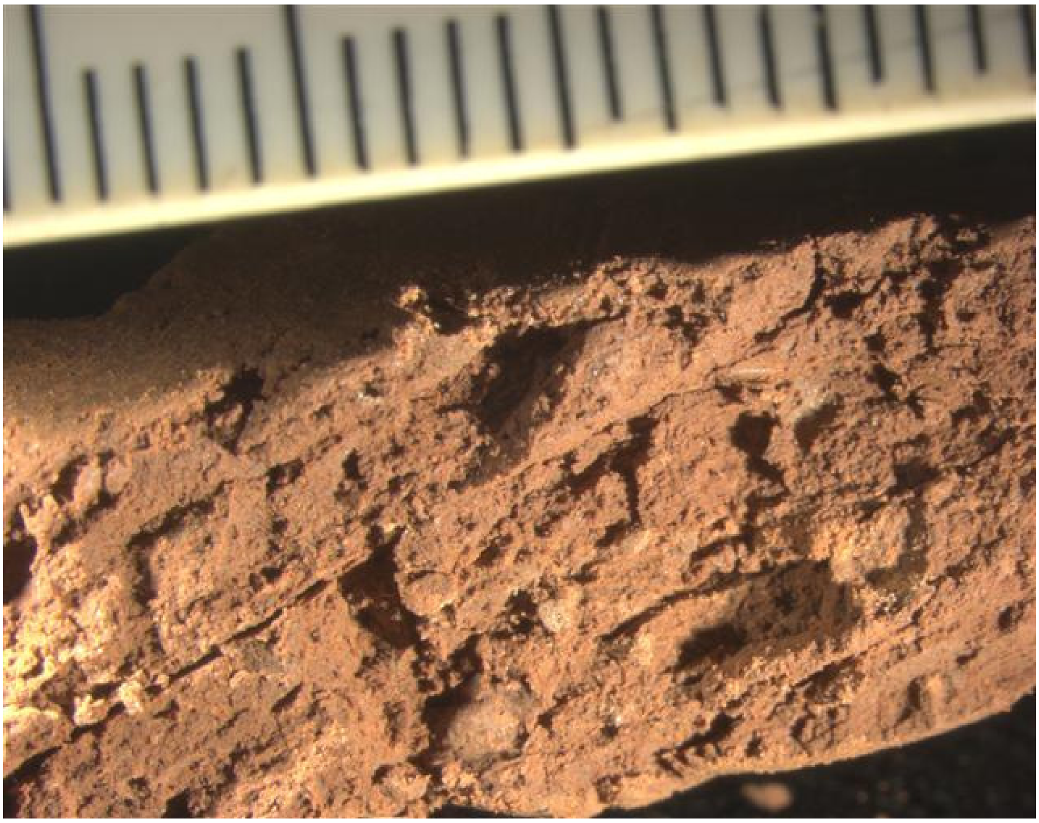


Figure 4.46 Fracturing within the remoulded zone of pile MR1 581mm below ground level. Ruler is in original position of the pile and photograph is taken looking down on the top of the section.

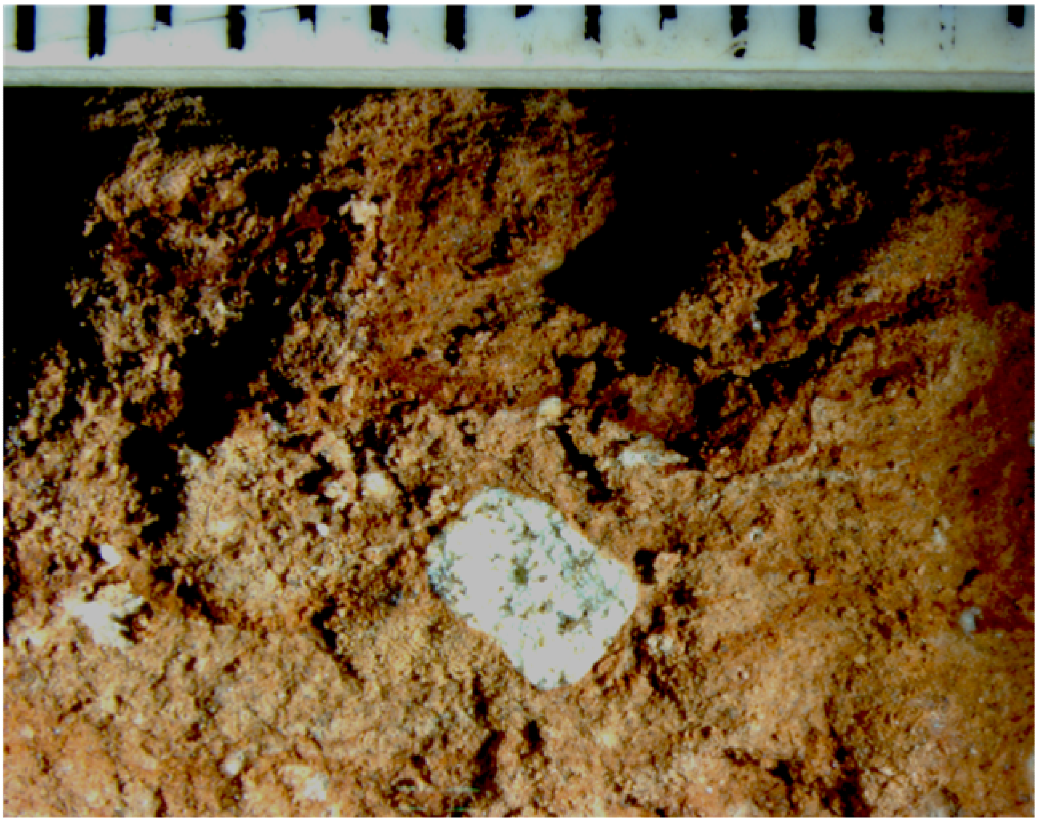


Figure 4.47 Sample taken from the remoulded zone surrounding MR2 690-1000mm below ground level, ruler shows the original location of the pile. Photograph is taken from above; increments indicate lengths of 1mm.

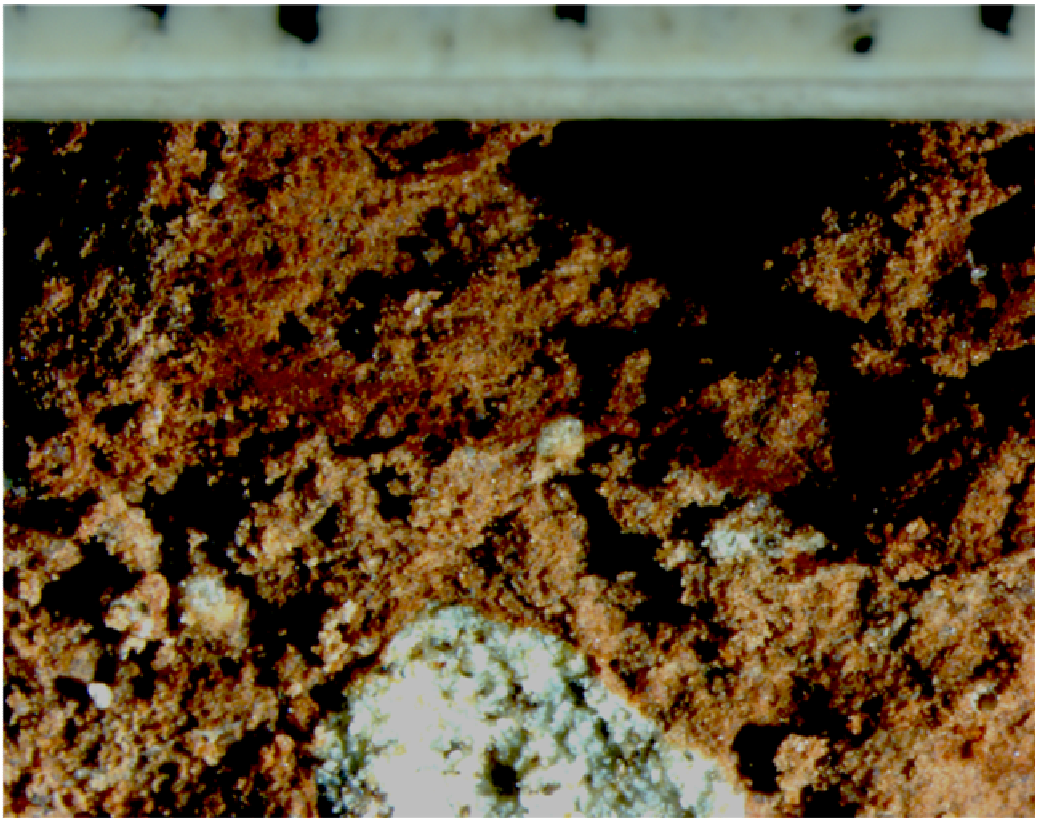


Figure 4.48 Enlarged section from figure 4.47, the remoulded zone surrounding MR2 690-1000mm below ground level, ruler shows the original location of the pile. Photograph is taken from above; increments indicate lengths of 1mm.

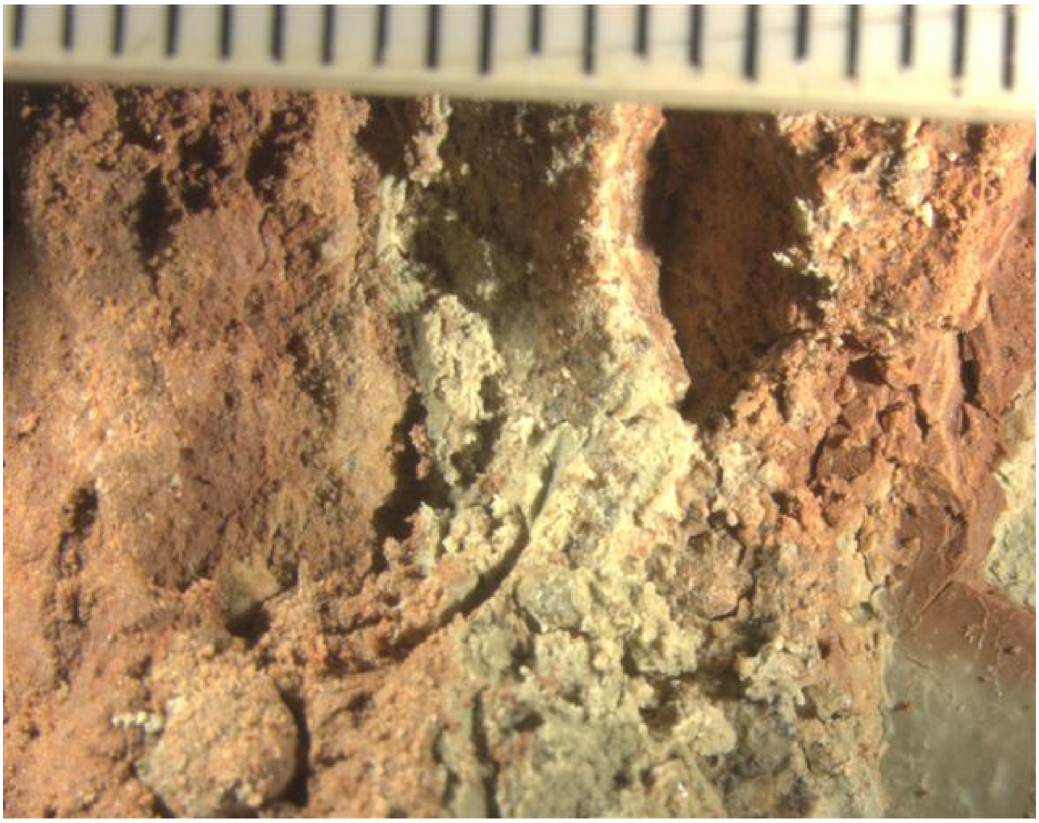


Figure 4.49 Section from around pile MR2 taken from below 1337mm below ground level shows the boundary between the undisturbed material (shown here as a green silty material) at the right of the photograph, with two layers of brown, remoulded material at the left of the picture. The pile was to the left of the picture.

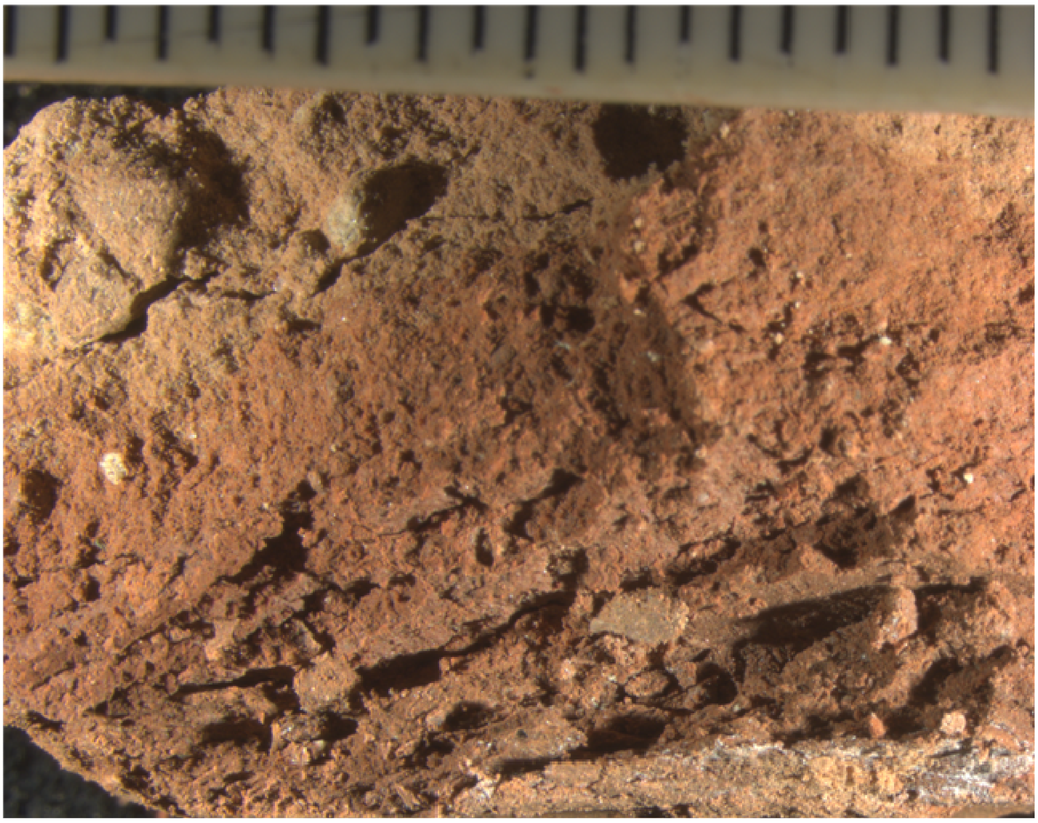


Figure 4.50 Remoulded zone from around pile MR3 0-510mm below ground level. Photograph is taken from above, with the ruler in the position of the pile. Increments are 1mm in length.

Figure 4.51 Enlarged image of the area shown in fig 4.50 from around pile MR3 0-510mm below ground level. Photograph is taken from above. The photograph is 7mm in diameter and the pile would have been at the top of the picture

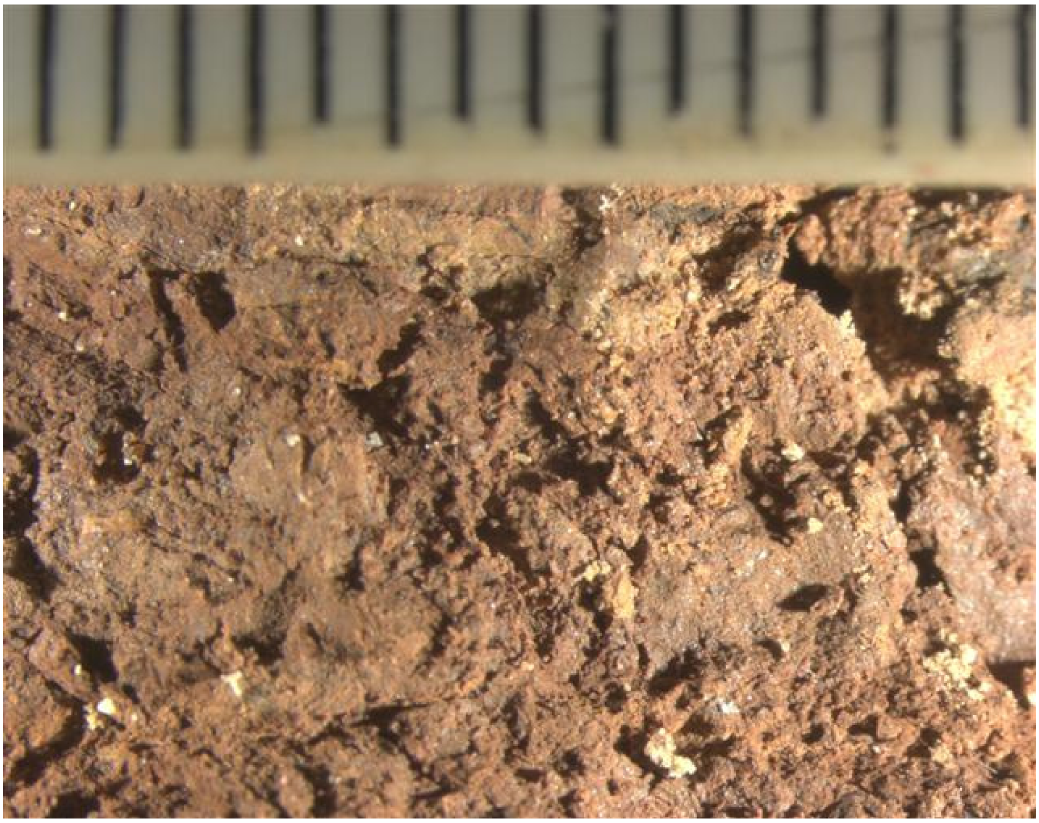


Figure 4.52 The remoulded zone from pile MR4, 0-451 below ground level. Ruler is in original position of pile and shows increments of 1mm.

