Remoulding of the Mercia Mudstone Group around CFA pile shafts

Observations of the remoulded zone around continuous flight auger piles constructed in the Mercia Mudstone Group

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Abstract: A field test has been undertaken to investigate changes to *in situ* Mercia Mudstone at the pile soil interface after installation of four 5.5 m long 350 mm diameter CFA piles. The test investigated whether a remoulded zone exists, the extent of the zone, changes caused by remoulding and the effect of the installation method. The piles and surrounding soil were excavated after installation to a depth of just under 2 m. The sections of pile and surrounding soil were returned to the laboratory where a variety of detailed observations at both micro and macroscopic scales were undertaken, together with chemical and mineralogical analysis. It was found that a remoulded zone existed in all piles but that this varied in thickness both laterally and vertically around a pile. Across all piles the maximum thickness observed was 55 mm. The average thickness, fabric and texture were all affected by installation method. A distinctive vertically orientated fabric was observed in which up to four vertically orientated layers could be distinguished. There was evidence of changes in texture/fabric, structure, colour, mineralogy and chemistry.

Introduction

In this paper a field test conducted in the Gunthorpe Member of the Mercia Mudstone Group is described. The test was conducted to investigate changes brought about at the soil-pile interface created by the installation of the continuous flight auger piles. The Mercia Mudstone Group is known to contain soils with an aggregated structure Davis (1967), consisting of silt sized particles which are aggregates of clay particles as described in the next section. It has been demonstrated by Chandler *et al.* (2001) and Atkinson *et al*. (2001) that the properties of such soils can change significantly if remoulding causes the silt sized particles to break down or disaggregate into the constituent clay particles. The aim of the field test was to investigate the thickness of the remoulded soil, and by examining the mineralogy and fabric of the zone, the degree of remoulding and consequent release of clay particles which has taken place and any additional mechanical disturbance applied to this zone. There are very few direct measurements or observations of changes at the pile/soil interface reported in the literature and these have focussed on changes to the mechanical properties and water contents, for example Leach *et al*. (1976) and Pellew (2002), rather than textural and mineralogical changes.

The field test also examined the effect of the mode of installation of the piles on these features by allowing over rotation of the auger and adding water during the installation of some of the piles. It is clear from the investigations by Chandler *et al.* (2001) and Atkinson *et al*. (2001) that the response of the Mercia Mudstone Group to remoulding is highly dependent on the precise stratigraphy encountered. Consequently, the study did not examine the effect of remoulding on the strength of the soil pile interface directly by loading the piles, although a limited laboratory investigation of the response of the Gunthorpe Member to remoulding has been reported in (Seward, 2009) and Stallebrass & Seward (2011)

Tests were conducted at Ibstock Brick Pit in Leicestershire, UK, the location of which is given in Figure 1a. Ibstock Brick Pit is stratigraphically in the Gunthorpe Member of the Mercia Mudstone Group. Four piles, each 5.5 m long and 350 mm diameter were installed in June 2007, and for each pile two variables (addition of water and over-rotation) were altered. A schematic overview is given in Figure 2a. The piles were left to cure for one week, and subsequently exhumed. A trench surrounding each pile was dug, and sections of pile approximately 500 mm long and their surrounding soil up to 200 mm in thickness were retrieved, up to a total depth of 2 m. Pile sections were then boxed and returned to City University London to be studied.

Observations of the remoulded zone and interface with the *in situ* soil are presented at various scales together with measurements of the chemistry and mineralogy of *in situ* and remoulded soil. These observations are used to draw general conclusions about changes in the soil at the pile soil interface for CFA piles excavated in mudstones.

Stratigraphy of Mercia Mudstone at Ibstock Brick Pit

The Gunthorpe Member of the Mercia Mudstone Group comprises 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, 1992). The member is a deposit from a series of lakes present in the UK during the Triassic, and represents a period where stagnant water bodies in a desert characterised the environment, with little in the way of disturbances or flood events.

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 test gives a proportion of clay sized particles far smaller than the actual percentage of clay minerals. Chandler *et al.* (2001) and Atkinson *et al*. (2001) both studied the effect of mechanically disaggregating these particles on the index properties of the mudstone. They obtained quite different results both in terms of the effort required to disaggregate particles and the effect on index properties, with the latter strongly dependent on the clay mineralogy, which appears to vary quite significantly between members. Chandler et al. (2001) found that in the Gunthorpe member the dominant clay minerals are illite, chlorite-smectite, smectite interlayers in chlorite-smectite and chlorite usually present in small quantities.

During excavation of the piles at the test site the southern wall of the pit adjacent to the test site was logged down to a depth of 2350 mm below the local ground surface in the pit, 388 mm lower than the deepest section of pile excavated. Figure 2b shows the local stratigraphy which revealed a large variation in host mudstone. The dominant lithology was designated Lithology A, a centimetre-scale laminated stiff silty clay with brick red/brown silty clay beds, interspersed with centimetre-scale red/purple hard beds. In Lithology A the silty clays ranged 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 923-1200 mm depth, hard, olive green/grey sandy silt was seen interbedded with the same red/brown silty clay material that was recorded in Lithology A.

Lithology B was similar to Lithology A with the following differences:

- A high instance of fissile layers and discontinuous lenses of hard green/grey sandy silt material, up to 20 mm in height and 120 mm in length.
- Presence of lenses with uneven erosive bases, vertically spaced approximately 40mm apart
- Presence of beds of silt of uniform green/grey colour.
- No apparent grading within beds and muscovite and biotite mica abundant on bedding planes.

Lithology C consists of clay rich horizons interbedded with two very hard 20 mm silt beds. Strong cohesion was observed between the clay rich horizons and the silt beds. Lithology F consists of hard, olive green beds of sandy silt, with a few layers of red/green silty clays. Beds are approximately 20 mm thick, fissile along bedding planes, but very strong perpendicular to the bedding plane. The beds harden downwards, down to 2350 mm where hardness rapidly increased. At this level it was not possible to cut or penetrate the material using the excavator bucket from the type mechanical excavator used to excavate the piles. This layer, a hard fissile olive green sandy silt bed is designated Lithology D.

The lithology observed on site is consistent with what would be considered normal stratigraphy for the Gunthorpe Member as described by Mader (1992), although the green clay beds and gypsum veins described by Mader (1992) were not observed at Ibstock. Because the Gunthorpe Member is typical of members within Unit B of the Mercia Mudstone (Howard *et al*., 2008) it may be assumed that the site is also a representative location for the behaviour of continuous flight auger piles in this Unit.

Field test

The field test required the construction of a line of continuous flight auger piles, which would be left to cure and then excavated so that the pile-soil interface and any zone of remoulded soil could be examined. The method used to install each of the piles was varied to investigate the effect that this might have on the pile soil interface and remoulded soil zone. None of the piles were loaded.

In order to examine changes to the soil at the soil pile interface it was necessary to excavate the soil around the piles to provide a record of the soil pile interface that extended around the circumference and a significant depth below ground surface, in this case 2 m. This soil is a very strong and extremely stiff mudstone which would best be classified as a weak rock rather than a soil. Excavating the soil was only really feasible using mechanical excavation and because the soil is also much stronger and stiffer vertically than horizontally with thin hard layers, the soil would tend to break rather than cut smoothly. It was important to ensure the inevitable disturbance caused by excavating the soil was kept as far away as possible from the area of interest. Thus, the aim was to excavate 650 mm square and 500 mm deep samples of soil and pile which would be the maximum manageable size, ensuring the boundary of the sample was far from the soil pile interface. Once these samples had been removed the soil pile interface could be examined in detail in the laboratory in a controlled environment. Because of the extent of the soil pile interface that was to be examined, approximately 8.8 m^2 over all four piles examining the interface *in situ* or attempting to use hand tools to excavate a continuous record of smaller samples was just not feasible and would have exposed the interface to the environment in the Brick Pit and the changeable weather conditions.

To sample the soil and pile together it was necessary to cut sections of pile. This was done using a diamond saw, which if properly cooled generates the least heat of the available cutting methods. The soil was excavated using a mechanical excavator, which had sufficient power to reach 2m depth. In practice, the excavation using a mechanical excavator was more difficult and less precise than envisaged, leading to samples that were generally smaller than the planned size, as noted below. It was decided that the *in situ* soil was sufficiently permeable that it was likely that any short term variations in water content that were set up during the installation of the piles would have reached a steady state during the six days before excavation of the piles took place and hence there would be no advantage in taking water contents of the surrounding soil *in situ*. It is generally accepted that it is impossible to preserve the *in situ* state of soil during sampling and this was not attempted here. The aim was to preserve the fabric and to a lesser extent the water content of the soil at the interface by the presence of up to 150 mm of surrounding soil.

The piles were all installed on 26th June 2007 between 13:00 and 16:00. There were four test piles 5500 mm deep and 350 mm in diameter and one practice pile 2000 mm deep and 350 mm in diameter. They were all installed using a Casagrande B125 rig in Continuous Flight Auger (CFA) mode. The concrete used was a C28/35 strength structural concrete with a pumpable mix.

The different installation methods used for the four test piles were as follows:

- MR1-OR: Dry (no added water) and with the auger over-rotated at the toe for ten minutes
- MR2 : Dry and with no or minimal over-rotation of the auger
- MR3-W/OR: Water added and over-rotated at the toe for ten minutes
- MR4-W: Water added and with no or minimal over-rotation

Over-rotation of piles MR1-OR and MR3-W/OR was designed to mimic over-rotation which occurs when a pile auger reaches a hard bed within the stratigraphy and has to be rotated with little penetration in order to pass through this layer. This was performed for both piles by drilling the auger down to the toe (at 5500 mm depth) and then rotating the auger for ten minutes at this level. Water was added to piles MR3-W/OR and MR4-W to simulate the addition of water to a pile shaft experienced when water bearing beds are augered through during drilling, thus releasing water into the pile shaft. Reduced pile capacities have been reported for piles constructed in water bearing Mercia mudstones, Suckling (2007). A hose was used to pour water down the pile shaft for the duration of augering. While the actual volume of water was not measured in this instance, water was continuously added for a 10 minute period during installation of both "wet" piles. The hose was removed as the auger was removed. The addition of water whilst the pile is augered and the over rotation of the auger simulate events they may occur in practice during the construction of continuous flight auger piles.