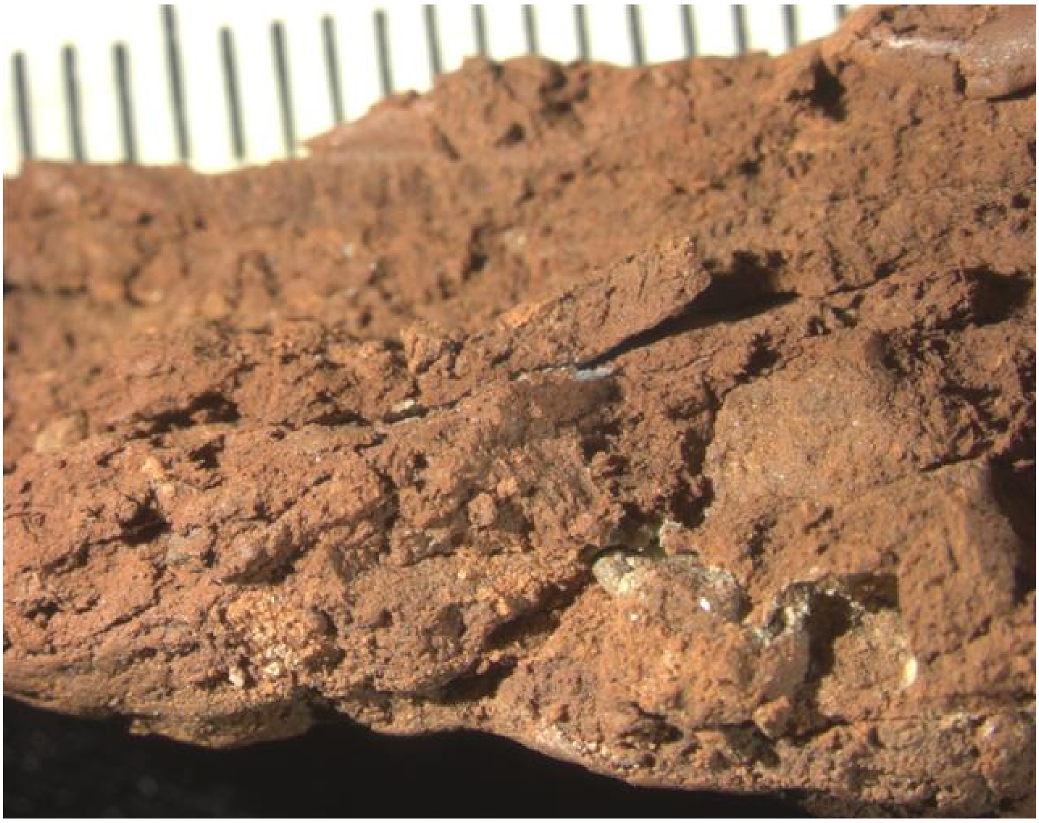


Figure 4.53 The remoulded zone from around pile MR4, 922mm below ground level. Ruler is in the position of the pile and shows 1mm increments

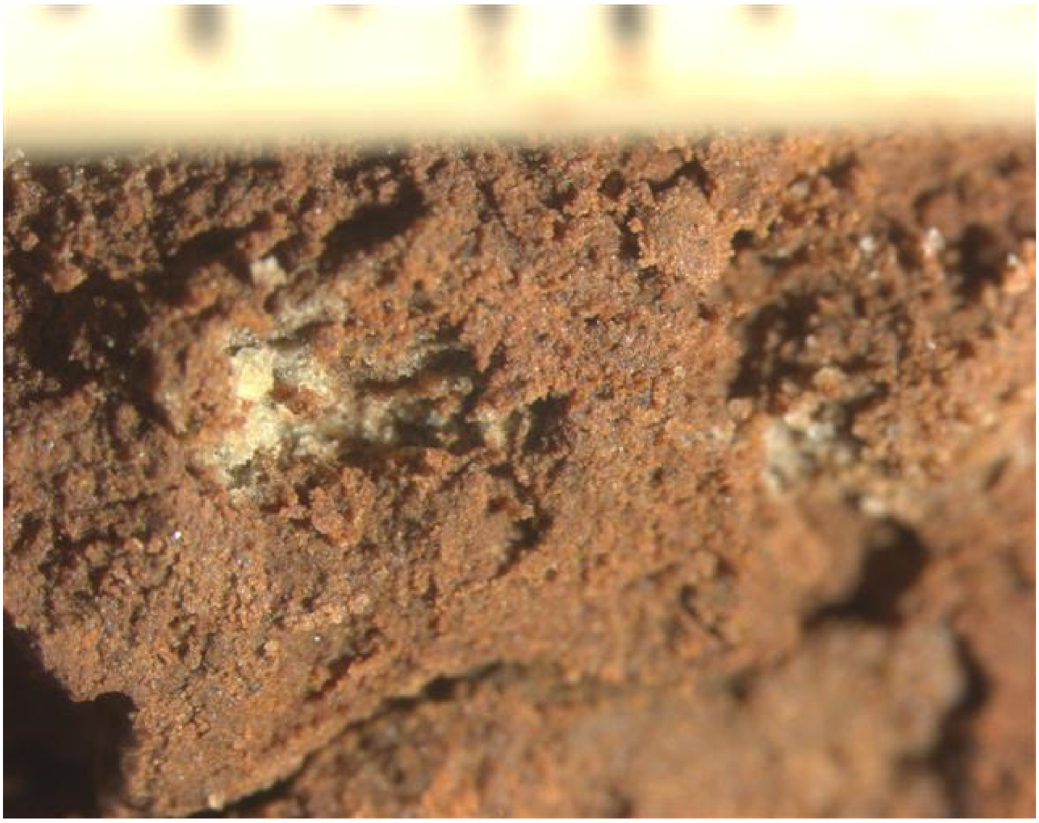


Figure 4.54 The remoulded zone surrounding pile MR4 at 922mm below ground level. Quartz aggregations are seen within this layer. Ruler is in the position of the pile.

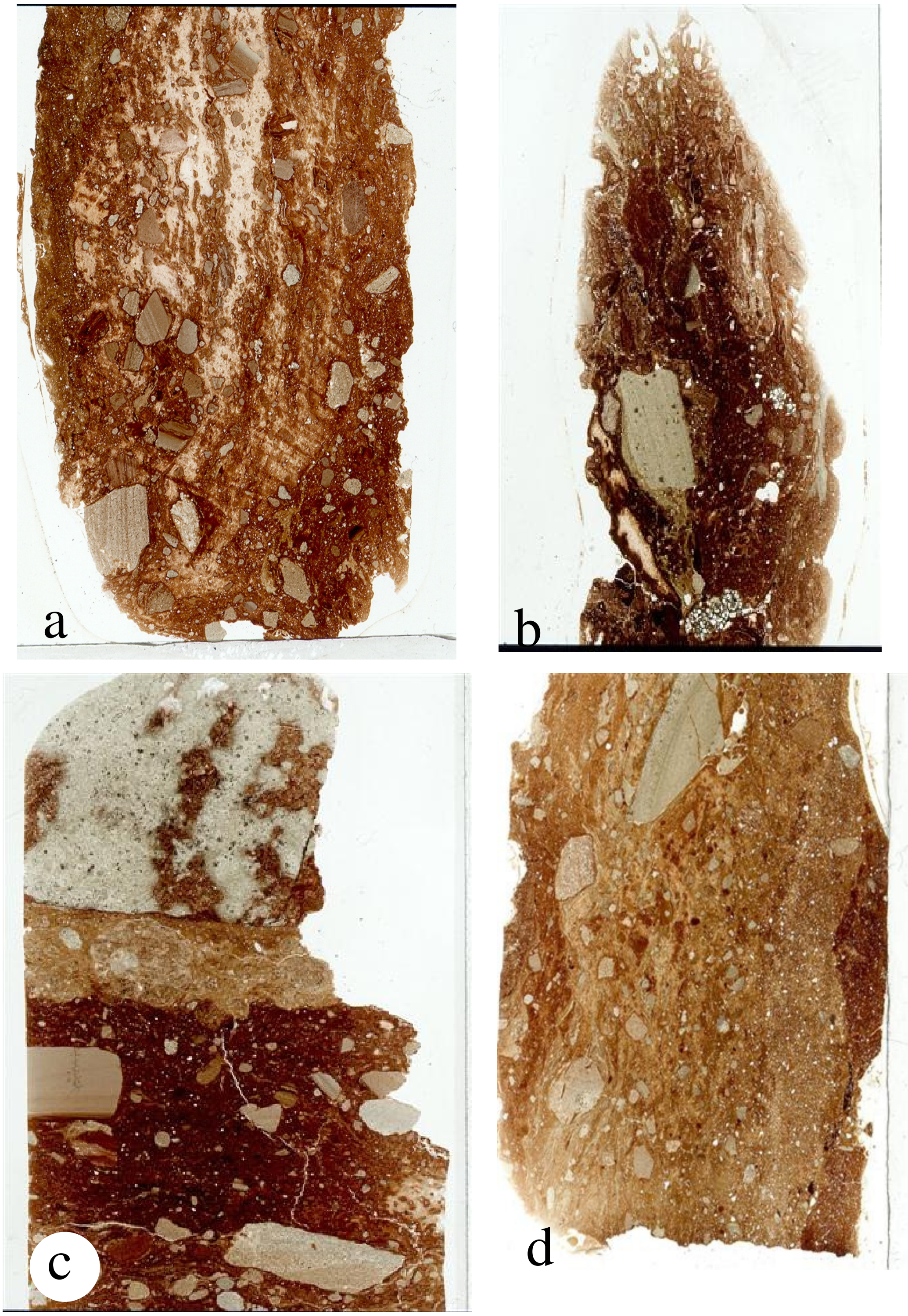


Figure 4.55 Vertically taken thin sections through the remoulded zones around all four piles. a) MR1, slide is 28mm wide b) MR2, slide is 22mm wide c) MR3 slide is 31mm wide d) MR4 slide is 43mm wide. The inner surface of the soil-pile interface is to the right of each picture, apart from figure 4.55c where the soil-pile interface is at the bottom of the picture

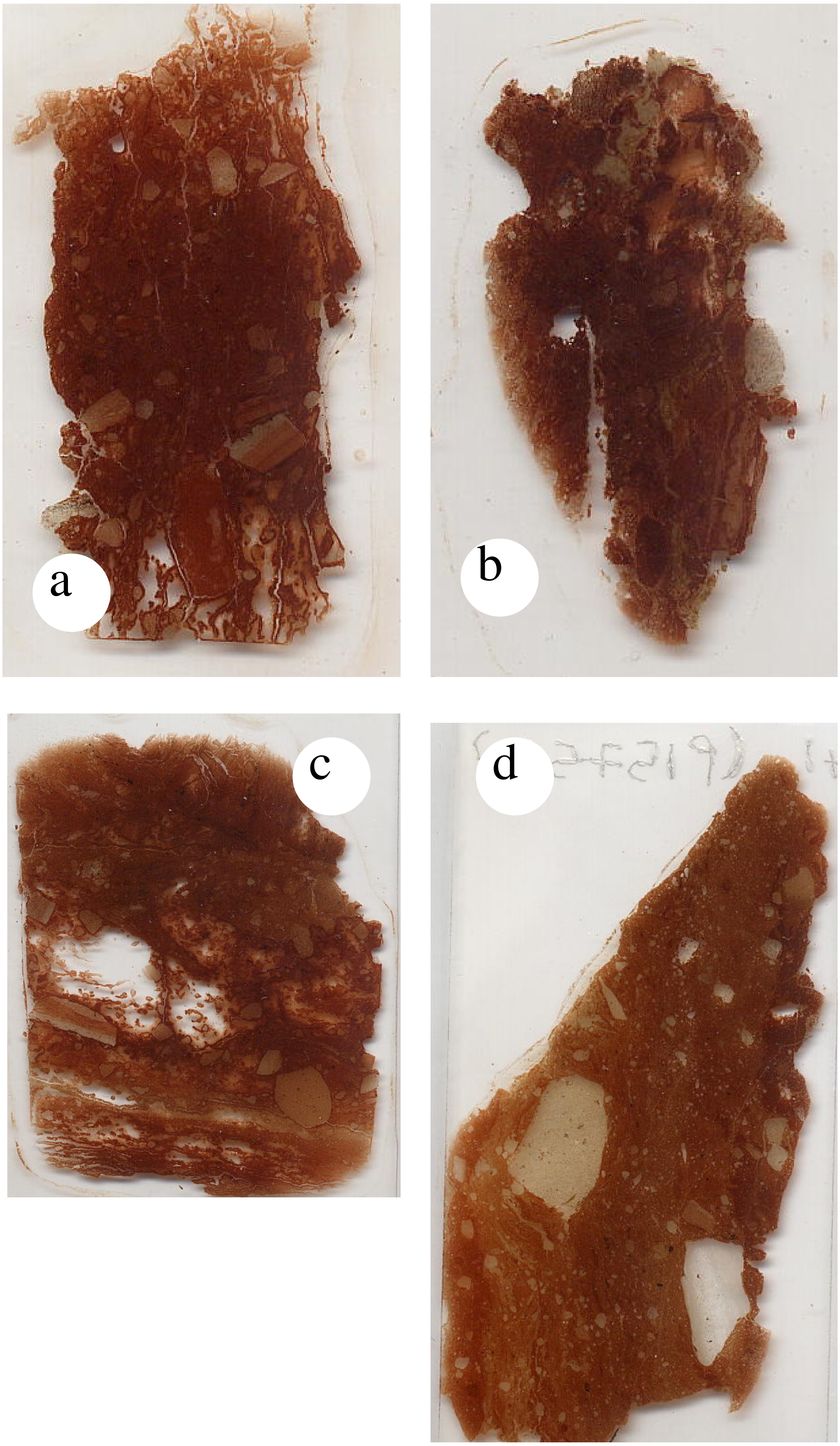


Figure 4.56 Horizontally taken slides from around all four piles) MR1, slide is 19mm wide b) MR2, slide is 17mm wide c) MR3, slide is 48mm wide d) MR4, slide is 40mm wide. In all cases except photo c the pile is to the right of the picture. In the case of photo c the pile it to the bottom of the picture.