Piles were left to cure for six days before excavation of the piles which began on 3rd July 2007 and took four days. The aim of excavating the piles was to remove a section of pile with the surrounding soil, causing as little disturbance to the soil as was possible. It is very rare to exhume piles in this way and required the development of a special method which in practice was as follows:

1. A hook was fixed into the top of the section of pile.
2. A mechanical excavator with a 600 mm wide bucket excavated a trench 500 mm deep around all four sides of the 650 mm x 650 mm sample. In practice it was difficult to do this accurately due to the hard but fissile nature of the soil. In addition, the process was more successful if shorter lengths of pile were sampled.
3. Industrial cling film (Stretchwrap), was immediately wrapped around the sample, which both protected the sample and helped to confine the sample and prevent it separating from the pile section.
4. A diamond wire saw was used to cut an approximately horizontal plane (between 0 and 10 degrees to the horizontal) at 500 mm or less depth. Water used to cool the wire saw was minimised, but was still sufficient to cool the saw. In some cases soil samples became detached from the pile during this process and if sufficiently large these were labelled and preserved separately.
5. Polythene was placed on the base of a 900 mm x 900 mm x 700 mm sample box constructed from plywood. A large heavy duty polythene bag was placed in the box.
6. The mechanical excavator was used with slings placed over the hook to lift the block sample into a sample box. Although the stretch wrap was confining the sample, not all the soil surrounding the pile was retained during this process.
7. Once the sample was placed in the centre of the sample box inside the polythene bag, the void around the sample was sealed at the base of the sample with expandable foam. Although the sample boxes were designed to be a relatively close fit to the samples, in practice less soil was retrieved than anticipated and additional heavy duty polythene bags were used as packing.
8. The top of the box was 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.

The samples were transported to City University London on 9th July 2007. All the samples were stored in the laboratory and opened and studied over a period of about two months.

Soil samples obtained from Field trial

As discussed in the previous section, the excavation process did not always yield samples of the planned dimensions. In total, 16 sections of pile were removed from the site during this field study, together with additional large intact samples which became detached from the piles, but whose location was known. These provided data for soil up to 200 mm from the pile surface and covered an estimated 70% of the surface of the excavated piles

Once the stretch wrap had been removed from the samples, the soil was then separated from the pile, split into specimens of less than 30 000 cm^3, photographed and sealed in cling film and wax. The position of these specimens with respect to the pile was also noted. At this stage, smaller specimens required for the various observations and tests were also retrieved.

The authors believe that the sampling process did not have a significant effect on the texture of the soil at the soil-pile interface as very few relict structures were observed showing that a vertical stress had been placed on the samples.

In most cases, the surface of the pile was observed to be sub-vertical, with a rough surface with some aggregate protruding by up to 10 mm.

Observations of intact soil and remoulded zone

Around all four piles a remoulded zone of thickness 0 (in localised areas) – 55 mm was noted. This remoulded zone was distinct in texture and colour from the undisturbed soil found at Ibstock Brick Pit and showed a sharp vertical boundary between the two areas, Figure 3 shows a typical view of the remoulded zone. Very localised uplifting of bedding was occasionally observed in the undisturbed material, in the 10-20mm directly adjacent to the remoulded zone. In general, the remoulded zone was found to be a brown, silty clay rich layer, showing sub-vertical fractures in a fanning outwards pattern, with the colour of the zone not being observed to change in areas adjacent to green silt rich beds in the stratigraphy. A summary of observations from the remoulded zone of each pile can be found in Table 1. It is important to note that while this paper refers mainly to the average thicknesses of the remoulded zone, in all cases, the thickness varied greatly over short distances both laterally and vertically around the pile (as shown in Figure 4). Averages have been given to enable comparisons of remoulded zone thickness between piles and with depth below ground surface.

The lowest average thickness of remoulded zone was found in MR2 – the pile which was normally augered without the addition of water. The greatest average thicknesses were found in pile MR3-W/OR and MR4-W, the two piles where water was added during augering. The remoulded zone around the two wet piles was always present, whereas around the two dry piles the zone would disappear locally over a distance of 10-20 mm. The remoulded layer for both over-rotated piles had a greater average thickness than that for their normally augered counterparts. Around pile MR1-OR a weak but definite downwards thickening trend was observed in the remoulded zone with the thickness of the remoulded zone increasing from an average of 22 mm at the top to an average of 55mm at a depth of approximately 2m.

The remoulded zone around all piles showed vertical layering in places (Figure 5). This layering was more commonly seen and more pronounced in the wet piles (MR3-W/OR and MR4-W) but showed no other trends (e.g. more likely with depth). Layering was mostly observed as a colour change between red-brown and pale brown seen at a distinct vertical or sub-vertical surface. In some samples (e.g. MR3 W/OR, Figure 5) green/grey agglomerations of silt sized, quartz rich particles ~1mm in diameter were observed concentrated into one layer, this was particularly prevalent around pile MR3-W/OR where the remoulded zone was split into three layers, the middle layer was comprised of up to 50% agglomerations. The lowest percentage of agglomerations was seen in the remoulded zone surrounding pile MR2, where only a small amount were observed in the top 1000 mm. These observations indicate that the soil was remoulded to a more uniform state around this pile where the remoulded layer was narrower.

Around all piles, pieces of aggregate were found within the remoulded zone, which were unlike anything occurring naturally in the geology on site (Figure 6). These aggregates have therefore been assumed to have been derived from dried concrete on the auger, but indicate a substantial level of mixing within the remoulded zone.

The fabric of the remoulded zone surrounding the piles was observed to contain sub-vertical fissures fanning from the pile in a clockwise direction in most cases, which is consistent with the insertion of the auger that was also clockwise. This was most pronounced within the dry piles, MR1-OR and MR2 where strong, invasive fissuring was observed at all depths, cross cutting layers where these were present. These fissures are most clearly seen in the microscopic observations given below.

Microscopic observations

Specimens taken from the remoulded zone were viewed both under a light reflected microscope as thin sections and under an Axiocam binocular microscope as complete specimens. These observations provided more detail on the composition of the remoulded soil and the state of the remoulded soil when the stresses causing the fissuring took place.

A summary of observations from the Axiocam can be found in Table 2. Using this technique it was easier to image the fissures mentioned in the section above, and a good example of these can be seen in Figure 7 showing a section of the remoulded zone from pile MR1-OR where a clockwise pattern of fissuring can be observed with fissures running from the bottom left corner of the Figure to the top right.

Figure 8 shows vertically orientated thin sections magnified but otherwise as viewed by the naked eye. This more detailed view indicates that there is little difference in the uniformity of the remoulded material around piles MR1-OR and MR2. In addition, the fissures present in the soil from MR1-0R do not bisect silt clasts possibly indicating that these were created whilst the remoulded soil was still relatively soft compared to the clasts.

The thin sections from piles MR3-W/OR (rotated anticlockwise by 90° with respect to the other slides) and MR4-W show a more clearly layered fabric and in the case of MR4-W a less well remoulded soil. This is probably caused by the increased water content in the soil leading to less disaggregation of silt sized particles into their constituent clay sized particles, a feature of the behaviour of the Gunthorpe Member clays observed by Stallebrass & Seward (2011). Fissures are not observed and were generally weaker and less present in these piles, see Tables 1 and 2, indicating that the soil was more ductile than in the dry piles at the time that the stresses causing fissuring were imposed.

Chemical analysis

24 samples from inside and outside the remoulded zone around all four piles were tested using inductively coupled plasma atomic emission spectroscopy (ICP-AES) techniques for major, minor and rare earth elements (Seward, 2009). Only the major elements will be discussed in this paper as minor or trace elements are unlikely to be present in the quantities required to initiate behavioural changes in the host soil. Two methods were used to prepare the samples before chemical analysis; the Lithium Metaborate Fusion Method and the Hot Block Method (Thompson & Walsh, 1983). Both methods require a very small sample, 100mg and 500mg respectively, which is first ground to a particle size of less than 250 µm before the samples are heated. This meant that aggregations within a given sample may have been split by the grinding action before being tested, however, as the sample was tested immediately after grinding there was no risk of degradation or leaching of compounds as there may be within nature or on site during pile installation.

Figure 9 shows the major element analysis of the undisturbed soil and remoulded soil around all piles (the remoulded soil includes samples taken from all layers where layers were present). The vertical lines represent the range of values obtained from the different samples and the diamond shaped markers the average value.

In all cases, the most abundant chemical compound was SiO_2, a major component of many rock forming minerals such as quartz, clays, micas and feldspar. The remoulded zone around all piles showed a greater average percentage of SiO_2 than the undisturbed soil (a difference of 13.3%). The second most significant compound CaO was found to be more abundant in the undisturbed material than the remoulded zone (11.9% and 9.24% of the whole rock composition respectively). It was suggested by Davies (1967) that CaO was a major cementing element within the Mercia Mudstone Group, so if aggregations of clays are split during the augering process then the cementing agent may be freed from aggregates at this time and be carried away by the pore fluid.

The mean values of % whole rock composition (not sieved or sorted with respect to grain size, thus giving an accurate overview of % of a given mineral found within a bulk sample) for Al_2O_3, Fe_2O_3, K_2O and MgO differ by less than 1% in the remoulded zone compared to the undisturbed material, with greatest difference for MgO which is lower in the remoulded zone than the undisturbed soil. However there is greater variability in the amount of these compounds found in the remoulded zone compared to the undisturbed soil. Al_2O_3 was also found to be marginally less abundant on average in the remoulded zone, by 0.34%. As Al_2O_3 is a major component of cement, it is therefore unlikely that the cement and the soil are mixed together during pile installation or that compounds are leached from the cement during curing (or if compounds are leached during curing then they are subsequently lost from the host soil).

The greater abundance of SiO_2 within the remoulded zone was also seen within the 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.

Mineralogical analysis

Specimens from both the remoulded and undisturbed zones of the soil collected were tested using X-Ray Diffraction (XRD). Specimens 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 in the undisturbed soil A mineralogical analysis was undertaken to establish what proportions of the clay minerals commonly found in the Gunthorpe member were present at the Ibstock site and to confirm that no other clay minerals were present that might affect the response of the mudstone to remoulding. It has been established by Atkinson et al. (2001) that clay mineralogy affects the amount of swelling that can occur when silt sized aggregates disaggregate to constituent clay particles during remoulding and this will in turn affect the remoulding process. These tests also allowed differences in the mineralogy of samples taken from the remoulded zone and the undisturbed soil to be quantified and these are also discussed below.

Specimens were approximately 10g in weight and were split into two so that each could be tested once for the whole rock mineralogy and once more for the clay fraction. Both samples were initially crushed in a pestle and mortar. To test the clay fraction, a clay rich suspension was extracted from the sample as described in Seward (2009) and the resulting slurry placed on ceramic tiles 20mm square and allowed to dry. The specimens prepared 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 slurry obtained from the whole rock sample was dripped onto silica tiles and once prepared, samples were analysed using a Nonius Diffractometer in reflection geometry with CuKa radiation, Gemonochromator and an INEL position sensitive detector. Data was collected for 15 minutes per sample. Processing involved 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%.

The results from XRD analysis are shown in Figures 10 and 11. The results from the clay fraction indicate that, in most samples, illite is the most abundant mineral, making up to 98% of the clay fraction, and on average between 55-70%. This is consistent with data from Chandler et al. (2001), as is the low % of chlorite. However in these samples, illite and smectite were combining rather than the chlorite-smectite combinations found by Chandler et al (2001) and there is also approximately the same average % of kaolinite as chlorite.

Illite-smectite interlayers (where smectite becomes incorporated into the structure of the illite resulting in a higher swelling clay than if pure illite was present) were present in approximately 50% of samples tested. In samples from around pile MR3-W/OR 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. This correlates well the observation reported above that the middle layer appeared to contain more aggregates of silt particles and less clay which has collected in the inner and outer layers. It may also indicate that the aggregates of clay particles that have been broken up during remoulding consist mainly of illite-smectite as this has clearly been free to move within the remoulded zone and create the variations observed.

Chlorite was present in almost all samples, with only one sample (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 extracted 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. Overall the % of clay minerals found was

In all whole rock 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 30% of the whole rock sample in both the undisturbed soil and 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-W/OR 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 a sample from pile MR4-W 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%. Dolomite was not found in any of the samples tested, despite being a common constituent of the Mercia Mudstone Group (Hobbs et al., 2002).

Water contents

Water content measurements were made for a range of soil samples taken from all piles and these are presented in Figure 12 to provide an indication of the variation in water content with distance from the pile and with depth. When plotted against depth there is a slight trend of decreasing water content with depth for the piles where the auger was over rotated (MR1-OR and MR3-W/OR). The greatest variability in water content occurred in the samples taken from MR4-W coinciding approximately with the depth at which there is a change in the strata to layers of sandy silt within the red brown silty clay of lithology A, see Figure 2.

In general, if the two highest values of measured water content are disregarded, (undisturbed soil around Pile MR4-W), there is the same variability in the water contents of the remoulded and undisturbed soil. However, on average in the remoulded soil water contents decrease by approximately 2% from an average of 17% near the pile to 15% at 40±8mm away from the pile and then increase in the undisturbed soil from approximately 13% at 50±8mm to nearer 20% at 150±8mm, although data at this radius is sparse and may be affected by a change in strata. Samples were on average 16mm cubes. There is also no apparent link between average water contents and whether the pile was installed "dry", MR1-OR and MR2, or "wet", MR3-W/OR and MR4-W, although water contents for remoulded soil around MR4 are on average 2% higher than around the other piles. Water contents obtained from around pile MR1-OR appear to be fairly constant although data is sparse.

As stated earlier because of the permeability of the mudstone and the length of time before the piles were exhumed, it is unlikely that changes in water content represent a transient response caused by the installation of the piles, but they should be a measure of the difference in the packing of the remoulded and undisturbed soil. If the mudstone had a significant clay content the remoulding should have created a more loosely packed soil, even if no swelling took place. The small average variation in water content in the remoulded zone is consistent with most remoulding and disaggregation of clay particles aggregates taking place near the pile as was observed and a mudstone which on average has a low clay content with low swelling potential. However, the variability in water content makes it difficult to draw any firm conclusions.

Discussion of results

Remoulding of soil during pile installation

The observations reported above can be explained by considering the continuous flight augering process. The often uneven boundary between the remoulded and undisturbed soil indicates that because of the layered nature of the *in situ* soil the auger breaks rather than cuts through some layers with the cutting teeth at the end of the auger. The size of remoulded zone, as much as 55 mm that is equivalent to an approximately 30% increase in radius, also indicates that material is being broken away. It is unlikely that the auger would move laterally by that amount whilst creating the cavity and if it did so the sides of the cavity would not change in dimension so dramatically over such a short distance, see Figure 4.

The very different fabric of the remoulded soil compared to the *in* situ soil indicates that during augering the soil is remoulded by the circular action of the flights. The vertical texture and mostly homogenous nature of the remoulded soil along with the observed uplift of some beds show that the broken up material which subsequently becomes the remoulded zone is moved vertically, presumably upwards towards the spoil heap.

The action of the auger on the host mudrock causes silt sized aggregations of clays to break down, leaving a fairly homogenous, clay rich vertical layer around the pile. However, the disaggregation of the silt and clay particles was not complete in any of the piles as evidenced by the silt sized clasts or aggregates containing silt and clay sized particles which were observed. It was noticed that there was not a greater abundance of the silt sized green aggregations adjacent to a green sandy silt bed, indicating vertical movement of silt aggregations within the remoulded zone.

The presence of uplifted beds adjacent to the remoulded-undisturbed soil boundary indicate that an upwards pressure was exerted on the undisturbed soil during the augering process - 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. It is not possible to determine which at this stage.

As fissures (where seen) were observed to cross the boundary between layers of remoulded material, it is logical to conclude that fissures are created after the remoulded zone has been deposited – this means that fissuring may occur either during removal of the auger, or as a thermal response to curing of the concrete. As noted above fissures did not bisect silt clasts indicating that they were created when the remoulded soil was relatively soft and fissures were less marked in piles MR3-W/OR and MR4-W, where water was added. Thus the remoulded soil around the wet piles appears to deform in a ductile manner as opposed to the brittle failure observed by the fissuring around the dry piles. This difference must occur soon after or during installation of the piles, because the permeability of the soil means that the water contents of the remoulded zones in all 4 piles soon become very relatively similar as evidenced by the water content data presented in Figure 12. Fissures also had a clockwise pattern which would be consistent with the movement of the auger in a clockwise direction implying that they were created by the auger.

Differences between remoulded and in situ soil

In situ soil was observed to be sub-horizontally bedded, with individual beds poorly cemented. No fissures were observed within the *in situ* soil. The *in situ* soil samples show a typical amorphous clay structure (as shown in the *in situ* soil in the thin section in Figure 8(c). Within the remoulded zone no bedding was observed – the remoulded zone consisted of a reasonably homogenous, red/brown to brown, apparently clay rich vertical layer showing none of the original textures or features of the intact soil still visible. In all piles except MR2 the remoulded soil was layered in some sections with up to three layers present. These layers were quite distinct with one layer generally containing aggregations of silt which had not been broken down by the remoulding process.

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 was possibly accidental). The remoulded zone around three of the four piles, pile MR4-W being the exception, contained splinters, aggregate particles and/or cracked off small blocks of cement or aggregate in varying sizes and with varying angularity. No such material was observed within the undisturbed soil and has been assumed to have been brought in by the auger as a result of dried material from previous piling jobs.

XRD analysis showed no major differences between the undisturbed and remoulded clay mineralogy, which is reasonable as XRD analysis should provide a measure of the total clay fraction irrespective of whether clay particles are in aggregates. Any differences in average percentage abundances are probably caused by the movement of the remoulded material upwards meaning that the full set of undisturbed soil samples do not correspond completely to the full set of remoulded soil samples. However, within the remoulded zone the mineralogy varied significantly between different layers providing evidence of disaggregation of clay particle aggregates providing free clay particles that collected in distinct layers. The free clay fraction measured in particle size distribution tests is 10% or less and the variations observed could not have resulted solely from movement of this clay fraction. The whole rock fraction showed that where the remoulded zone was split into layers, the percentage of quartz present decreased with distance from the pile, with the remoulded zone having on average 4% less quartz than the undisturbed material. When considered with chemical results, where SiO_2 was seen to be more abundant within the remoulded zone, it can be assumed that the remaining SiO_2 was present not as quartz, but also contained within other compounds.

The water contents in the remoulded zone appeared to show more variability than those in the *in situ* soil and some of this variability may be due to higher water contents occurring in the vicinity of the sandy silt layers at a depth below ground level of between 923 – 1200 mm. Average water contents increased slightly nearer the pile where soil may be more clay rich and consequently more prone to swell during remoulding. This effect is probably less pronounced because the clay minerals present were not highly active. Water contents in the over rotated piles tended to decrease slightly with depth, but there was little correlation between measured water content and whether the piles were installed wet or dry.

Effect of over-rotation

The greatest average thickness of the remoulded zone was observed in the two over rotated piles, MR1-OR and MR3 –W/OR. As the auger was over-rotated at the toe for 10 minutes, this observation is consistent with expectations as the time for over-rotation allowed each individual flight of the auger to come into contact with the *in situ* soil many more times than in a normally augered pile, causing more of the in situ soil to be removed. The soil removed in this way is added to the remoulded soil, but is not subject to as much remoulding as that in the original remoulded zone and consequently aggregates of silt and clay remain even around pile MR1-OR.

In pile MR3-W/OR the greatest abundance of aggregations of silt was observed. This is slightly counter-intuitive as silt aggregations are considered to be incompletely broken down host soil. A possible explanation is the presence of added water which may have temporarily created a slurry with a sufficiently high water content for the silt aggregations to be mixed without being disaggregated. These silt aggregations would then form a comparatively dense remoulded deposit, as free water seeped away.

Effect of adding water

The Mercia mudstone in the Gunthorpe Member does not contain high activity clays which would be likely to swell substantially on contact with water and consequently although there is some increase in water content and hence volume in the remoulded soil this would not be sufficient to cause the remoulded zone to be confined and increase the energy input into the remoulding process, but conversely appears to have led to formation of a slurry resulting in the layering observed.

In the piles which were augered with water added, it was more common for the remoulded zone to be split into vertical layers. It may be assumed that the layering within the remoulded zone is indicative of degrees of remoulding which have remained separated, causing the more highly remoulded material to remain adjacent to the pile with less remoulded soil remaining in a layer laterally further from the pile.