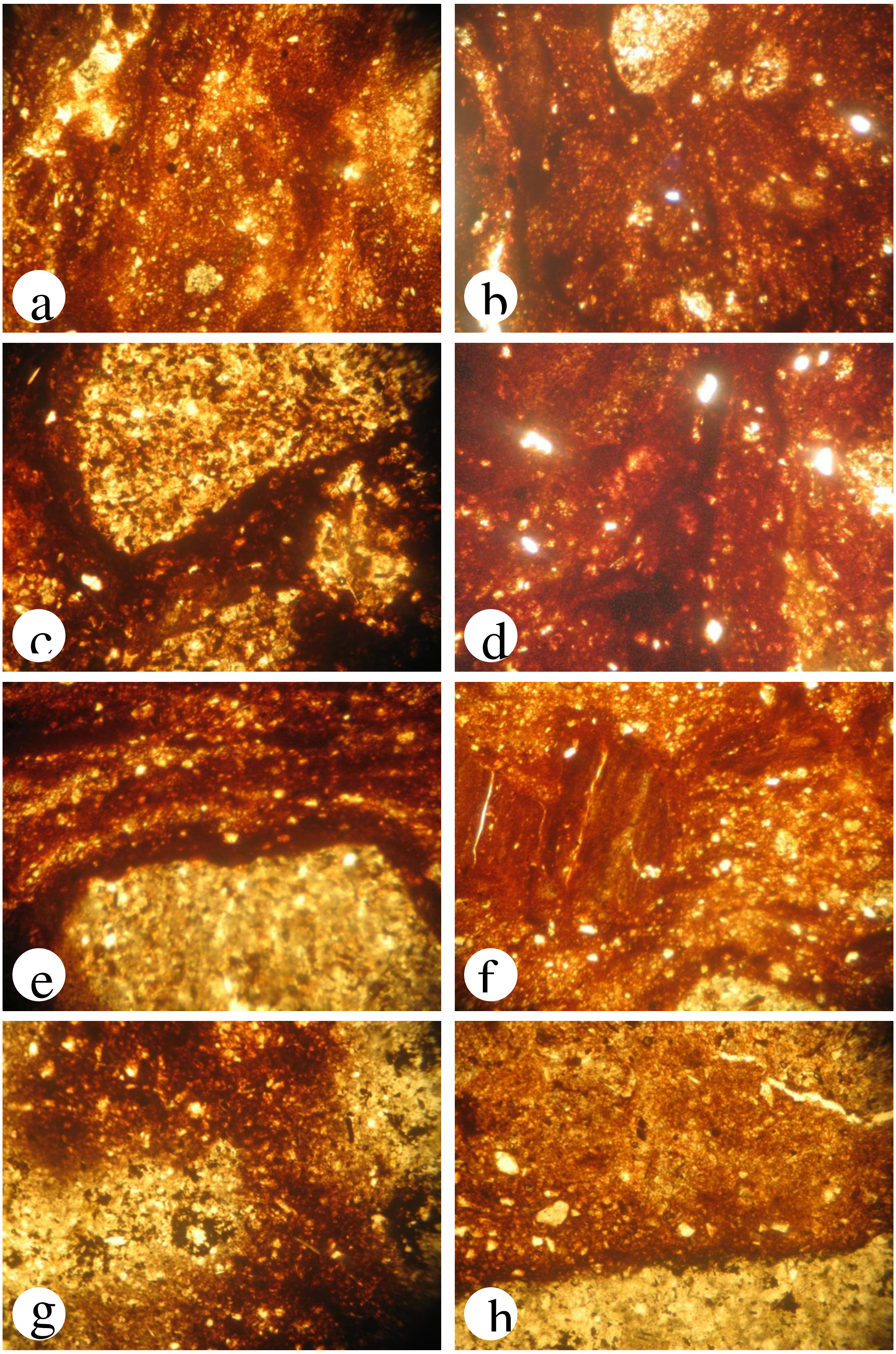


Figure 4.57 Slides viewed under the light reflecting microscope. Slides in same order as text, each photograph is approximately 2mm in diameter a) horizontally taken from the remoulded zone of pile MR1 b) vertically taken from the remoulded zone of pile MR1 c) horizontally taken from the remoulded zone of pile MR2 d) vertically taken from the remoulded zone of pile MR2 MR1 e) horizontally taken from the remoulded zone of pile MR3 f) horizontally taken from the remoulded-host soil interface around pile MR3 g) horizontally taken from the remoulded zone of pile MR3 h) horizontally taken from the

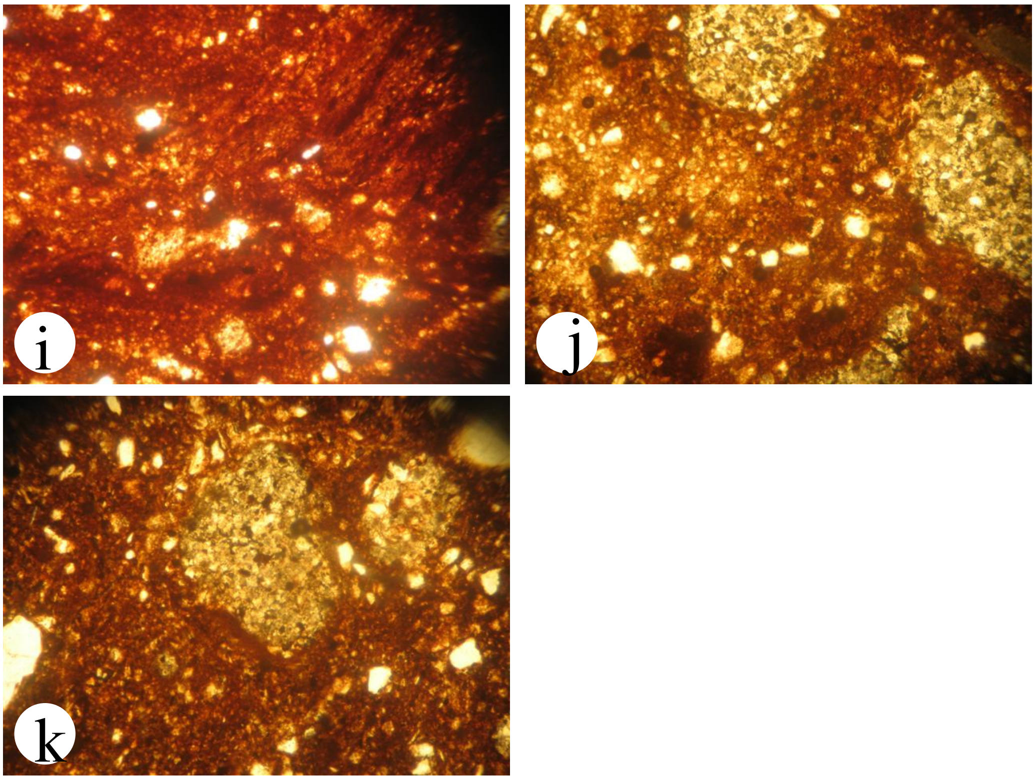


Figure 4.57 (Continued) i) vertically taken from the remoulded zone of pile MR3 j) vertically taken from the remoulded zone of pile MR4 k) horizontally taken from the remoulded zone of pile MR4

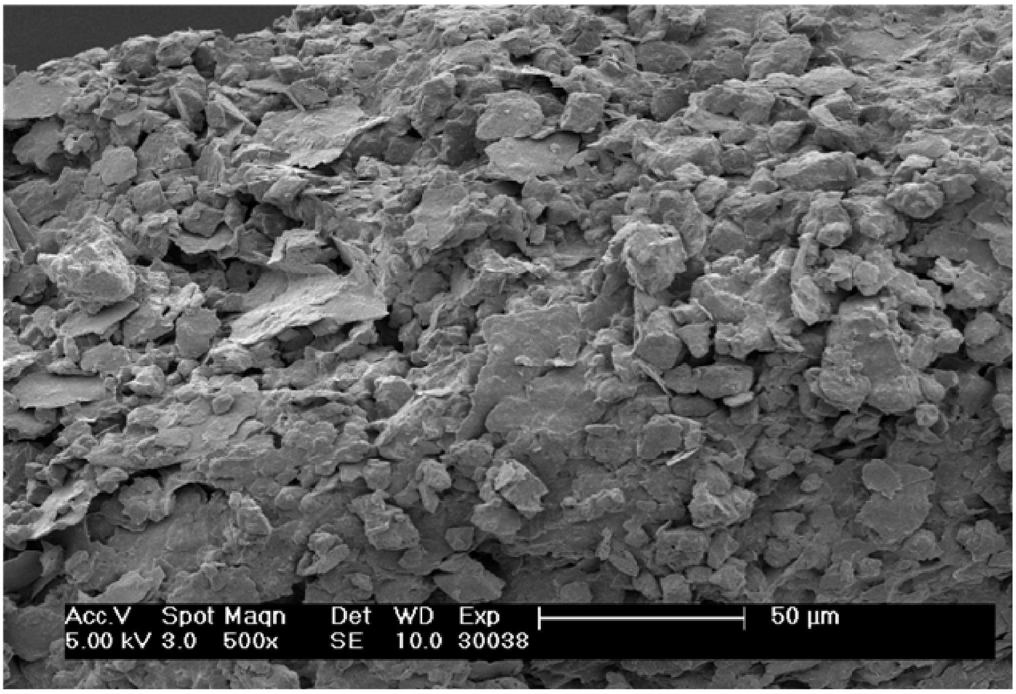


Figure 4.58 Scanning electron microscope photograph from undisturbed material surrounding pile MR1, 1177-1277mm below ground level and 50mm from the pile

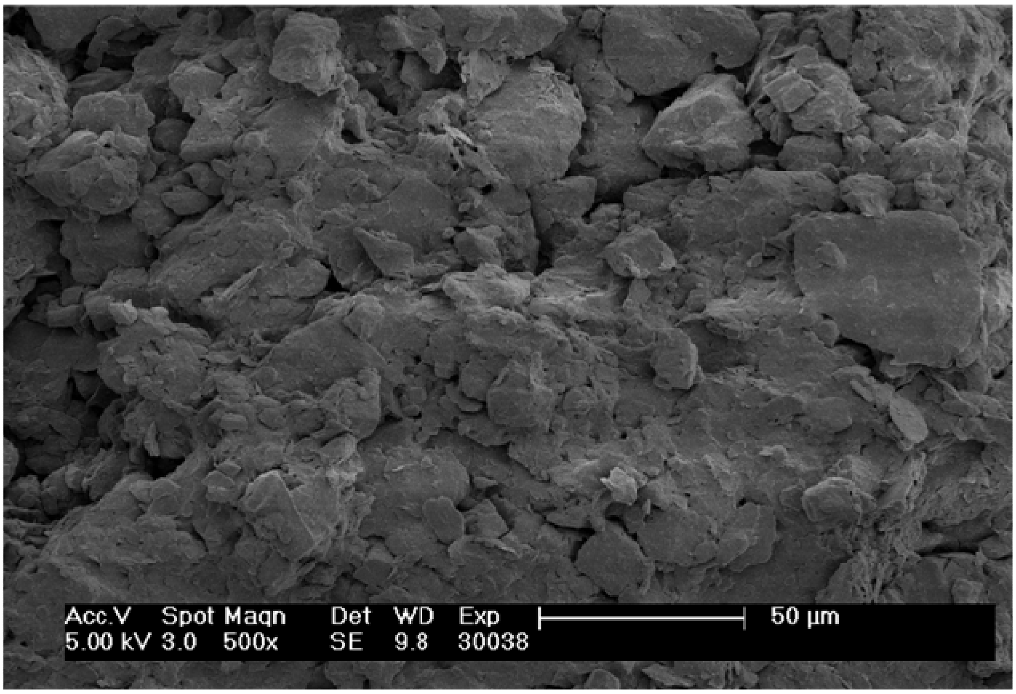


Figure 4.59 Sample taken from the remoulded zone surrounding pile MR1, 1177-1277mm below ground level, 0mm from the pile

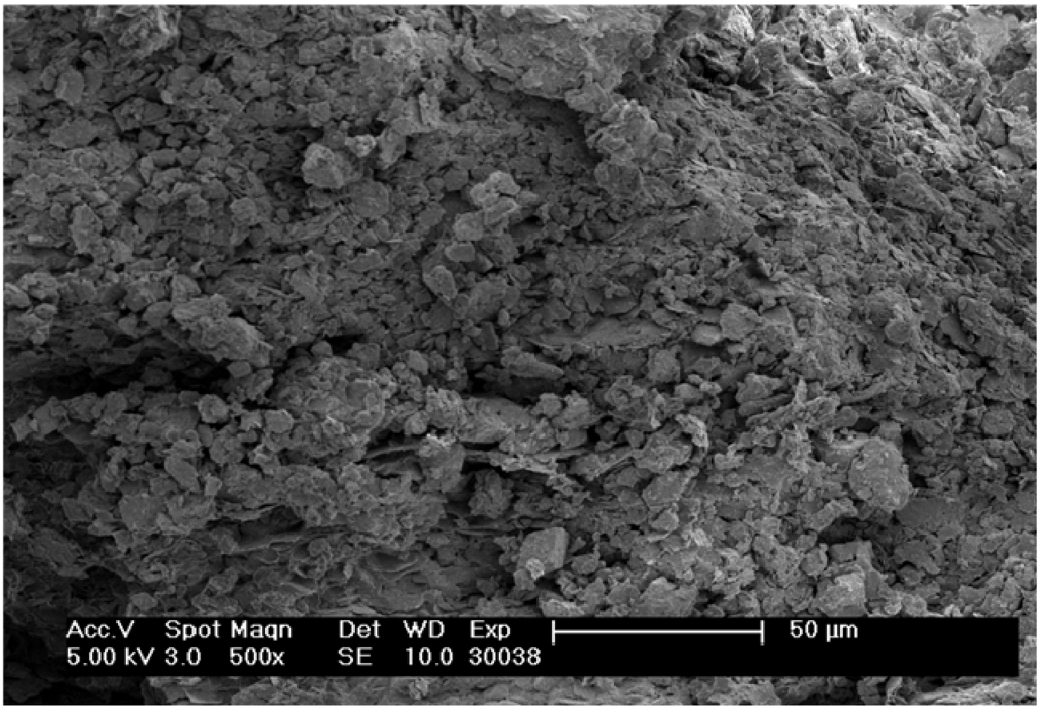


Figure 4.60 Sample taken from the undisturbed material surrounding pile MR2 1337mm below ground level, 50mm from the pile

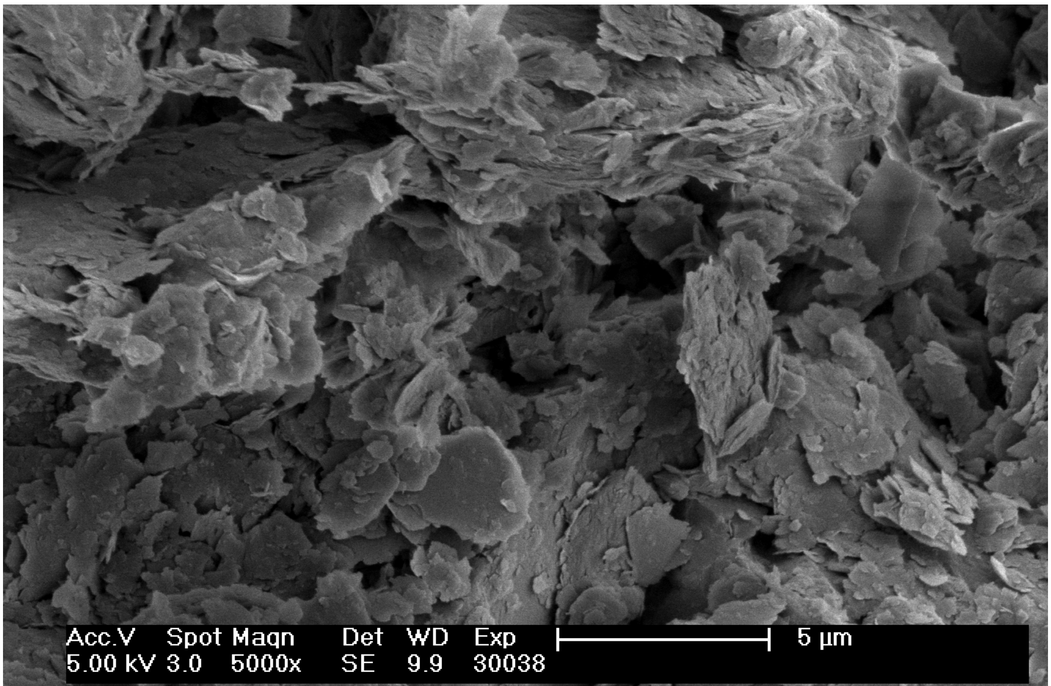


Figure 4.61 Enlarged view of the undisturbed samples taken from around pile MR2 1337mm below ground level, 50mm from the pile

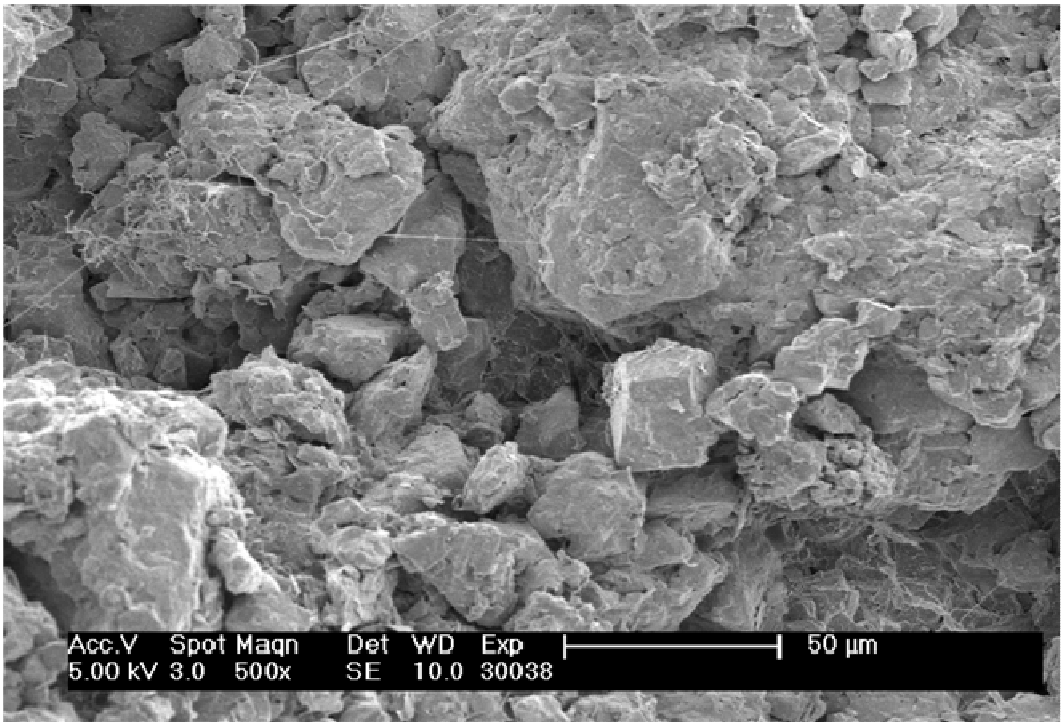


Figure 4.62 Photograph taken using the SEM of remoulded material from the zone surrounding pile MR2 1337mm below ground level, 0mm from the pile

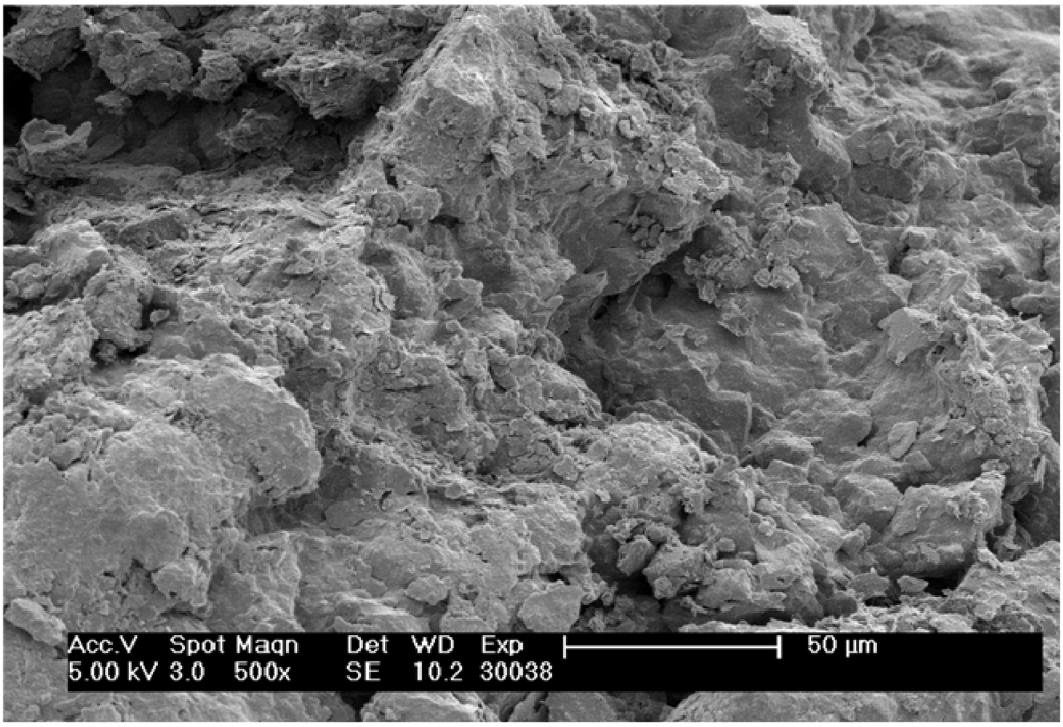


Figure 4.63 SEM photograph taken from the first remoulded zone of pile MR3, 860-960mm below ground level, 0-2mm from the pile

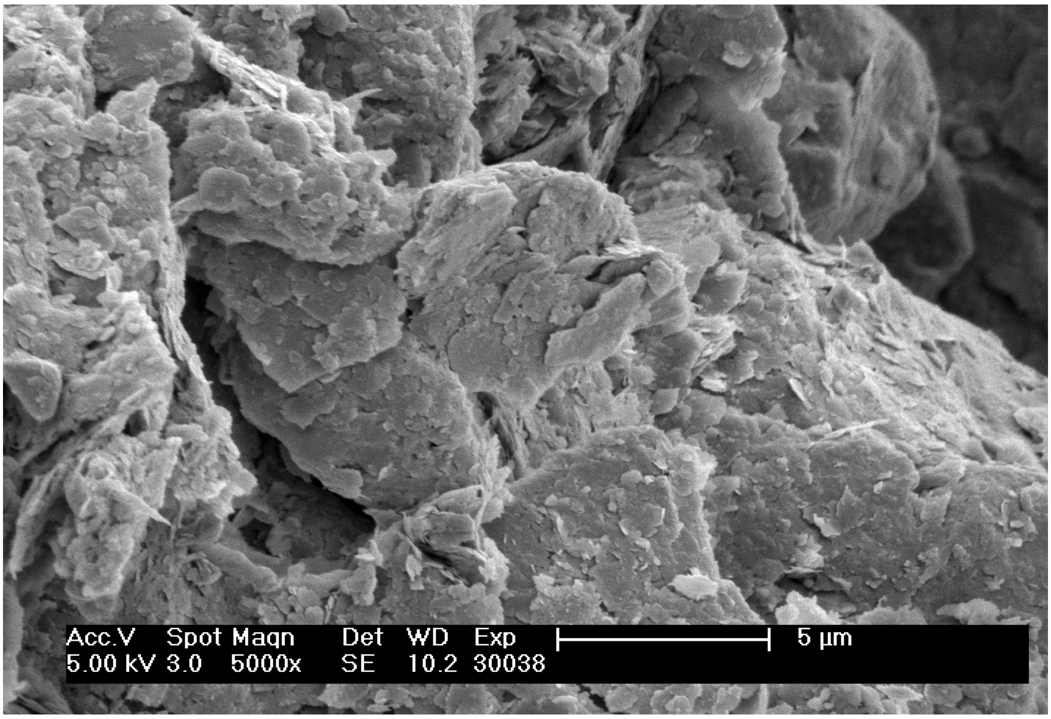


Figure 4.64 First remoulded layer taken from around pile MR3, 860-960mm below ground level, 0-2mm from the pile

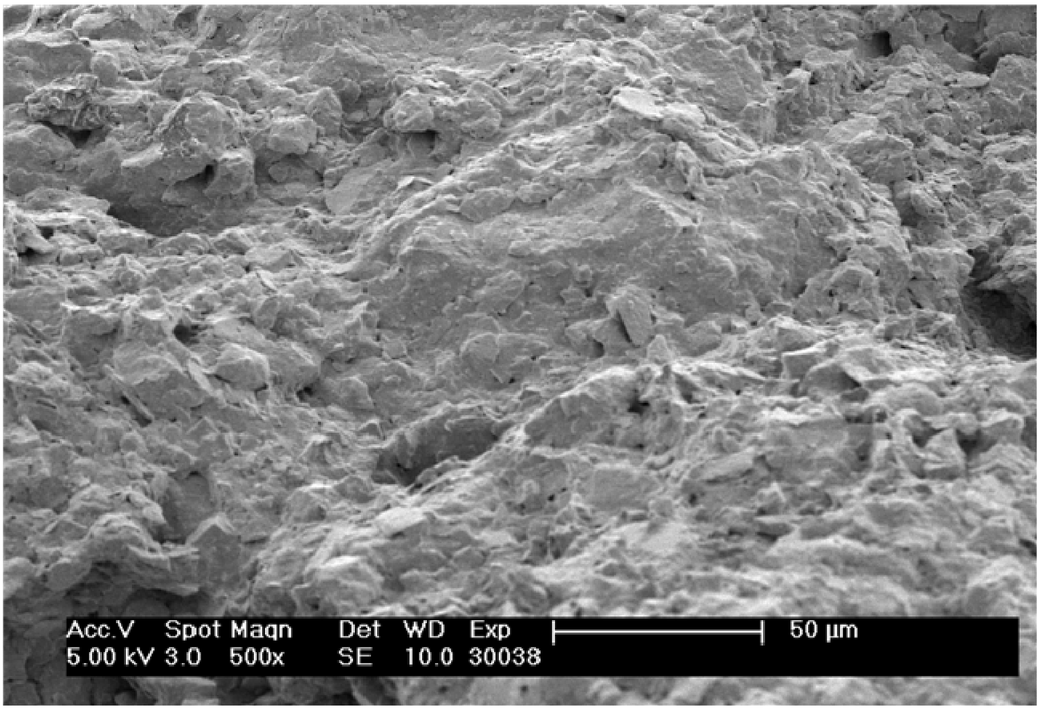


Figure 4.65 Sample taken from the second remoulded zone surrounding pile MR3, 860-960mm below ground level, 2-22mm from the pile

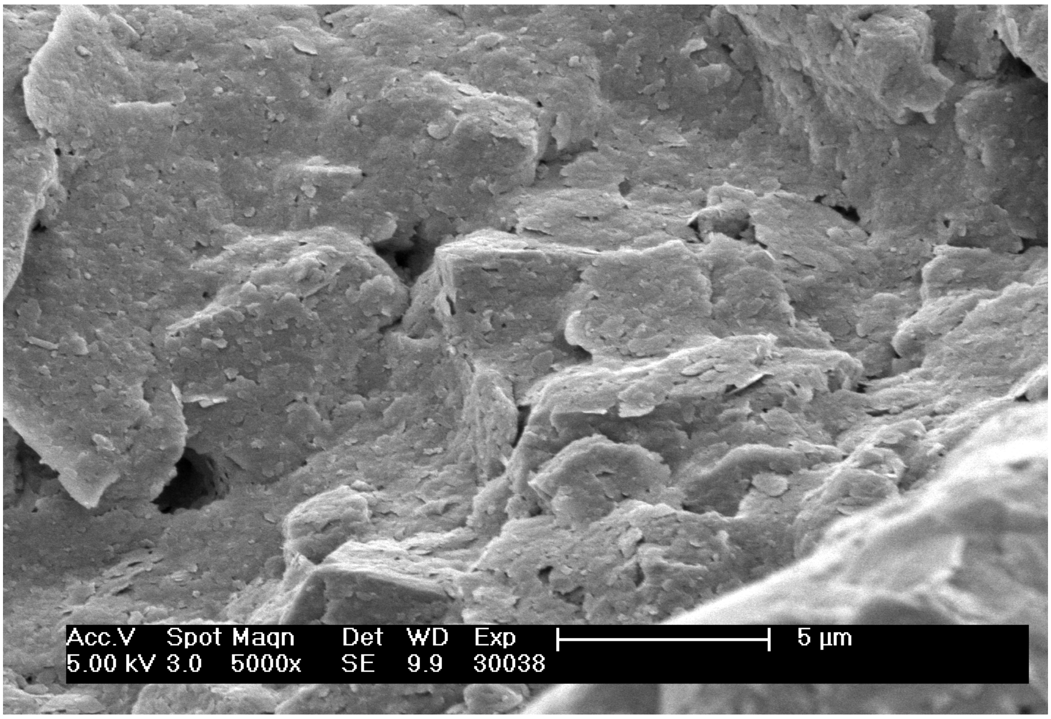


Figure 4.66 Second layer of remoulding from around pile MR3, 860-960mm below ground level, 2-22mm from the pile

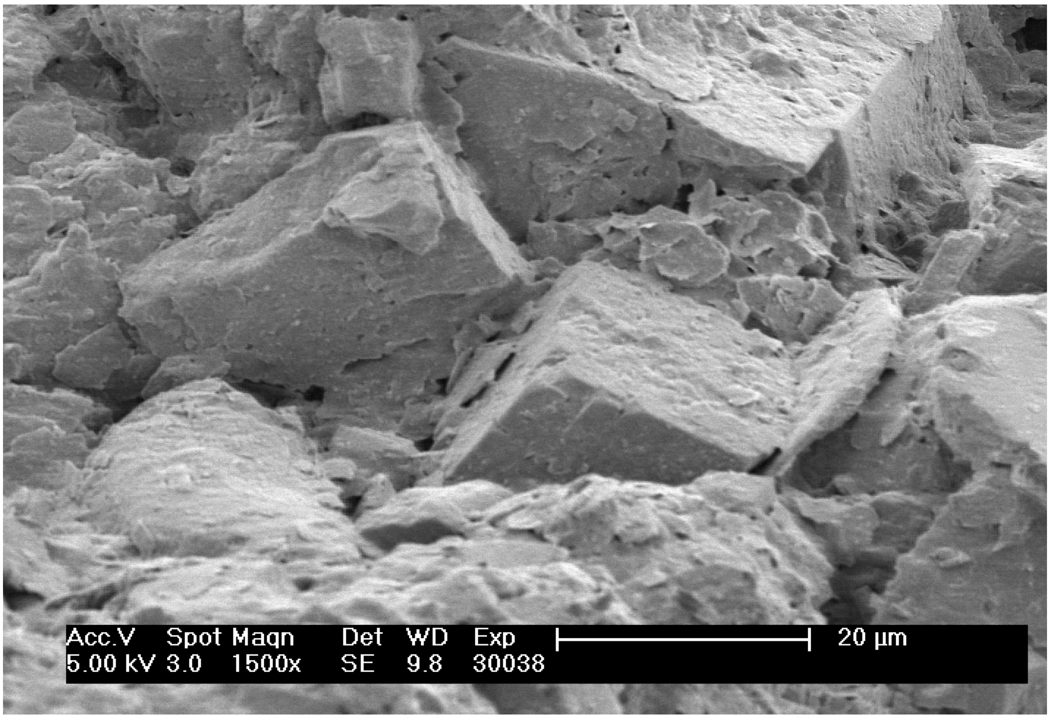


Figure 4.67 Second remoulded layer from around pile MR3, 860-960mm below ground level, 2-22mm from the pile

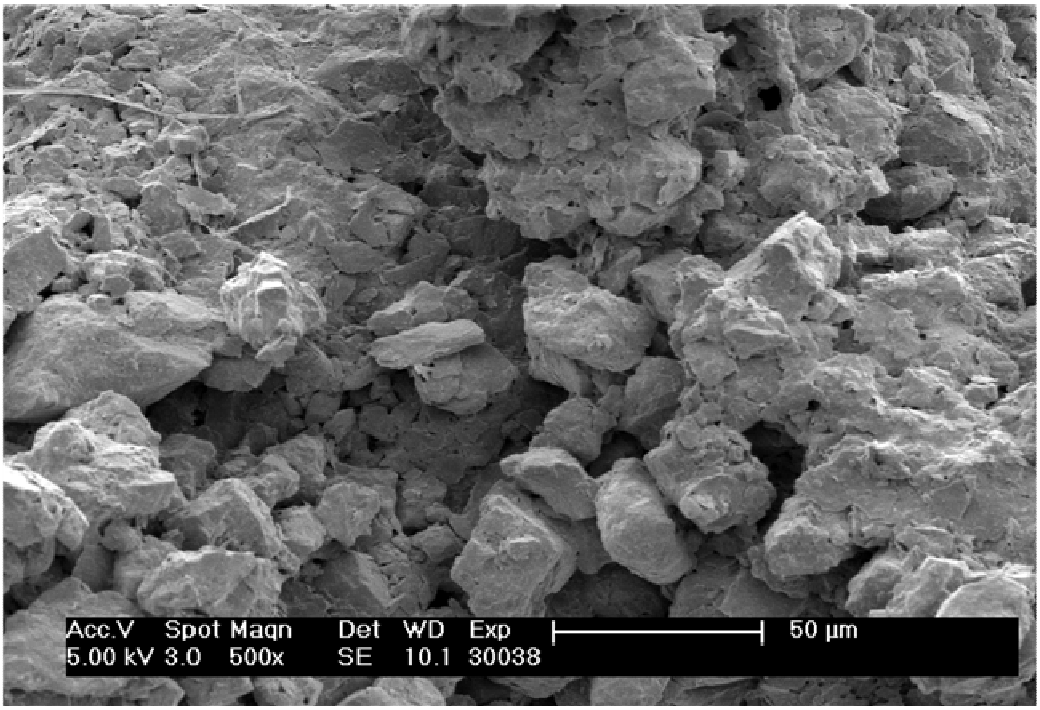


Figure 4.68 Third remoulded layer surrounding pile MR3, 860-960mm below ground level, 22-70mm from the pile