Engineering Implications

The engineering implications of the generation of a remoulded zone around a continuous flight augered pile depend partially on the effect of remoulding on the strength of the Mercia mudstone, which is a function of the clay mineralogy present in the mudstone, nevertheless there a number of observations from the field test described that may be important in determining the extent and behaviour of the remoulded zone, as follows:

- The size of the remoulded zone will be reduced if the auger teeth can cut through rather than break away the mudstone layers.
- The size of the remoulded zone will be reduced if the auger is not over-rotated. This normally occurs when the auger cannot penetrate a layer and consequently is also linked to the design of the auger cutting teeth.
- Over rotation will also cause more soil to be disaggregated and if this significantly increases the clay content of the remoulded zone there is likely to be a corresponding reduction in angle of friction and hence the pile capacity.
- Adding water to the pile bore appears to increase the size of the remoulded zone and consequently if water bearing layers are encountered this is likely to occur.
- The effect of adding water to the strength of the remoulded zone appears to depend on the permeability of the soil and the clay minerals present. If the clay minerals are not highly swelling then a slurry will be formed, less disaggregation will take place, there is unlikely to be a significant long term increase in water content and the angle of friction will not change significantly. However, the opposite may well occur if highly swelling clay minerals are present as described by Atkinson et al (2001).

Conclusions

In the summer of 2007, four piles were installed in the Gunthorpe Member of the Mercia Mudstone Group. The method of installation of the piles was varied by adding water and over-rotating the auger, such that the effect of both variables could be tested. Once the piles had been left for 6 days to cure, short sections (under 500mm in length) and their surrounding soil were excavated and transported back to City University London to be studied.

It was discovered that a remoulded layer of clay enriched, material which bore little physical resemblance to the host soil was formed around the pile shaft. This remoulded material had a distinct boundary with the host soil, and a horizontal thickness ranging from 0 (in highly localised areas) to 55mm, with this radial thickness varying greatly both vertically and laterally around all sections of a pile. Where the layer was present, it was often observed to have a distinctive vertical fabric composed of clearly defined layers, however the presence of this fabric was not observed to correlate with depth or thickness of the layer.

The pile with the thinnest remoulded zone was pile MR2, which was installed “dry” and without over-rotation, and had an average thickness of 12mm. Thus pile MR2 caused the least disturbance to the host soil of all four piles. The remoulded soil was divided into layers at some depths for all piles and there was evidence that the different layers have both a different fabric and mineralogy, with one or more clearly more clay enriched. The significant variation in clay mineralogy between layers is evidence of movement clay particles resulting from the breakdown of silt sized aggregates.

It was clear from the results obtained that over rotation of the auger increases the thickness of the remoulded soil layer surrounding the piles and also leads to greater remoulding of the soil. The remoulded zone for MR1-OR is relatively homogenous and may have swelled slightly during remoulding leading to fissuring when the auger is removed, which is not observed so clearly in soil surrounding MR2. The evidence of swelling supports the hypothesis that remoulding causes disaggregation of clay particle aggregates, such that more remoulding leads to a greater % of free clay particles and more swelling. The reduction in percentage of CaO in the remoulded zone also indicates that disaggregation and breaking of bonds followed by leaching of these minerals has occurred. However, the presence of water has less effect in the Gunthorpe member than it might have if a higher proportion of high swelling clay minerals were present. The plasticity indices for this soil are relatively low and so the main effect of adding water has been to increase the thickness of the remoulded layer and possibly to increase the incidences of this soil separating into layers. Additional work examining the influence of the structural and mineralogical changes on the mechanical properties of the soil is being undertaken.

The study described within this paper has provided an introduction to the issue of remoulding of in situ soil during continuous flight auger pile installation by means of one set of full scale tests. In particular, the study provided valuable information on the nature of the behaviour of the Mercia Mudstone during CFA piling and the remoulding mechanism, however it is important to note that these tests were all performed in the same location. To fully evaluate the behaviour of Mercia Mudstone and provide extensive recommendations additional tests would have to be carried out on other members of the Mercia Mudstone Group with a greater percentage of high swelling clay minerals which may behave differently when remoulded and if water enters the bore. Further work on other major soil types, in conjunction with load testing in the same ground, would be very helpful in determining which lithologies are the most vulnerable to remoulding and what the effects are on design of foundations.

References

Ambrose, K. (2006) personal communication

Arthurton, R.S. (1980) Rhythmic sedimentary sequences in the Triassic Keuper Marl (Mercia Mudstone Group) of Cheshire, northwest England, Geological Journal, **15**, 43-58

Atkinson, J.H; Fookes, P.G.; Miglio, B.F. &Pettifer, G.S. (2003) Destructuring and disaggregation of the Mercia Mudstone during full-face tunnelling; QuarterlyJournal of Engineering Geology and Hydrogeology, **36**, 293-303

Batchelder, M. & Cressey, G. (1998) Rapid, accurate phase quantification of clay bearing samples using a position-sensitive X-ray detector. Clays and Clay Minerals, **46**(2), 183-194

Chadwick, R.A. and Evans, D.J. (1995) The timing an direction of Permo-Triassic extension in southern Britain. 161-192; in Permian and Triassic rifting in Northwest Europe. Boldy, S.A.R. (editor). Geological Society of London special publication, No. **91**.

Chandler, R.J. and Forster, A. (2001) Engineering in Mercia mudstone (C570), Pub; CIRIA, ISBN: 0-86017-570-7

Davis, A.G. (1967) The mineralogy and phase equilibrium of Keuper Marl, Quarterly Journal of Engineering geology, **1**, 25-38

Forster, S.C. and Warrington, G; (1985) Geochronology of the Carboniferous, Permian and Triassic, in Snelling NJ (ed) The chronology of the geological record (Geological Society Memoir 10) 99-113

Gradstein, F.M., Ogg J.G. and Smith A.G. (2004) A Geologic Time Scale 2004, Cambridge University Press.

Hobbs, P.R.N., Hallam, J.R., Forster, A., Entwisle, D.C., Jones, L.D., Cripps, A.C., Northmore, K.J., Self, S.J. and Meakin, J.L. (2002) Engineering geology of British rocks and soils - Mudstones of the Mercia Mudstone Group. BGS Research Report RR/01/02.

Howard, A.S., Warrington, G., Ambrose, K. and Rees, J.G. (2008) A formal framework for the Mercia Mudstone Group (Triassic) of England and Wales; British Geological Survey Report RR/08/04
Leach, B.A., Medlund, J.W. and Sutherland, H.B. (1976) the ultimate bearing capacity of bored piles in weathered keuper marl; in Proceedings of the 6th European Conference on Soil Mechanics and foundation engineering 1.2, Vienna, 507-514
Mader, D. (1992) Evolution of Palaeoecology and Palaeoenvironment of Permian and Triassic Fluvial Basins in Europe; Volume 1, Western and Eastern Europe, Pub; Gustav Fischer Verlag
Pellew, A.L. (2002) Field investigations into pile behaviour in clay; Ph.D. thesis, Imperial College, London
Seward, L.J. (2009) The Effect of Continuous Flight Auger Pile Installation on the Soil-Pile Interface in the Mercia Mudstone Group. PhD thesis, City University, London, UK.
Sides, G. & Barden, L. (1970). The microstructure of dispersed and flocculated samples of kaolinite, illite and montmorillonite. Canadian Geotechnical Journal,8, 391-399
Suckling, T.P. (2007) Personal communication
Thompson, M., and Walsh, J.N. (1983) A Handbook of Inductively Coupled Plasma Spectrometry. London. Blackie and Son Limited.
Warrington, G. and Ivimey-Cook, H.C. (1992) Triassic. 97-106 in Atlas of Palaeogeography and Lithofacies. Cope, J.C. W. Ingham, J.K and Rawson, P.F. (editors) Geological Society of London, Memoir, No. 13

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Pile	Thickness of remoulded zone	*Approx. % of concrete/aggregate	*No. of layers	*Silt aggregations	*Fabric
MR1-OR	22mm average. Range 0-55mm	2% in 0-495mm and >1277mm sections	One: 0-1277mm Two: 1277-1981mm	2%: 0-495mm	Clockwise fissures at all depths
MR2	12mm average Range 0-22mm	Up to 10% at 0-1000mm	One: 0-1457mm Two:1457-1979mm	Very few noted 0-1000mm	Clockwise fissures at all depths
MR3- W/OR	35mm average Range 19-48mm	Up to 20% in layer one, c2% of all remoulded soil	One: 510-860mm Three: 0-510mm & 860-1210mm	Up to 50% in layer 2, where layered	Weak fissuring, generally a granular, massive texture
MR4-W	28mm average Range 7-55mm	None seen	One: 0-951mm & 1342-1962mm Two: 951-1342mm	Up to 2% in section 951-1342mm	Weakly seen at 451-951mm, generally a massive texture

*depths given relative to ground level

Table 1. A summary of the main observations of each of the piles

	depth	Fissures	Green silt clasts	Layering of clays
MR1-OR	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 -W/OR	0-510mm below ground level	Weak fissuring fanning clockwise from the pile	1mm in diameter	No
MR4-W	1342-1962mm below ground level	Weak fissuring	Up to 2mm in diameter	Dark and light bands of clays run parallel to the pile

Table 2: A summary of the main observations from the axiocam method.

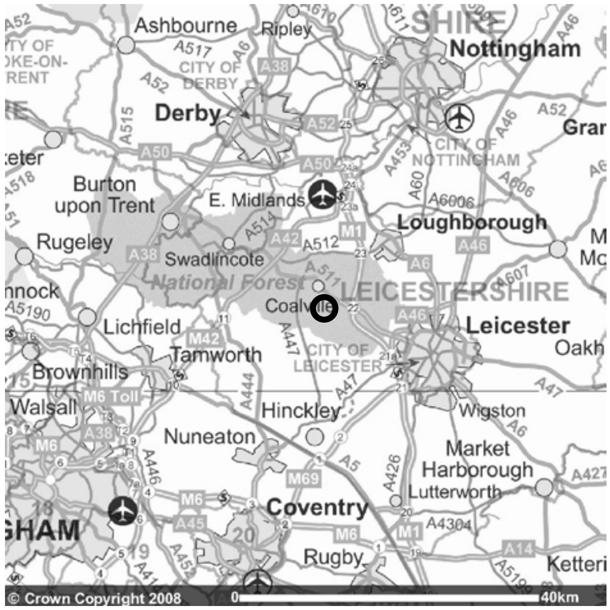


Figure. 1a OS map showing the location of Ibstock Brick Pit (circled). Reproduced from **(2008)** Ordnance Survey map with the permission of the Controller of Her Majesty's Stationery Office, © Crown Copyright NC/**11**/2008.