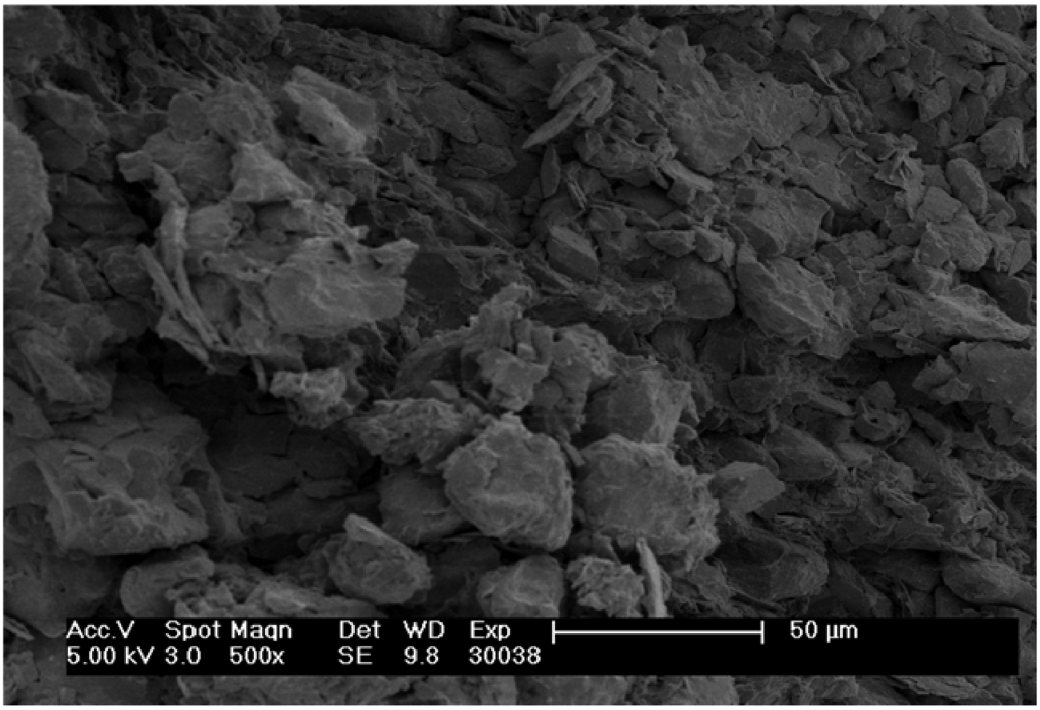


Figure 4.69 Soil from the remoulded zone surrounding pile MR4, 922mm below ground level, 0mm from the pile

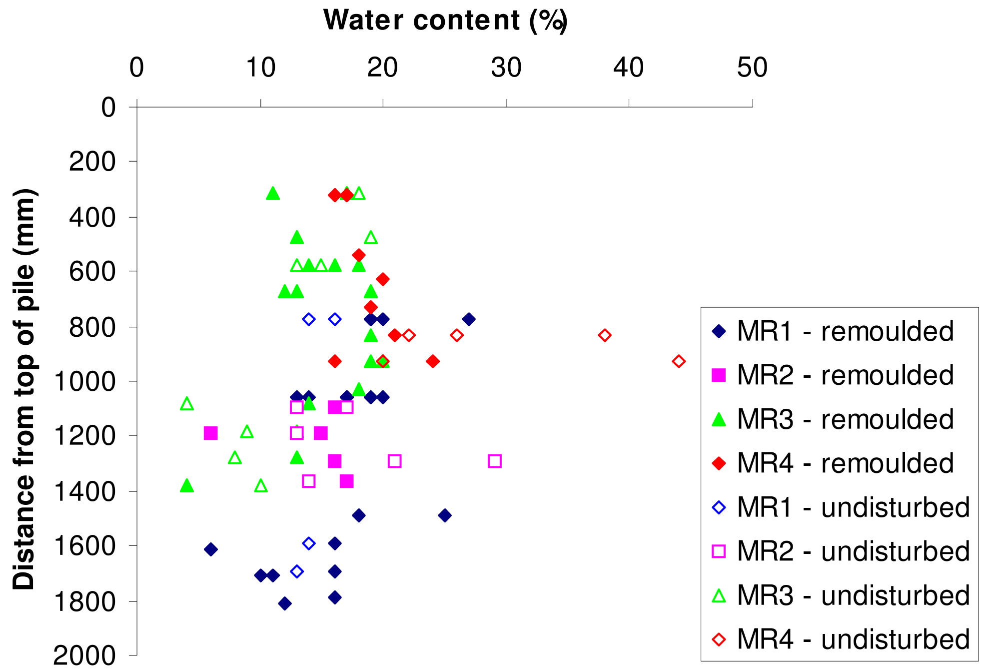


Figure 4.70 The water content variation with depth down the pile for all piles

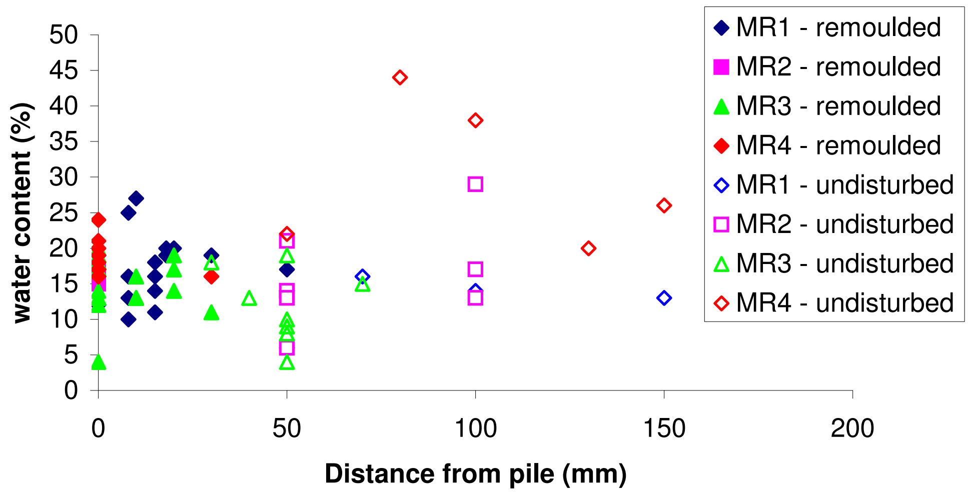


Figure 4.71 The water content variation with horizontal distance from the pile for all piles

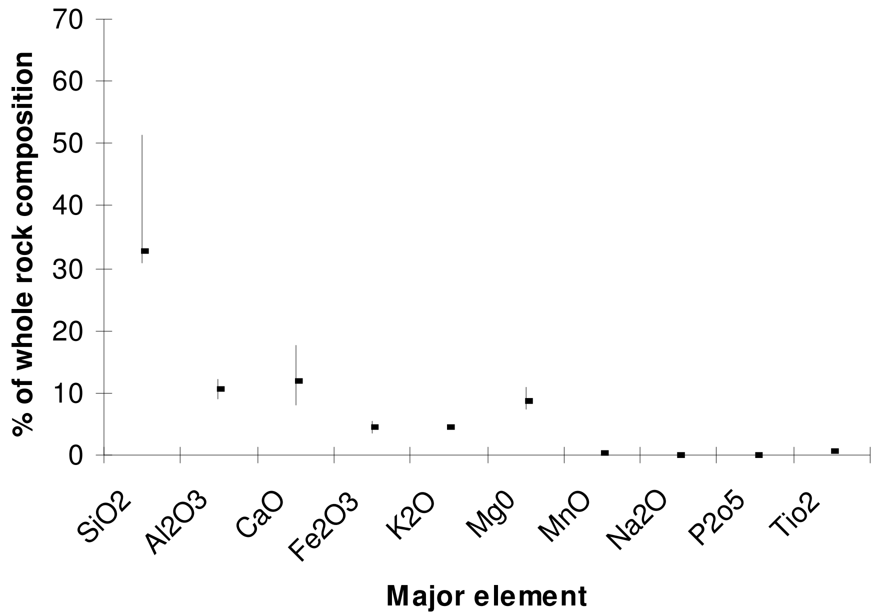


Figure 4.72 Chemical analysis of soil outside the remoulded zone - all piles

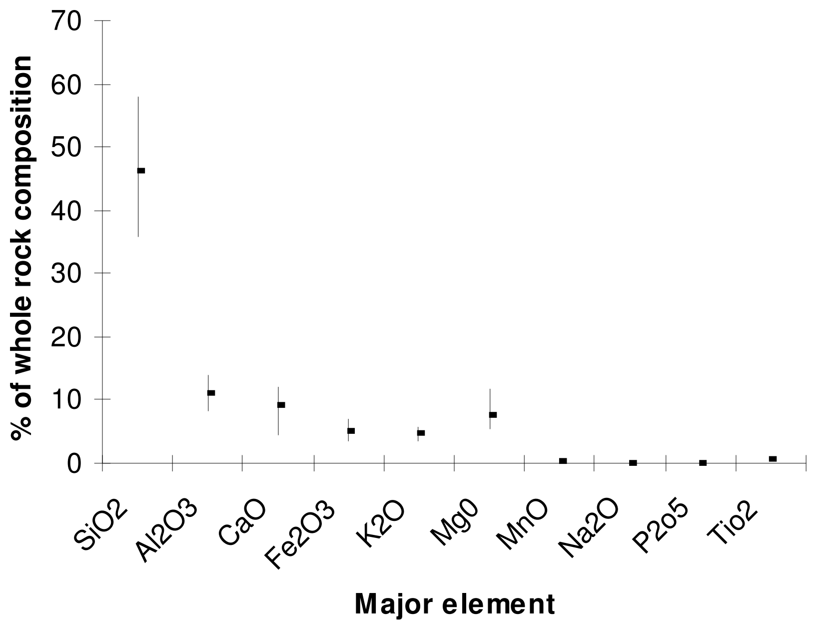


Figure 4.73 Chemical analysis of soil within the remoulded zone - all piles

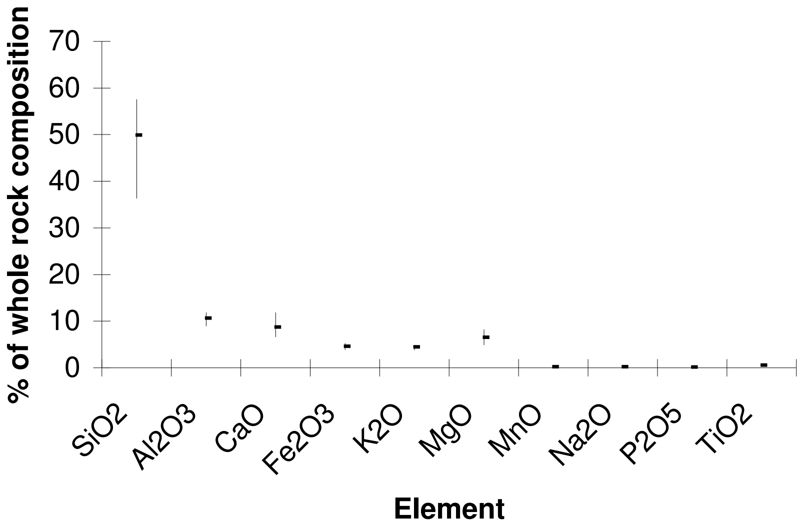


Figure 4.74 Chemical analysis of samples scraped from the pile shaft - all piles

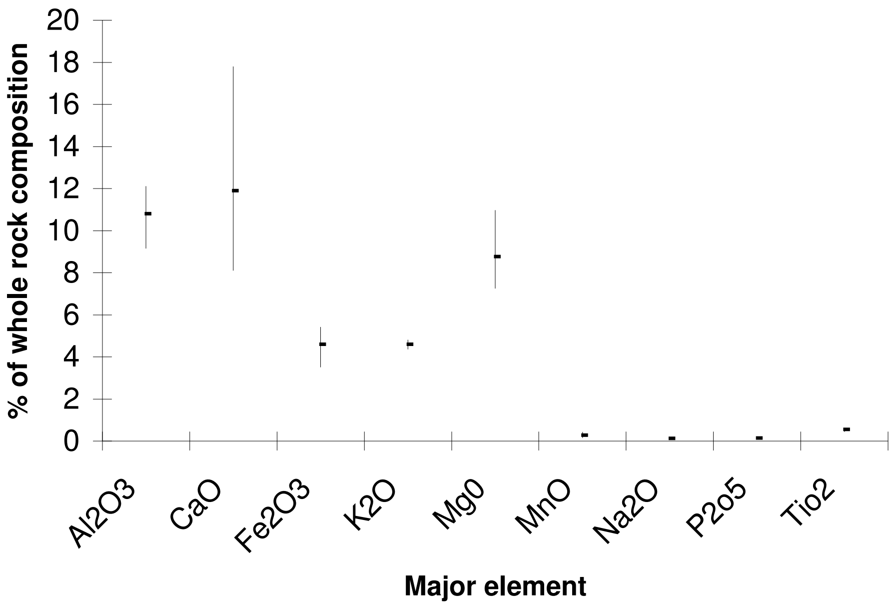


Figure 4.75 Chemical analysis of soil outside the remoulded zone excluding SiO_2 - all piles

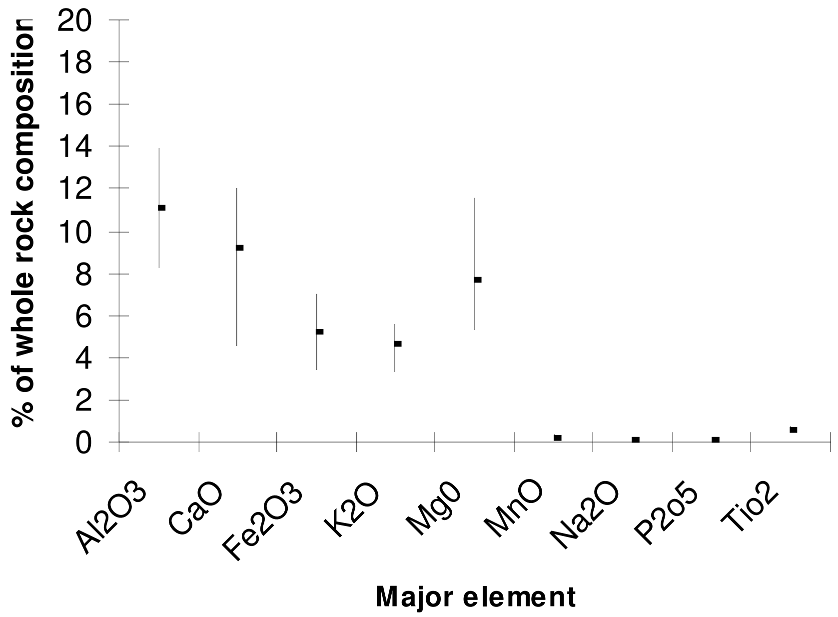


Figure 4.76 Chemical analysis of soil within the remoulded zone excluding SiO2 - all piles

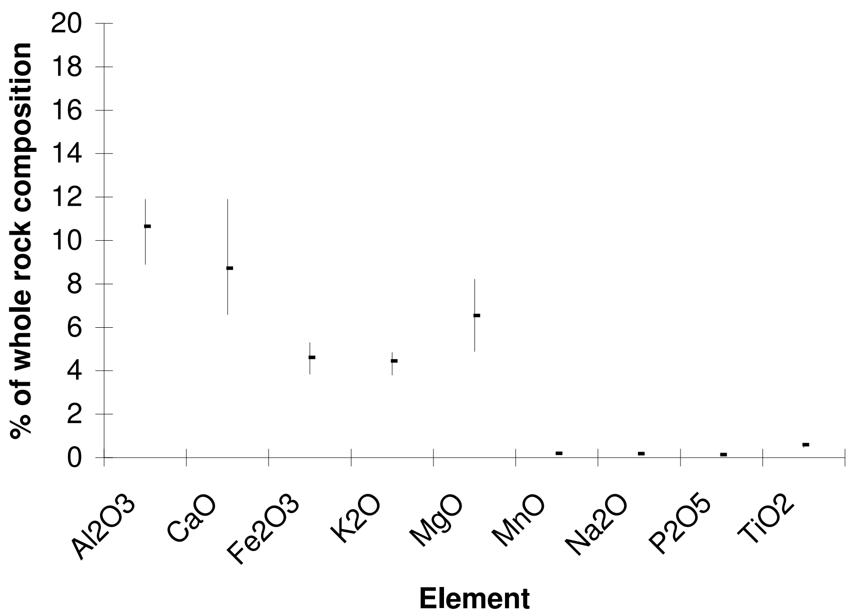


Figure 4.77 Chemical analysis of samples scraped from the pile shaft excluding SiO_2 - all piles

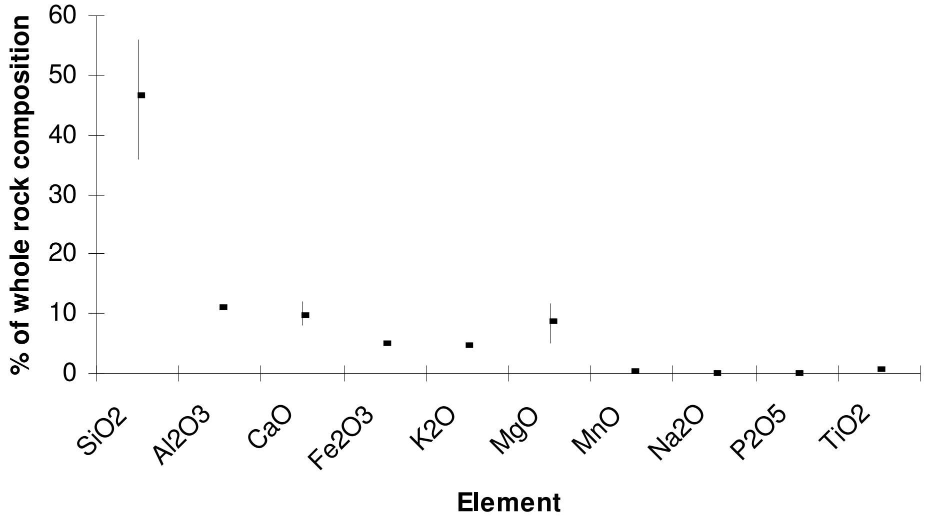


Figure 4.78 Chemical analysis of soil surrounding pile MR1

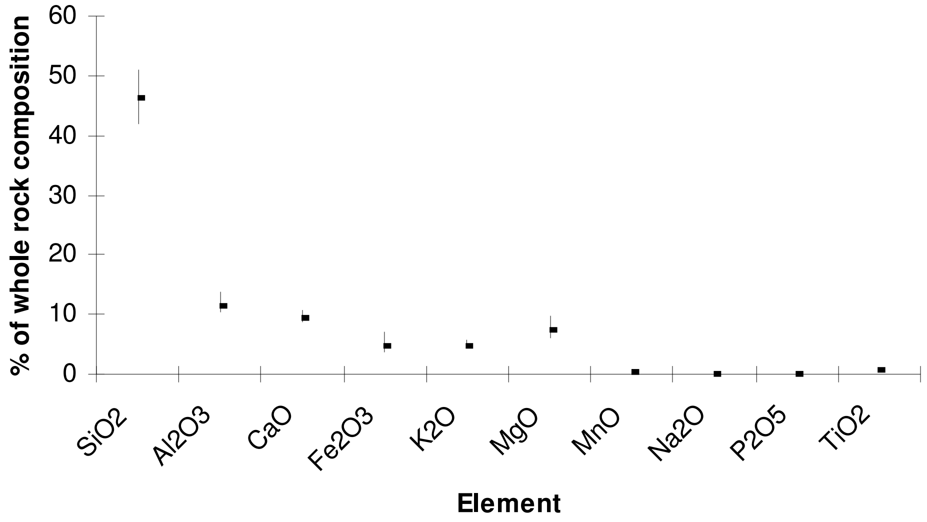


Figure 4.79 Chemical analysis of soil surrounding pile MR2

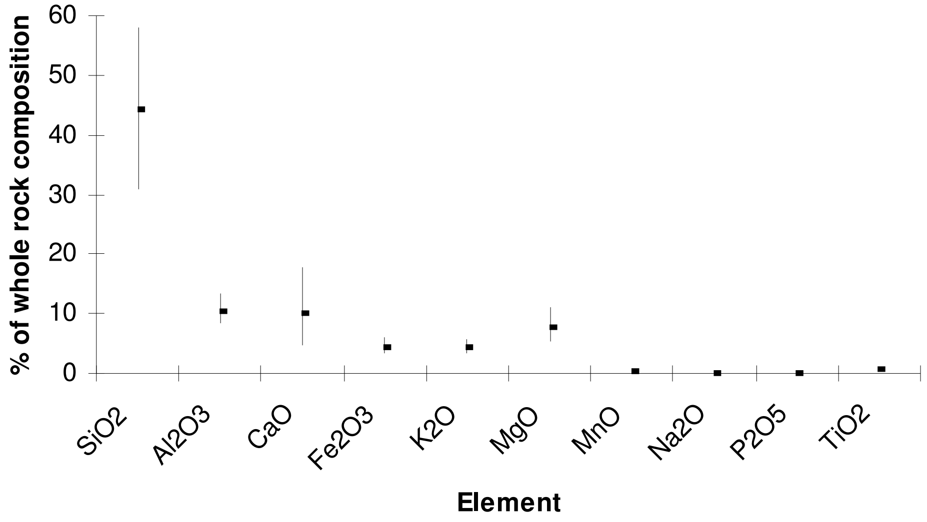


Figure 4.80 Chemical analysis of soil surrounding pile MR3

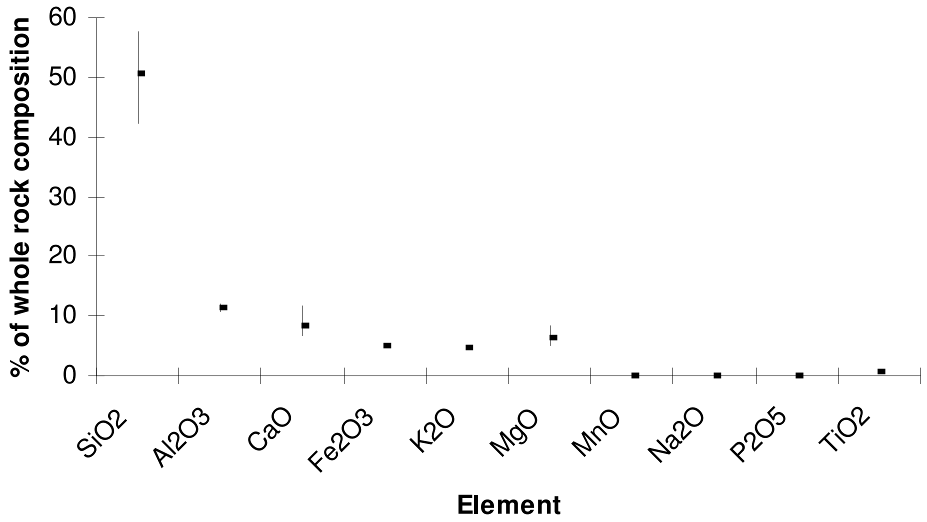


Figure 4.81 Chemical analysis of soil surrounding pile MR4

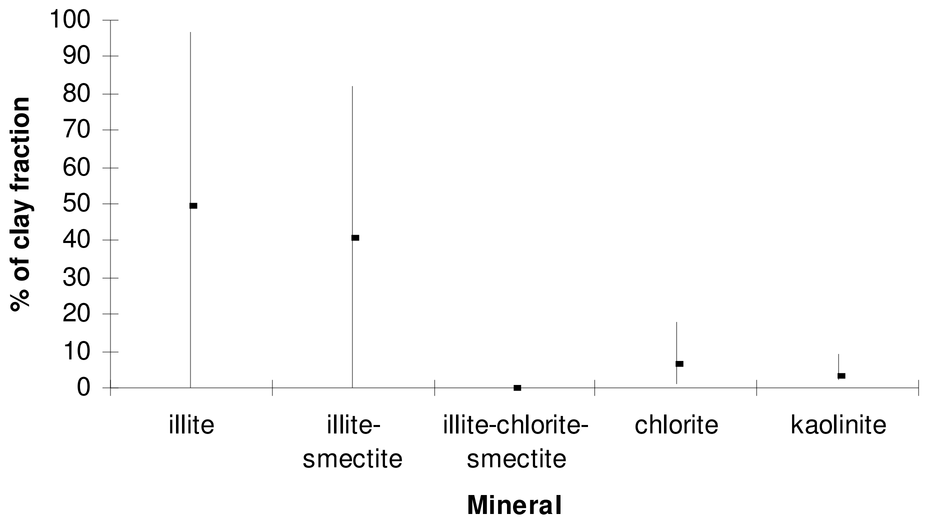


Figure 4.82 Abundances of minerals within the clay fraction of undisturbed soil

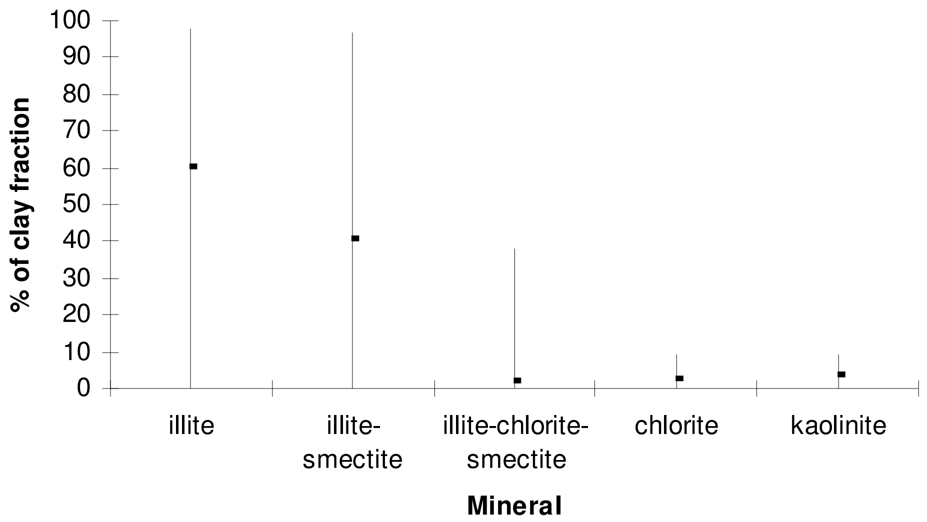


Figure 4.83 Abundances of minerals within the clay fraction of remoulded soil

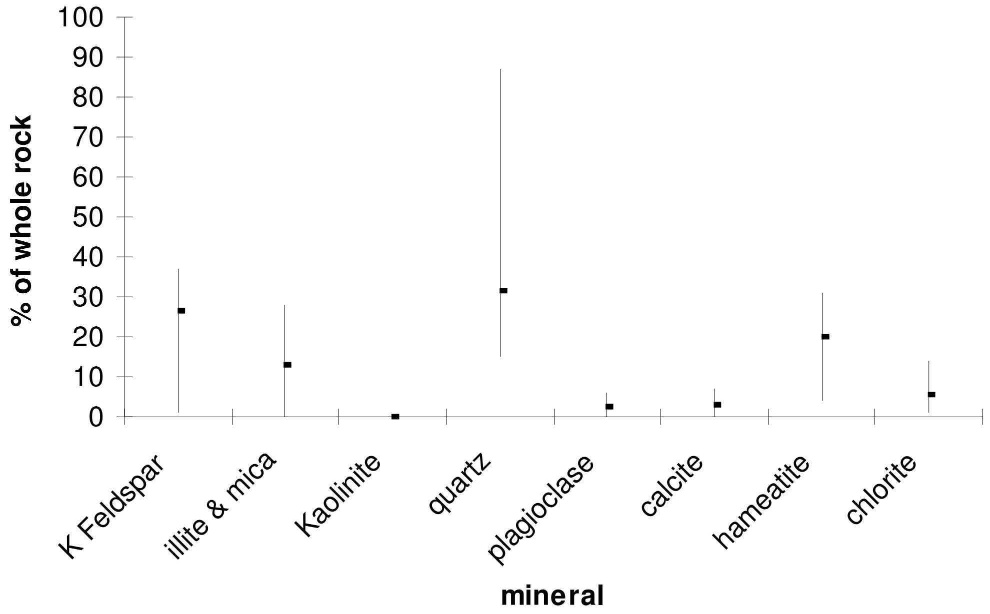


Figure 4.84 Abundances of minerals within the whole rock, undisturbed soil

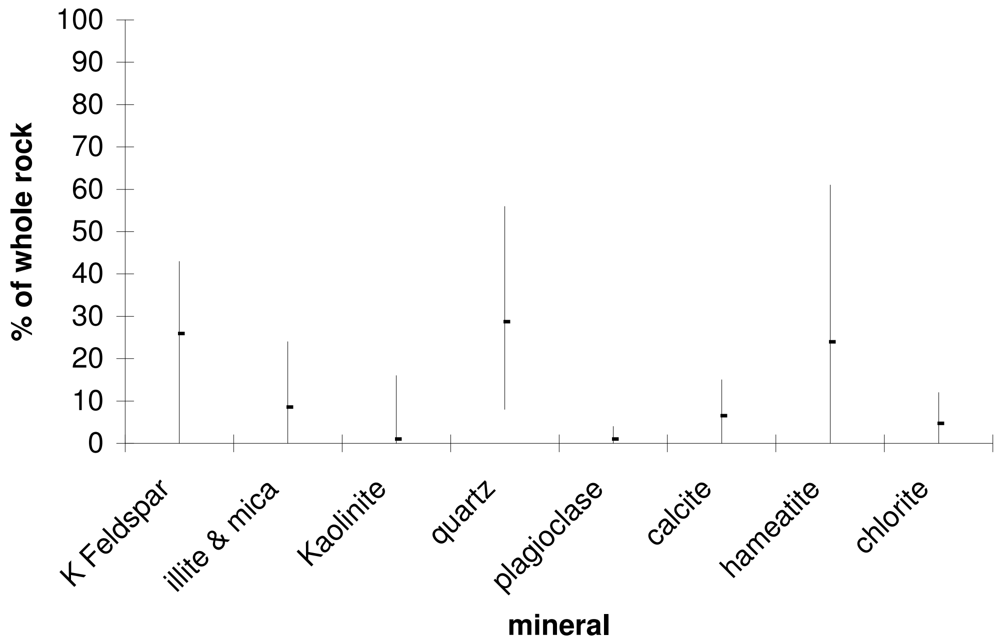


Figure 4.85 Abundances of minerals within the whole rock, remoulded soil

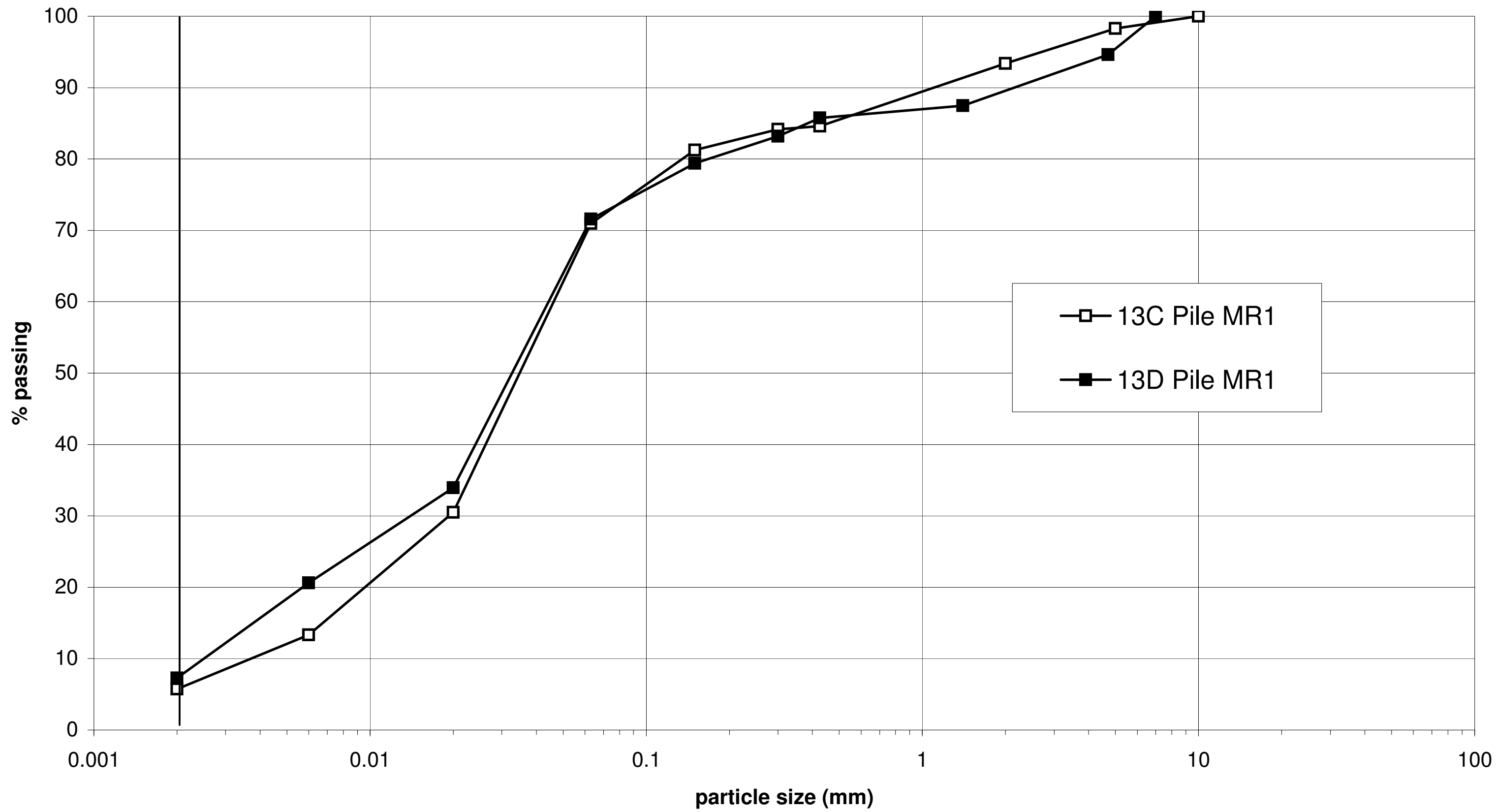


Figure 4.86 PSD curve for the samples taken from around pile MR1 (sample numbers are shown in Table 4.1)