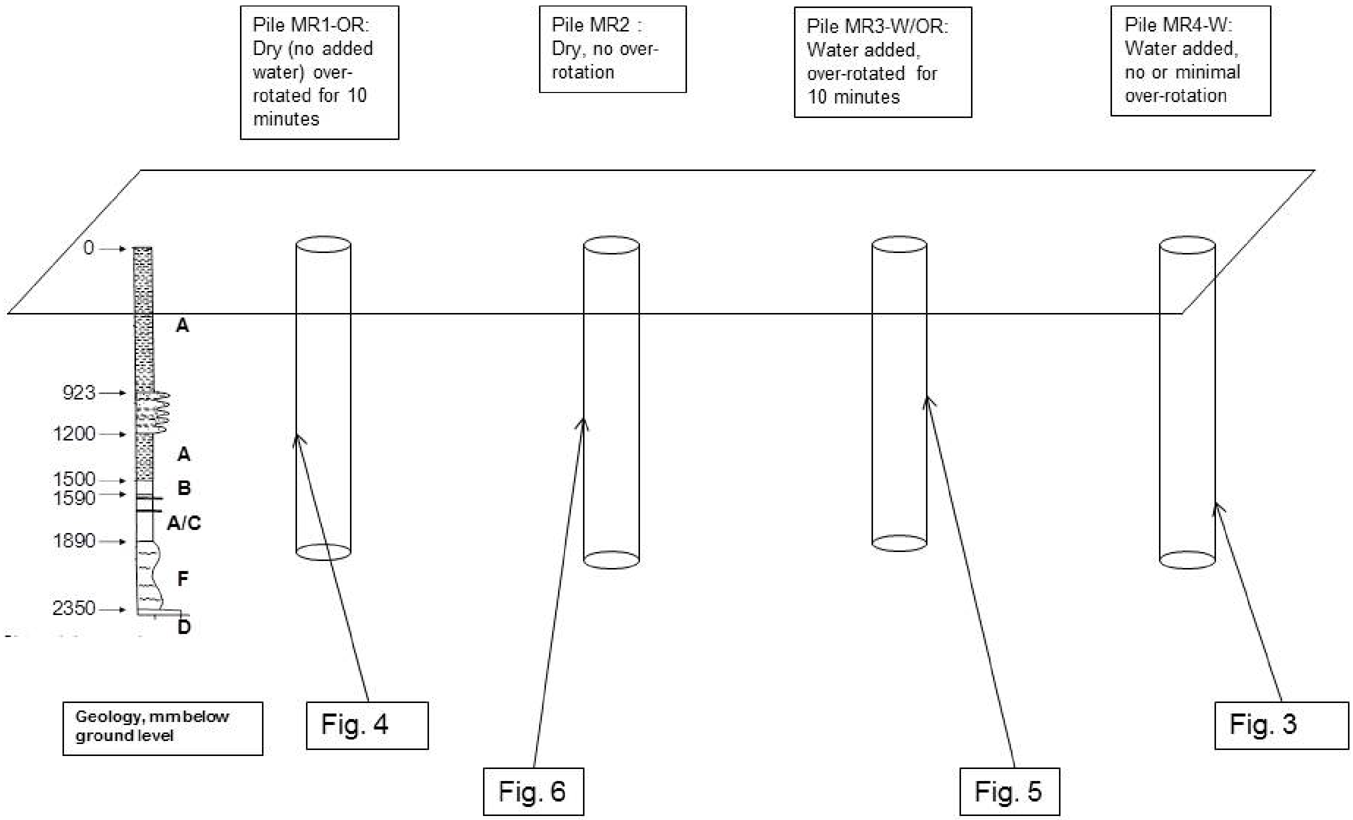


Figure 2a Schematic figure showing placement of piles in the ground, relative lengths of piles, approximate locations of figures 3-6 and stratigraphy (see figure 2 for stratigraphy).

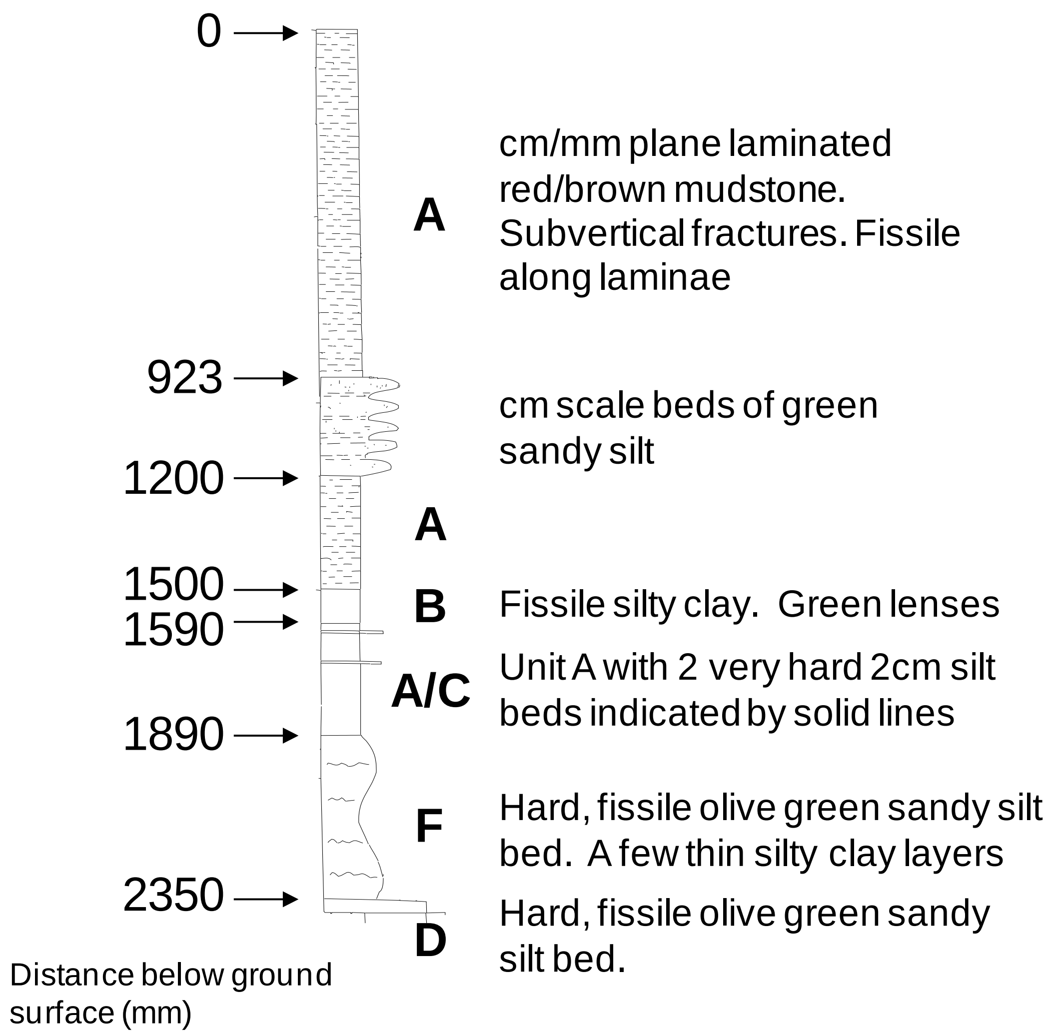
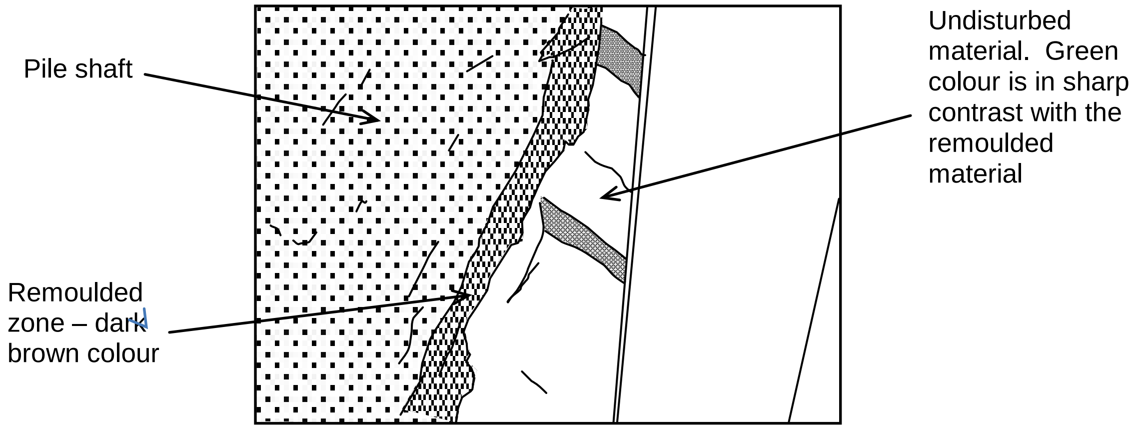


Figure 2b Stratigraphy of Ibstock Brick Pit, logged in the south wall of the excavation pit.



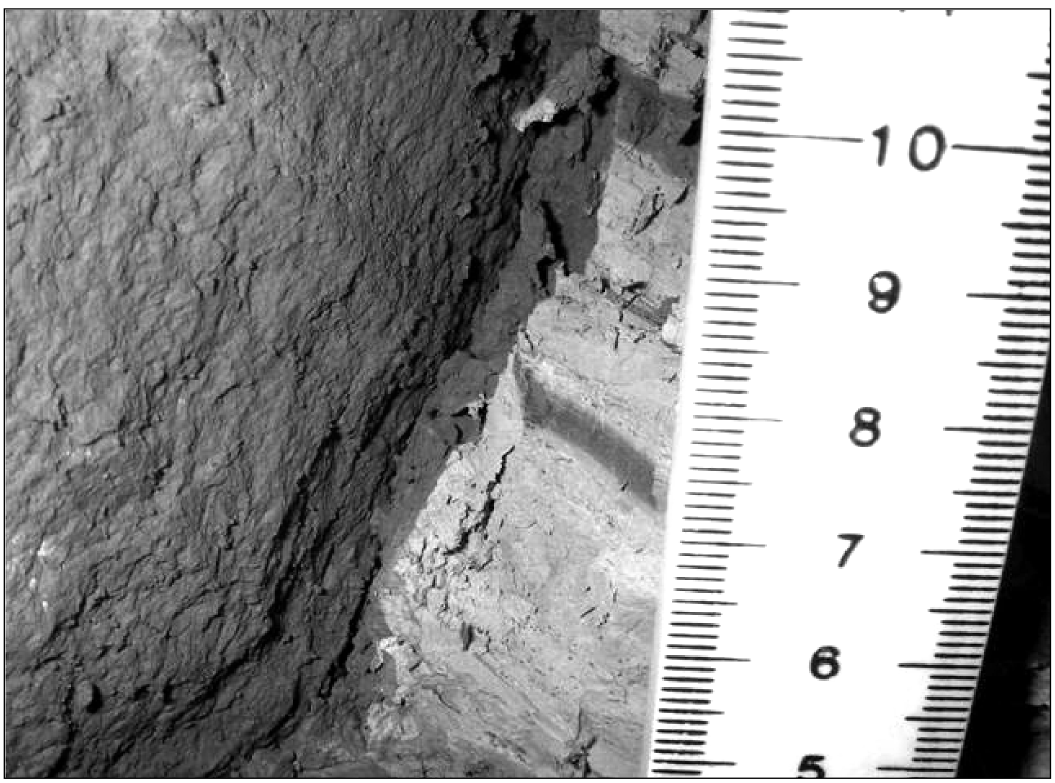


Figure 3 The remoulded material from 1600mm below ground level (pile MR4-W) showing the distinct colour and texture differences between the remoulded and host soils.

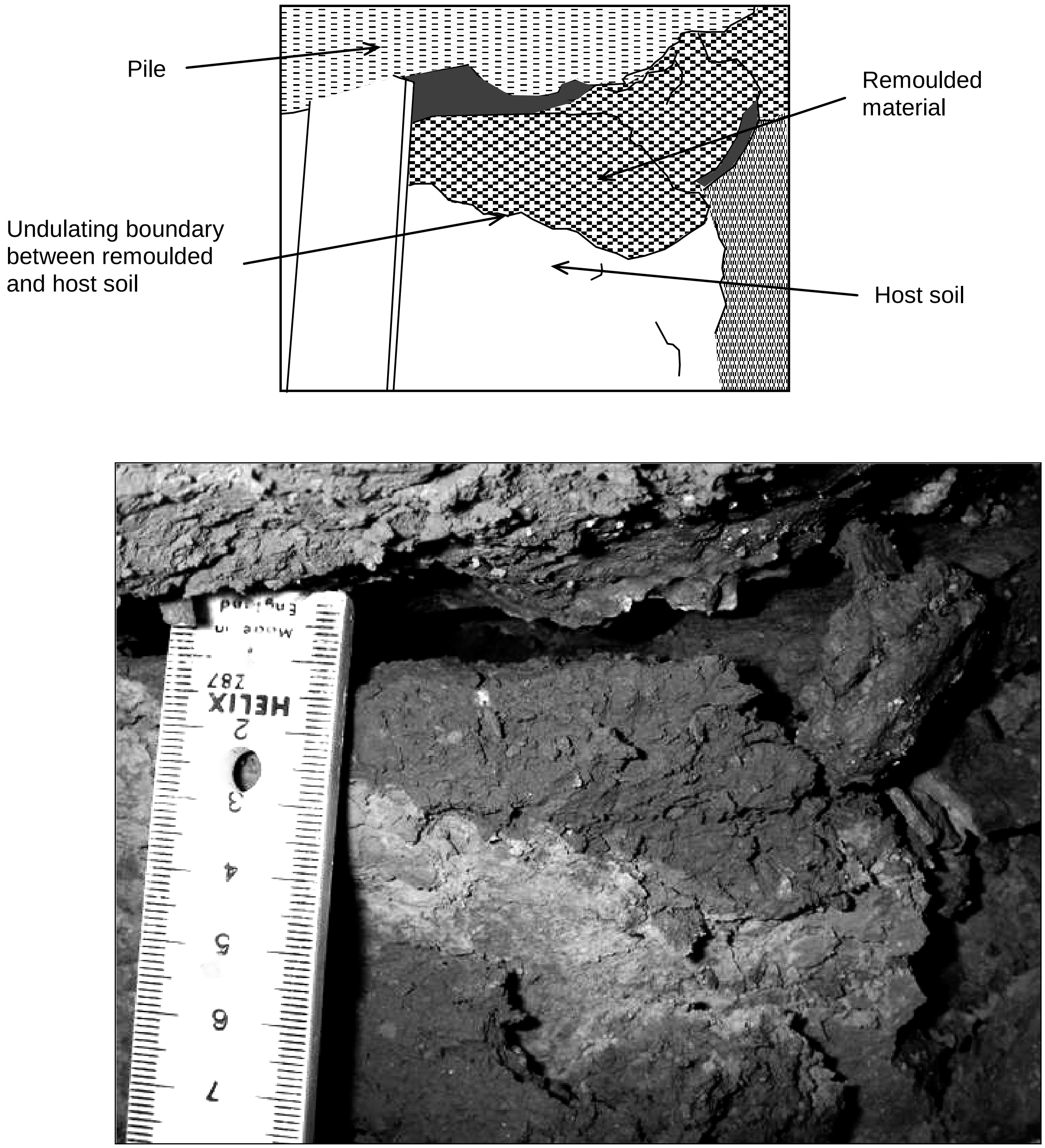


Figure 4 The boundary between the host soil and remoulded soil around pile MR1-D/OR, 819-1277mm bgl as viewed from above. The lateral variation in remoulded zone thickness can be seen.

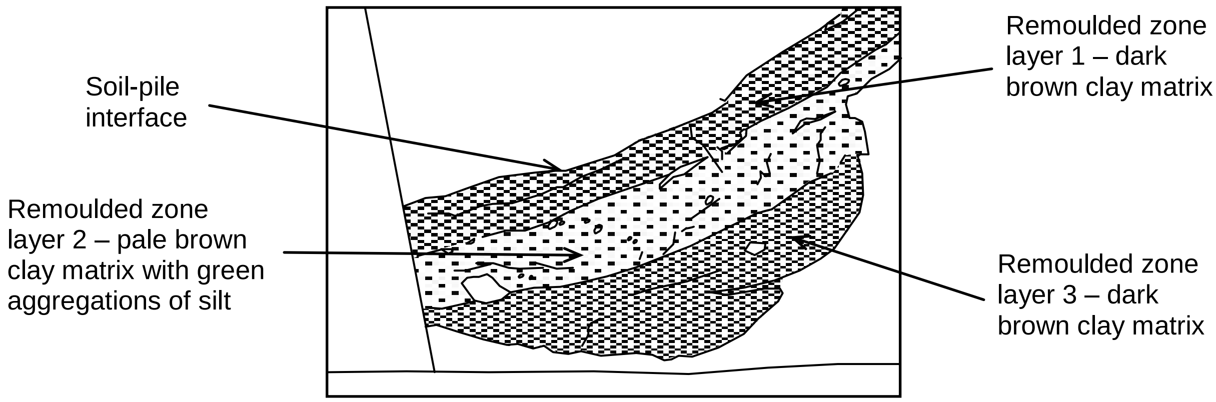


Figure 5 Zoning of remoulding with the soil surrounding pile MR3-W/OR 860-1210mm below ground level. Then soils is viewed from above, and the pile would have been at the top of this picture. In the middle layer, mm scale aggregations of green/grey silt can be seen.

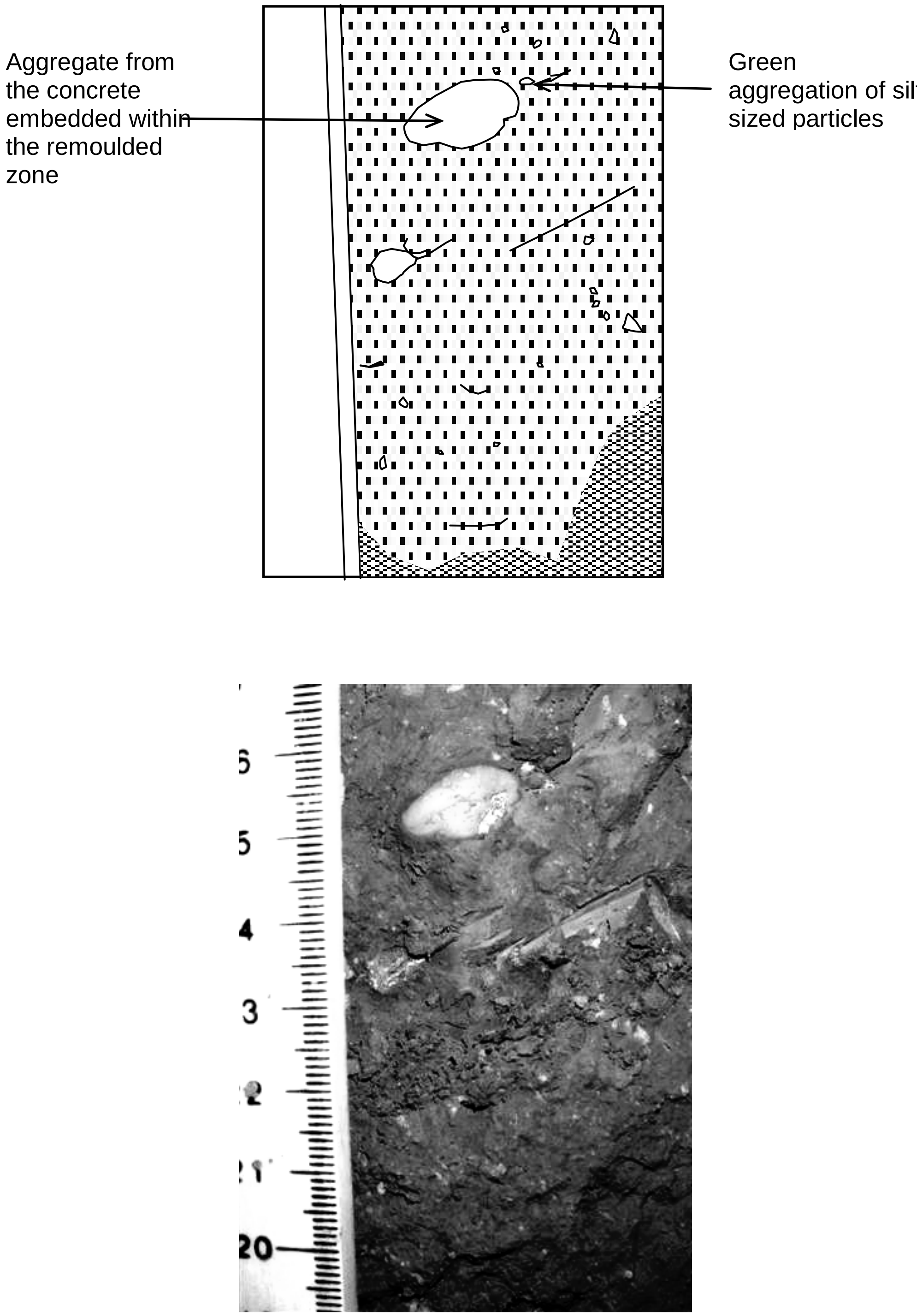


Figure 6 The vertical elevation of the remoulded surface of pile MR2 showing free aggregates within the remoulded layers. 1000-1457mm bgl.