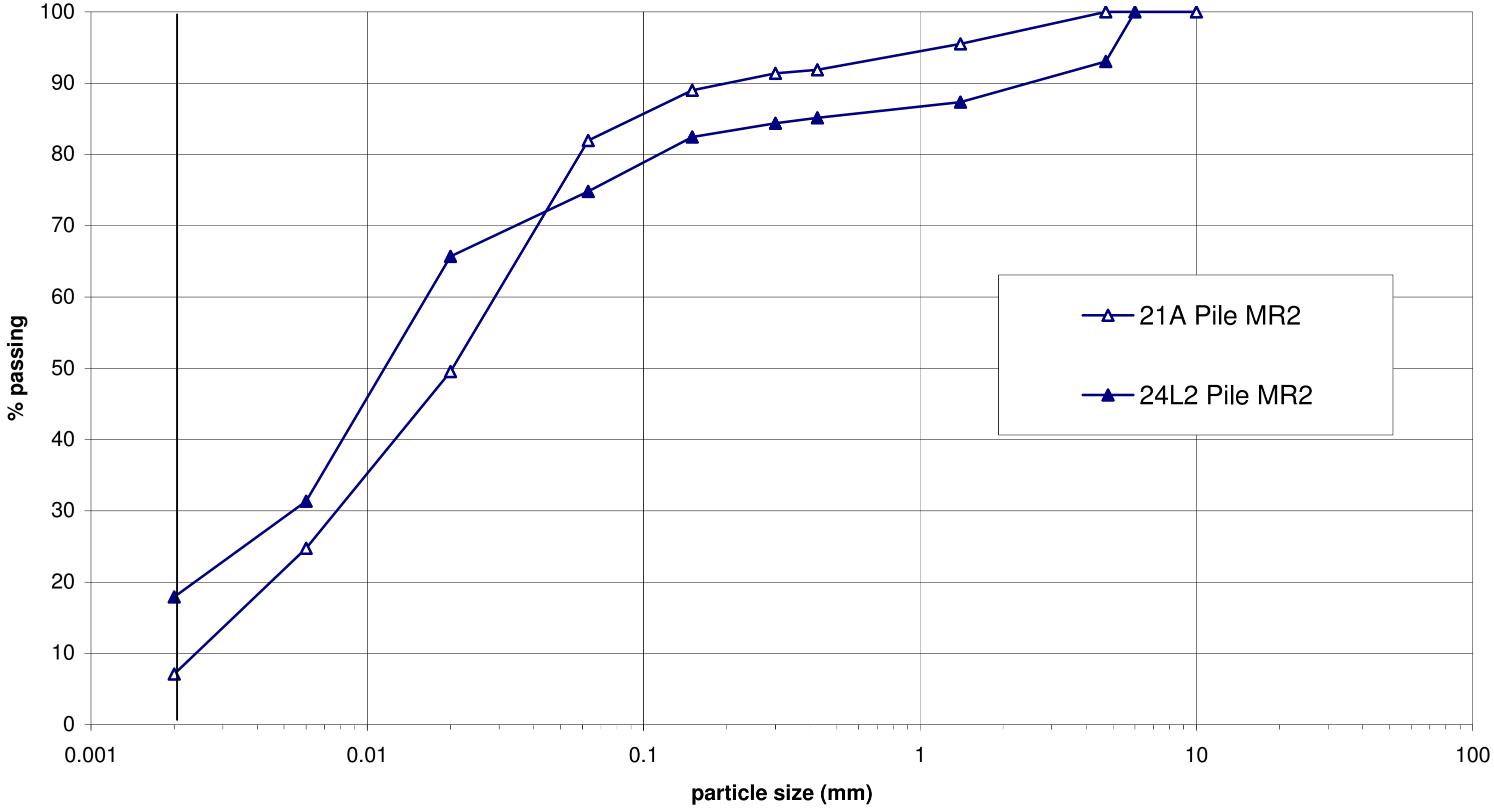


Figure 4.87 PSD curve for the samples taken from around pile MR2

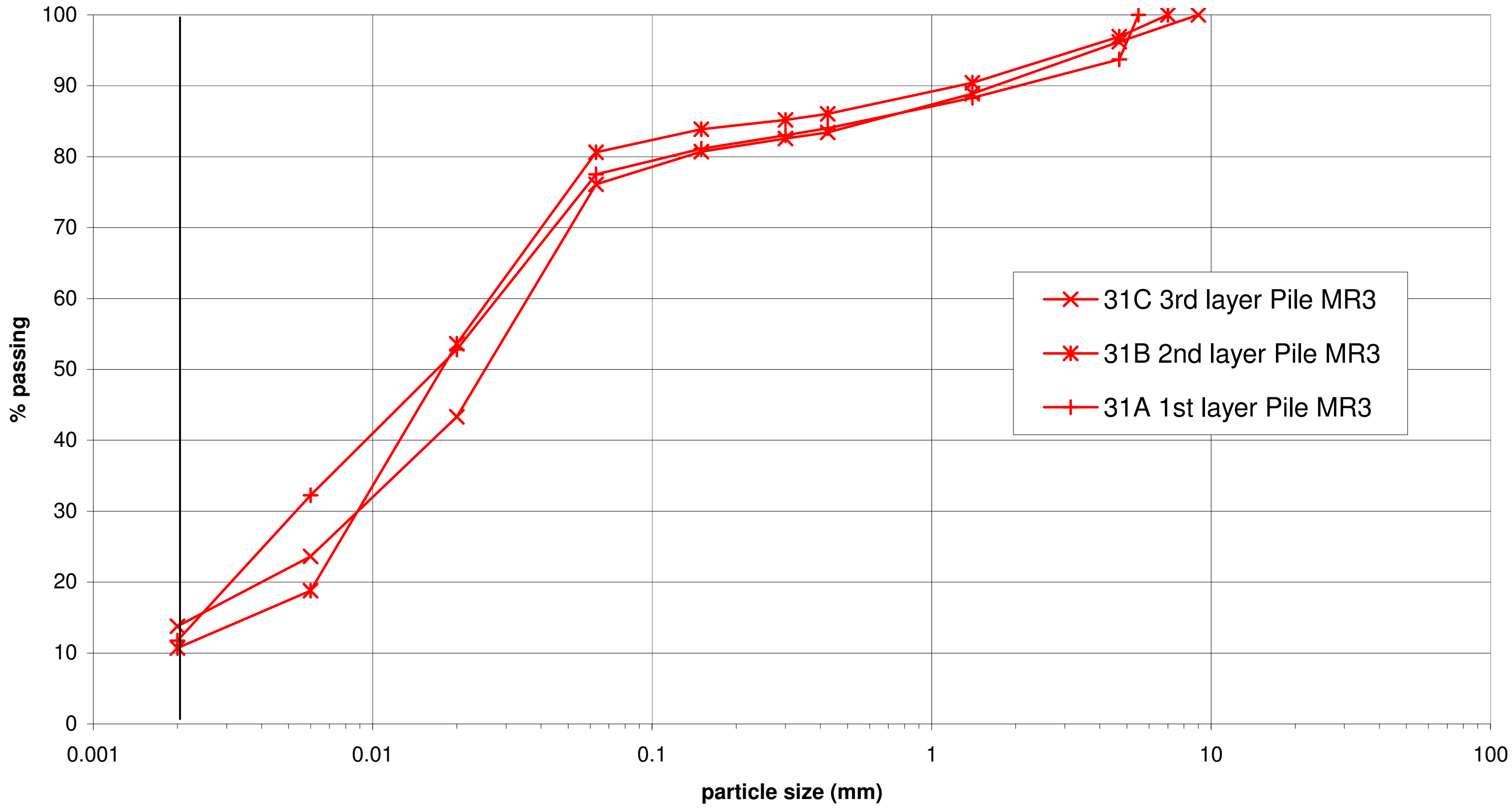


Figure 4.88 PSD curve for samples taken from around pile MR3

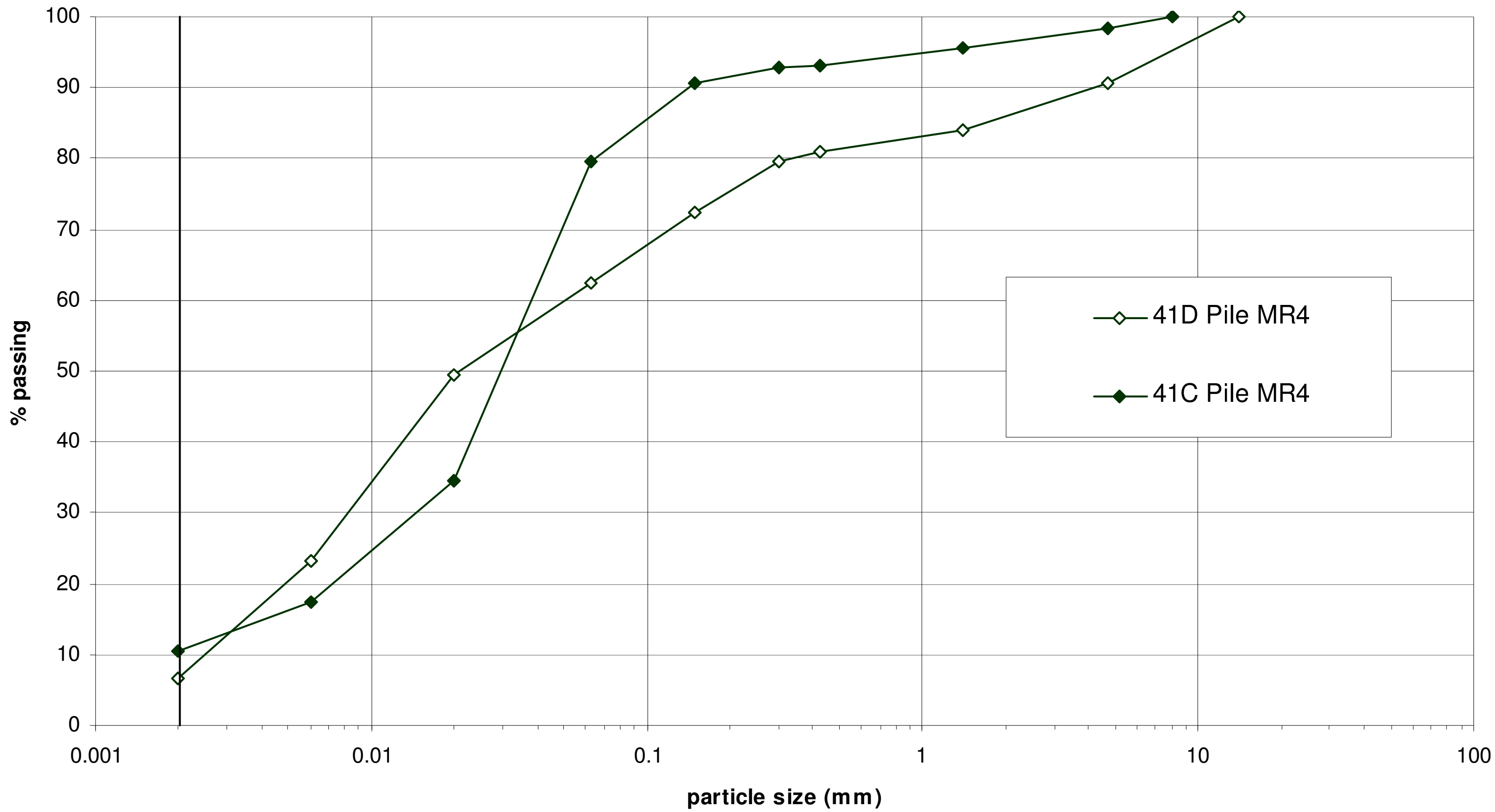


Figure 4.89 PSD curve for samples taken from around pile MR4

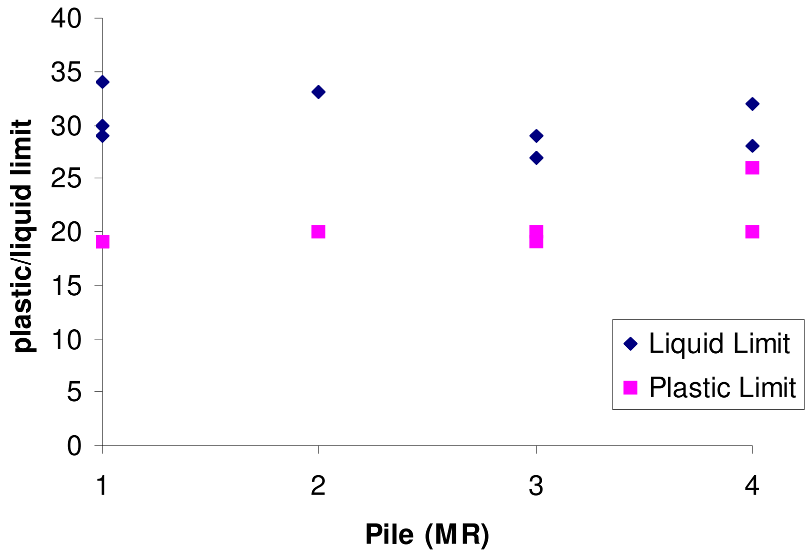


Figure 4.90 Plastic and liquid limits of soil taken from around all four piles

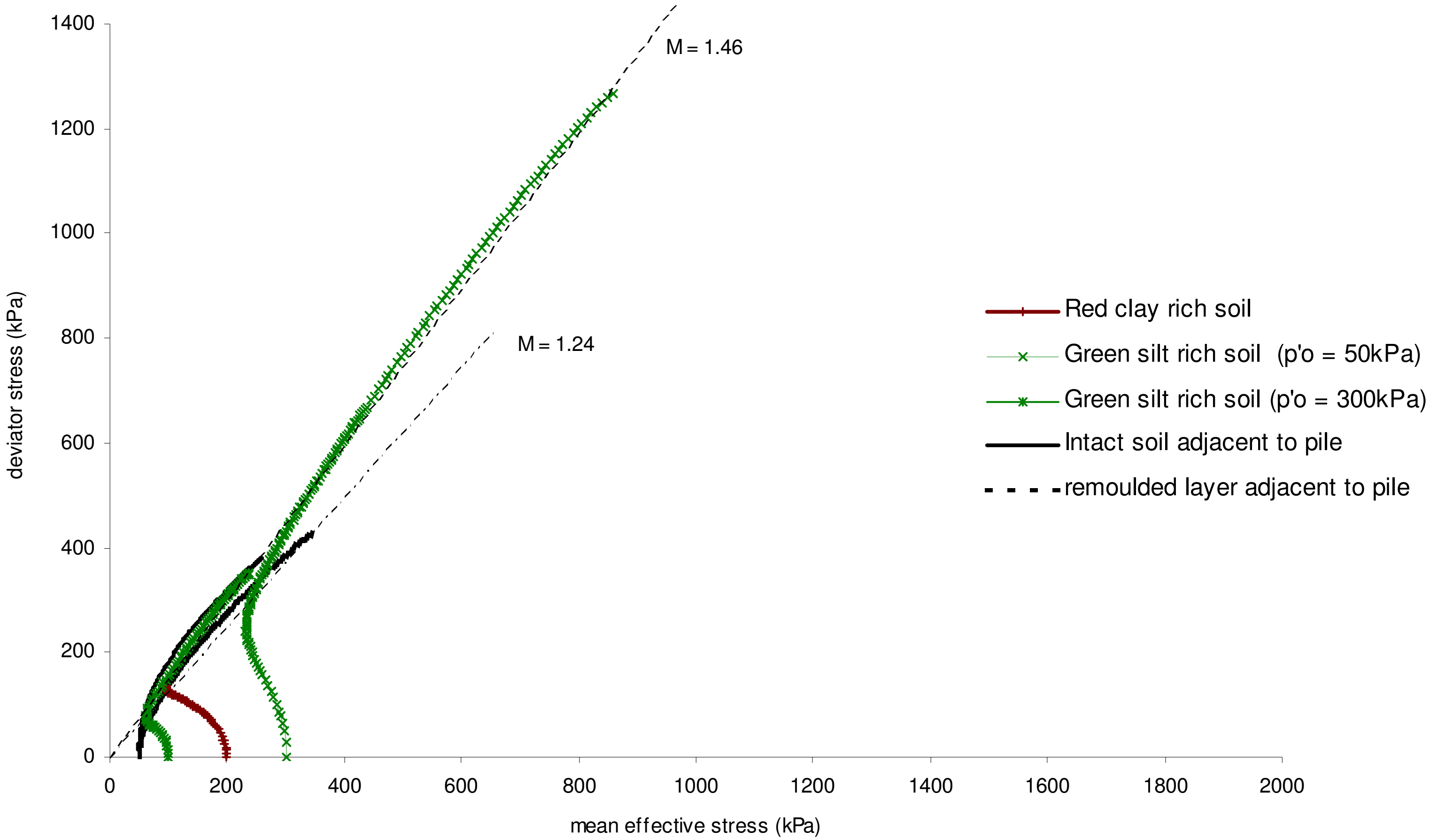


Figure 4.91 Mean effective stress plotted against the deviator stress for all triaxial tests