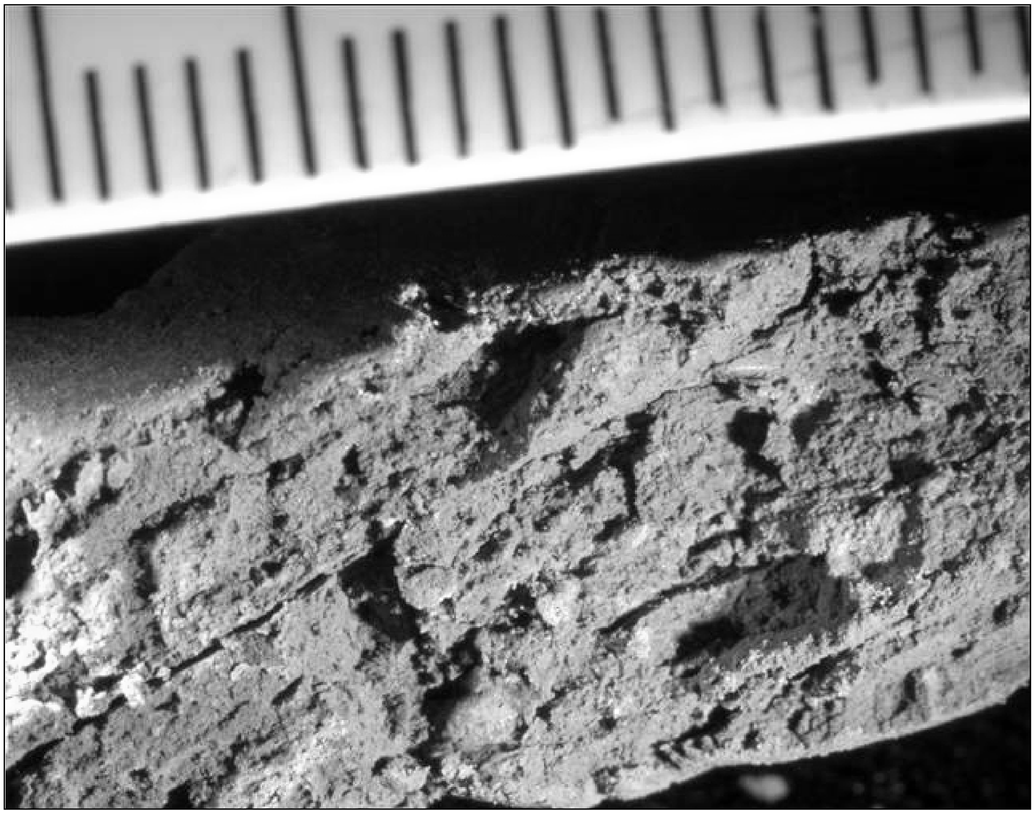


Figure 7 Fissures present within the remoulded zone of pile MR1-OR 581mm below ground level. Ruler is in original position of the pile and photograph is taken looking down on the top of this horizontal section through the remoulded zone.

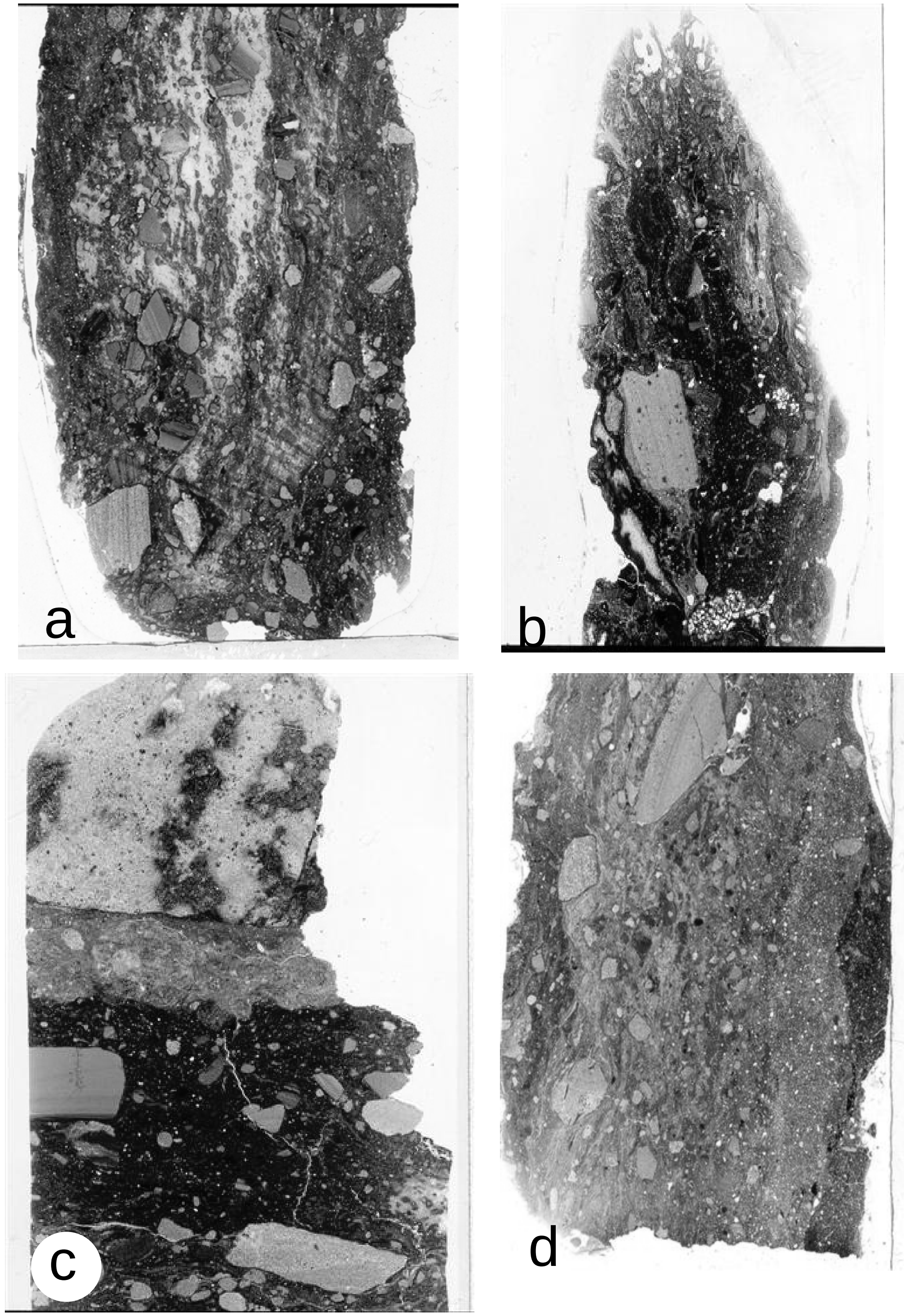


Figure 8 Vertically taken thin sections of vertical planes through the remoulded zones around all four piles. a) MR1-OR, slide is 28mm wide b) MR2, slide is 22mm wide c) MR3-W/OR slide is 31mm wide d) MR4-W slide is 43mm wide. The inner surface of the soil-pile interface is to the right of each picture, apart from (c) where the soil-pile interface is at the bottom of the picture

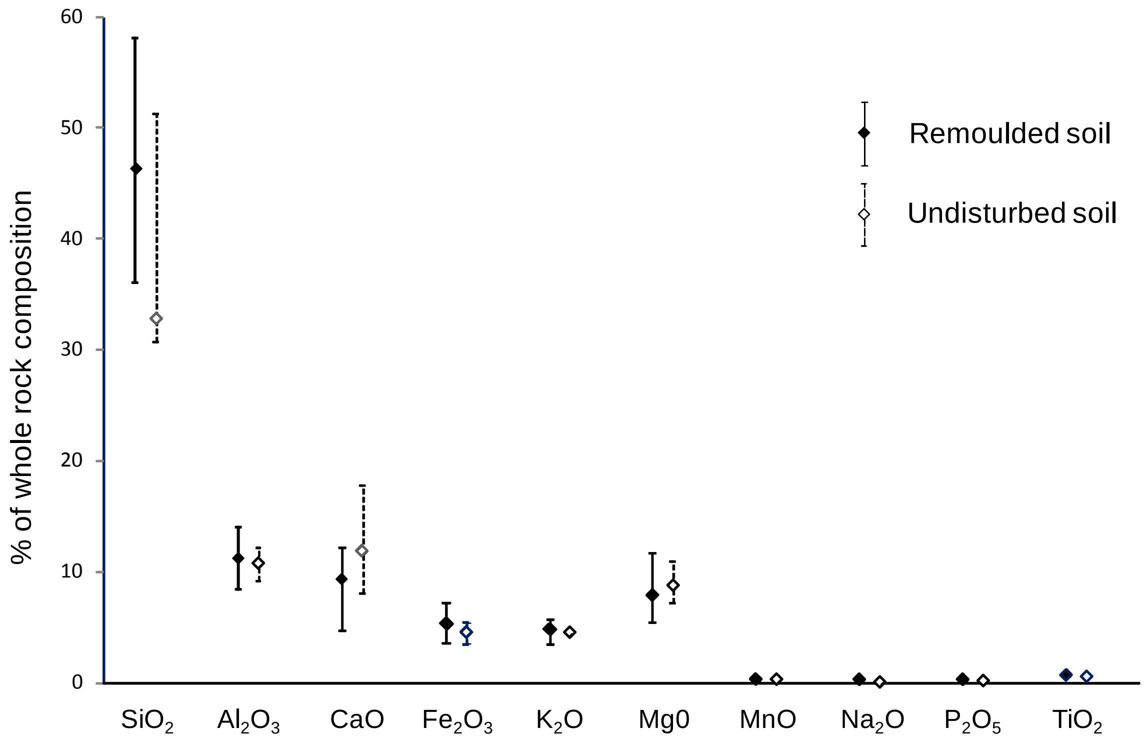


Figure 9 Chemical analysis of undisturbed soil outside remoulded zone and remoulded soil adjacent to the piles. Data is from samples from all piles. Error bars give maximum and minimum values measured.