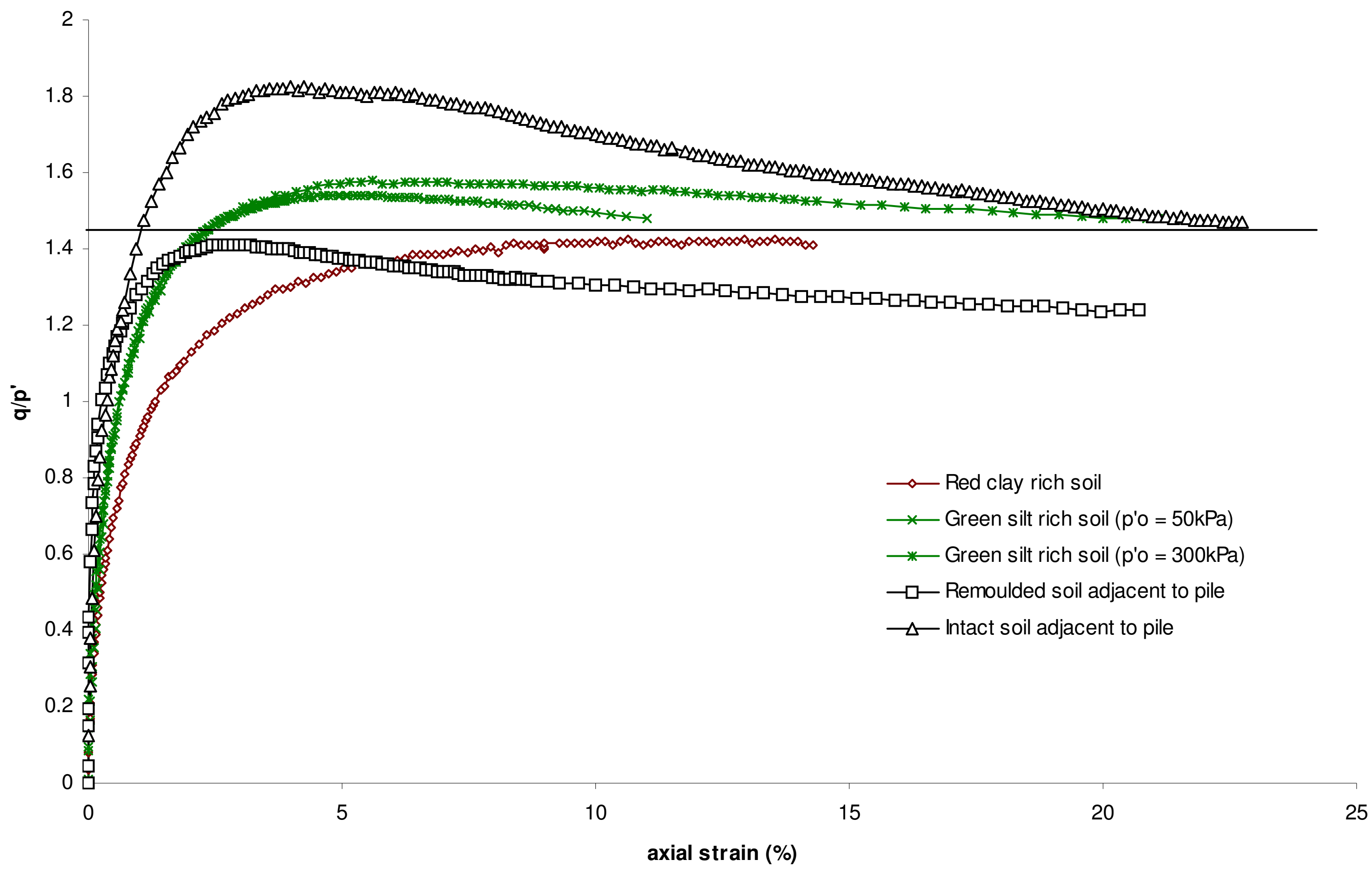


Figure 4.92 Axial strain plotted against q'/p'

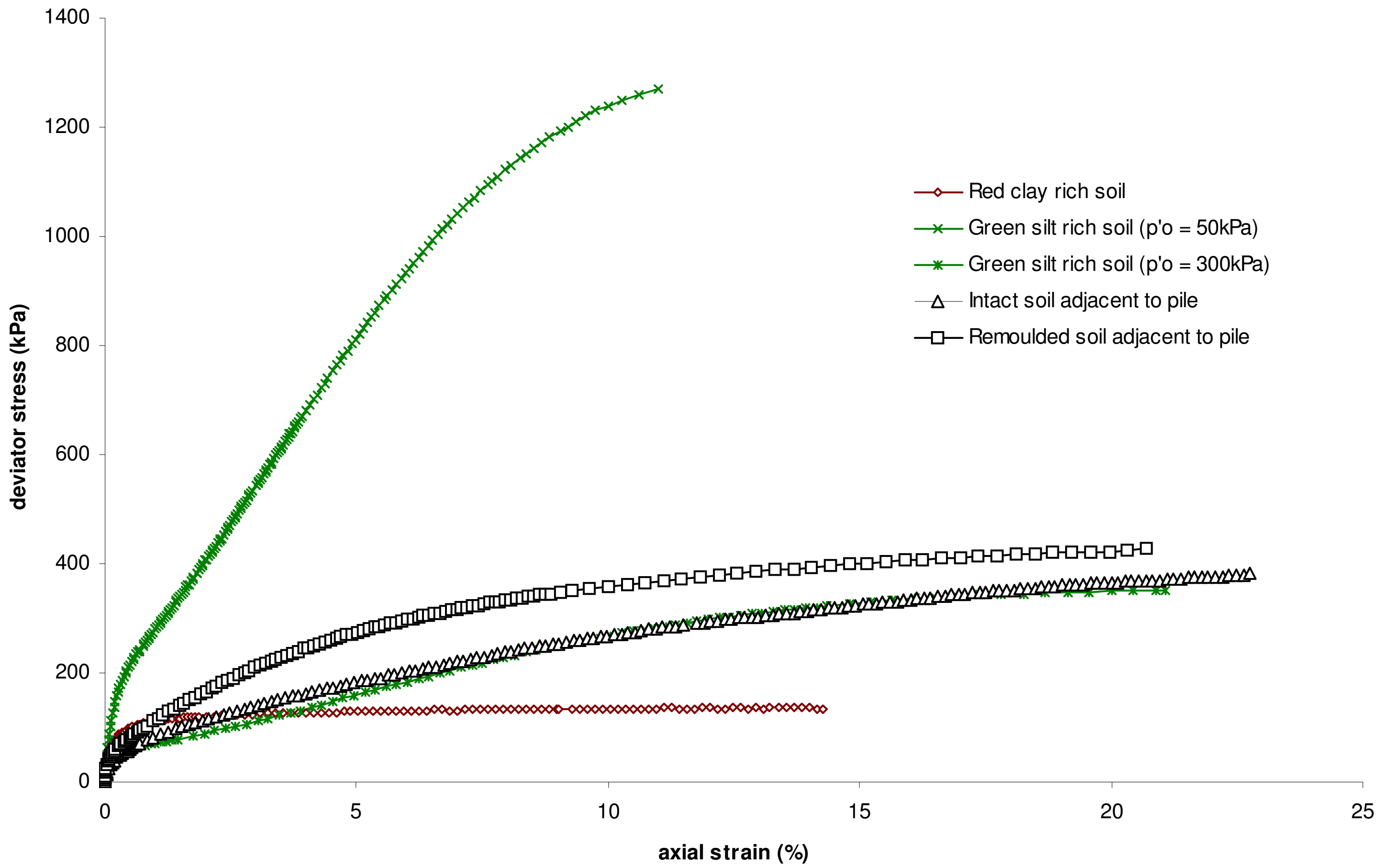


Figure 4.93 Axial strain plotted against deviator stress for all triaxial tests

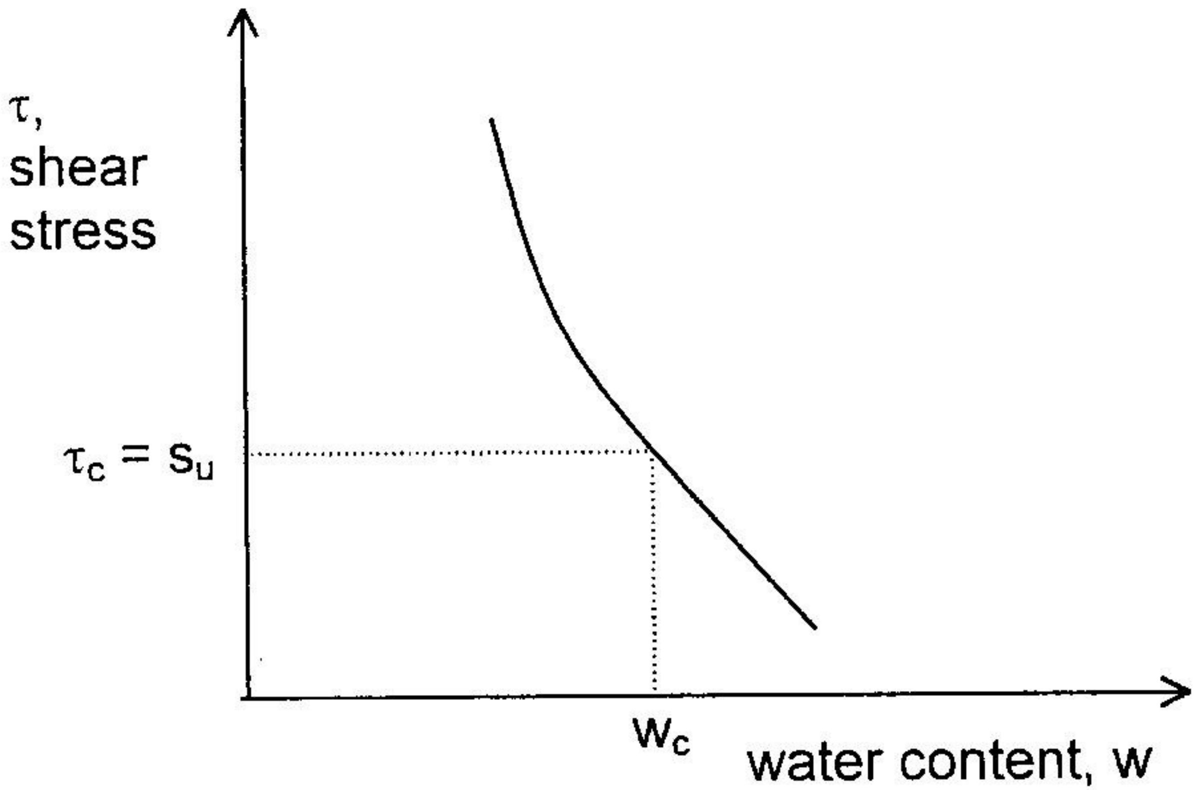


Figure 4.94 The effect of water content upon shear stress in an undrained soil (Stallebrass, 2009)

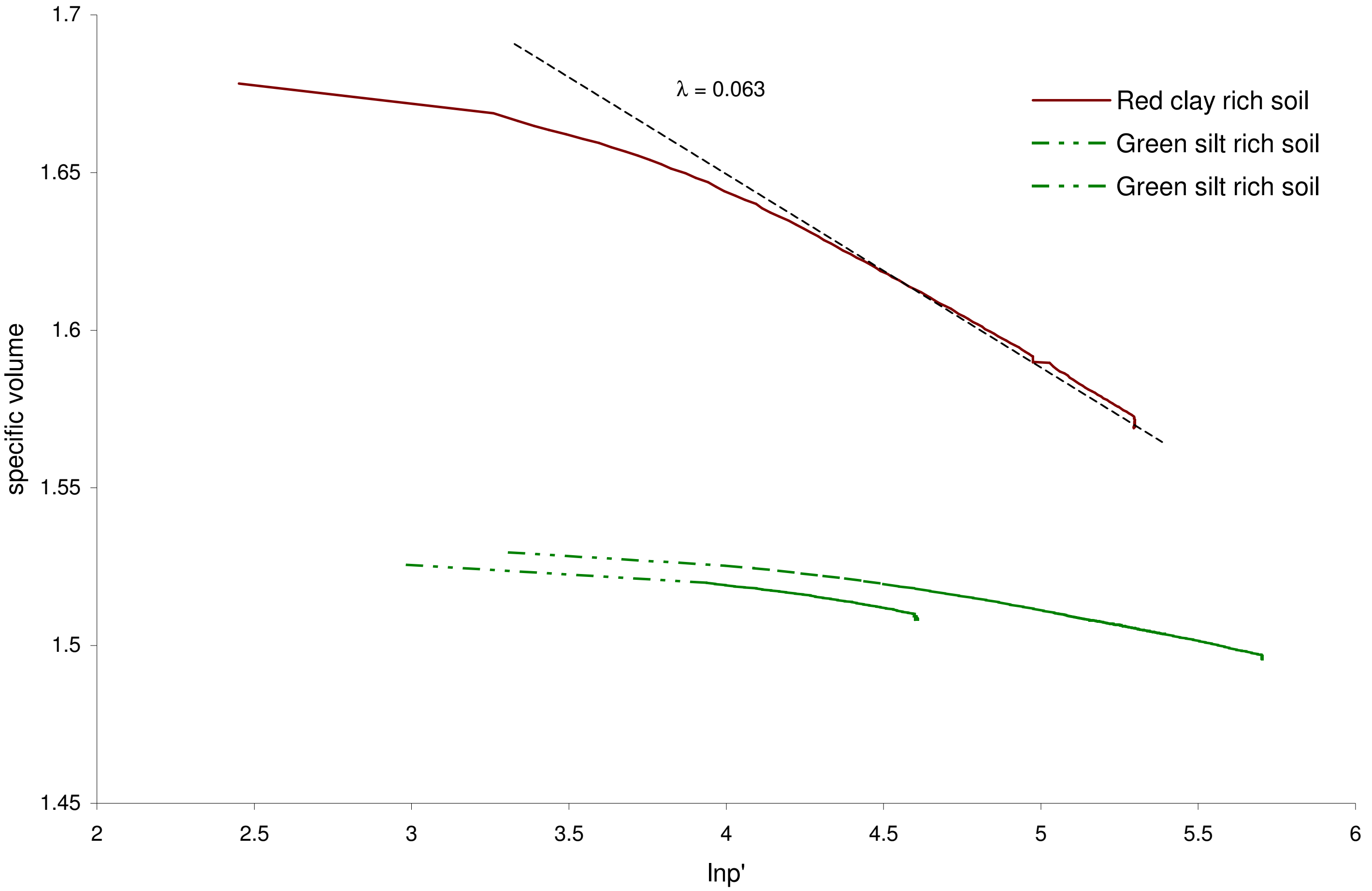


Figure 4.95 lnp' plotted against the specific volume for the bulk tests