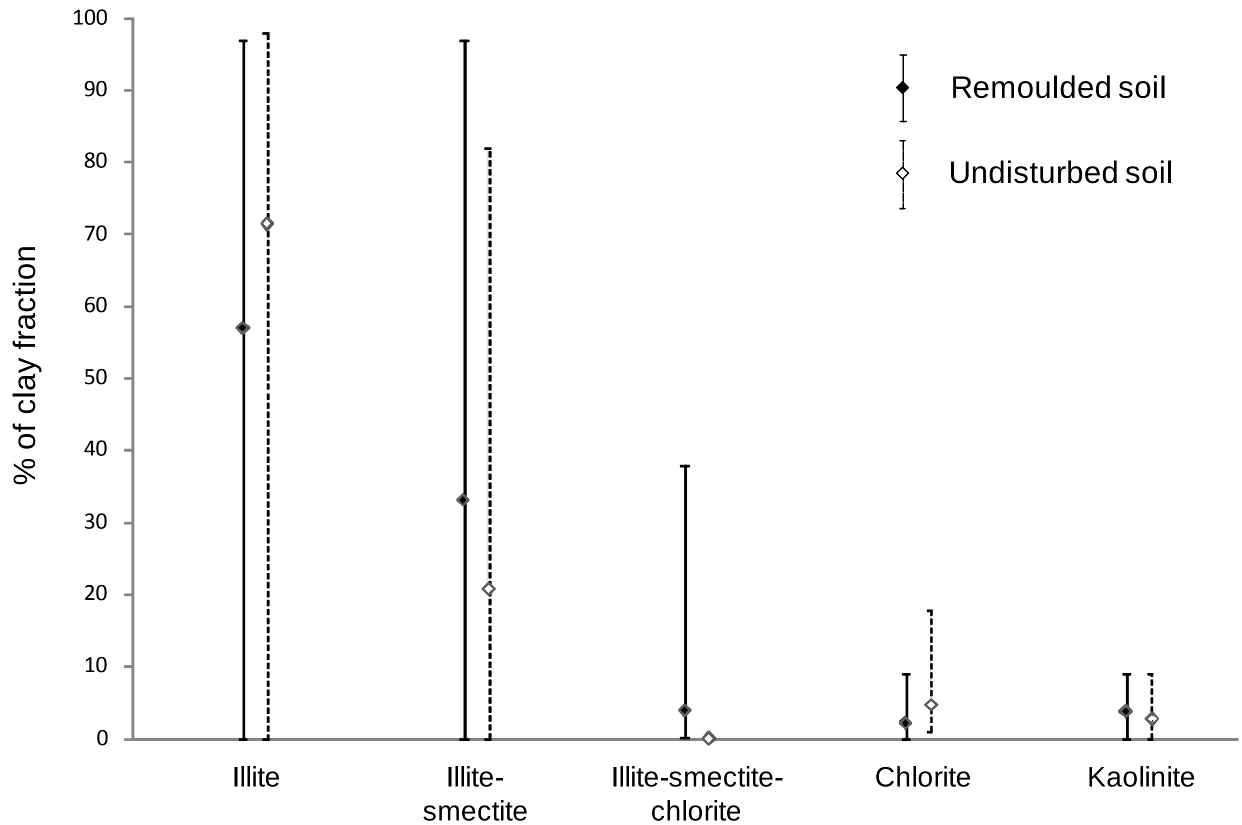


Figure 10 Abundances of minerals within the clay fraction of undisturbed soil outside remoulded zone and remoulded soil adjacent to the piles. Data is from samples from all piles. Error bars give maximum and minimum values measured.

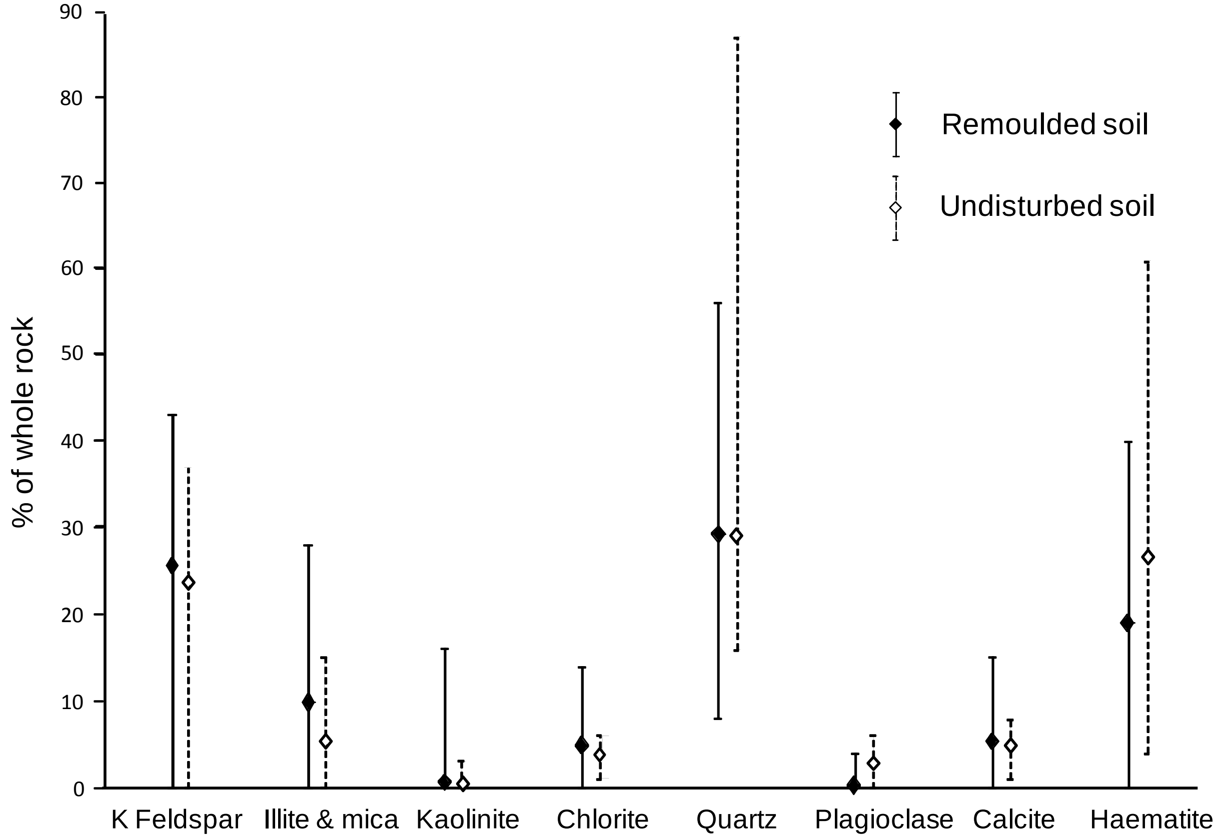
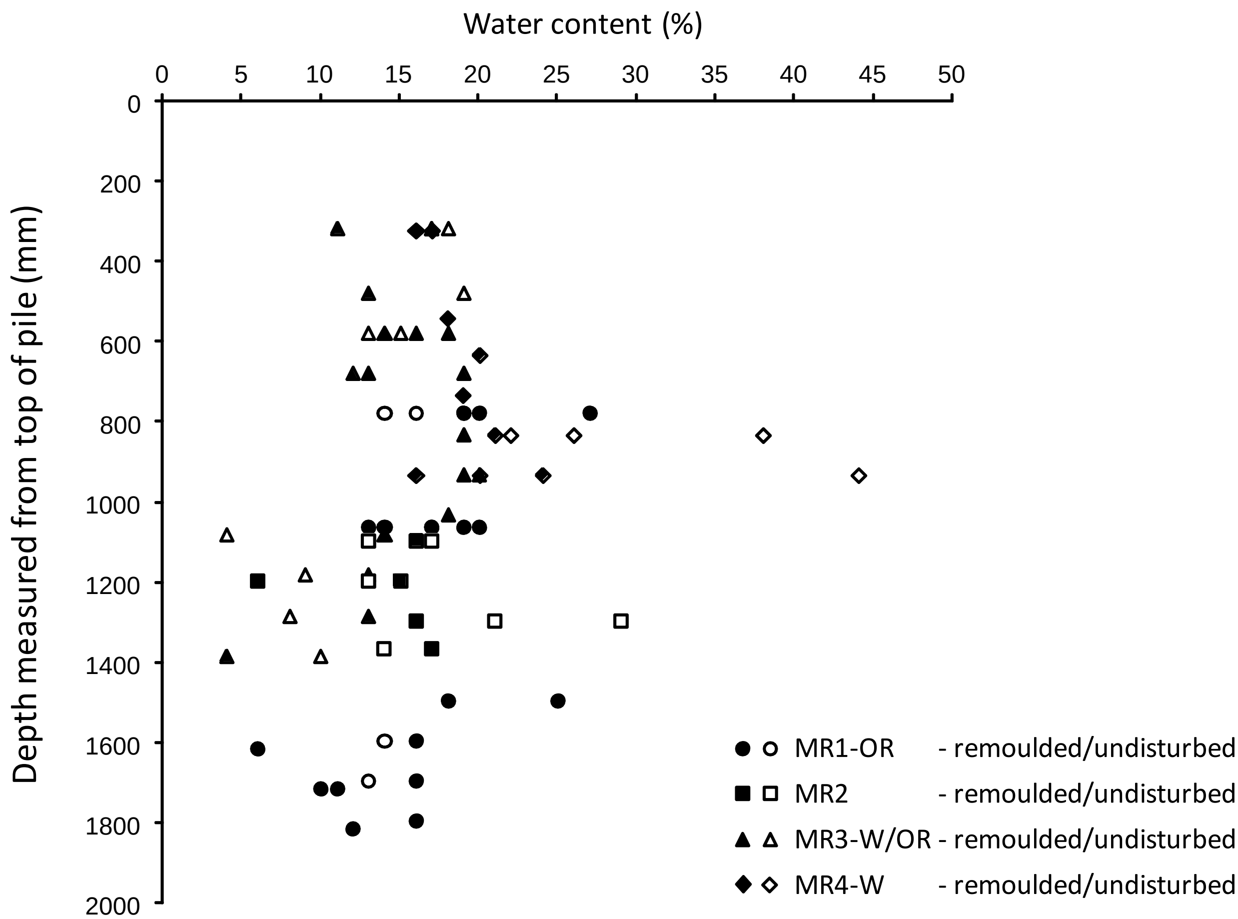
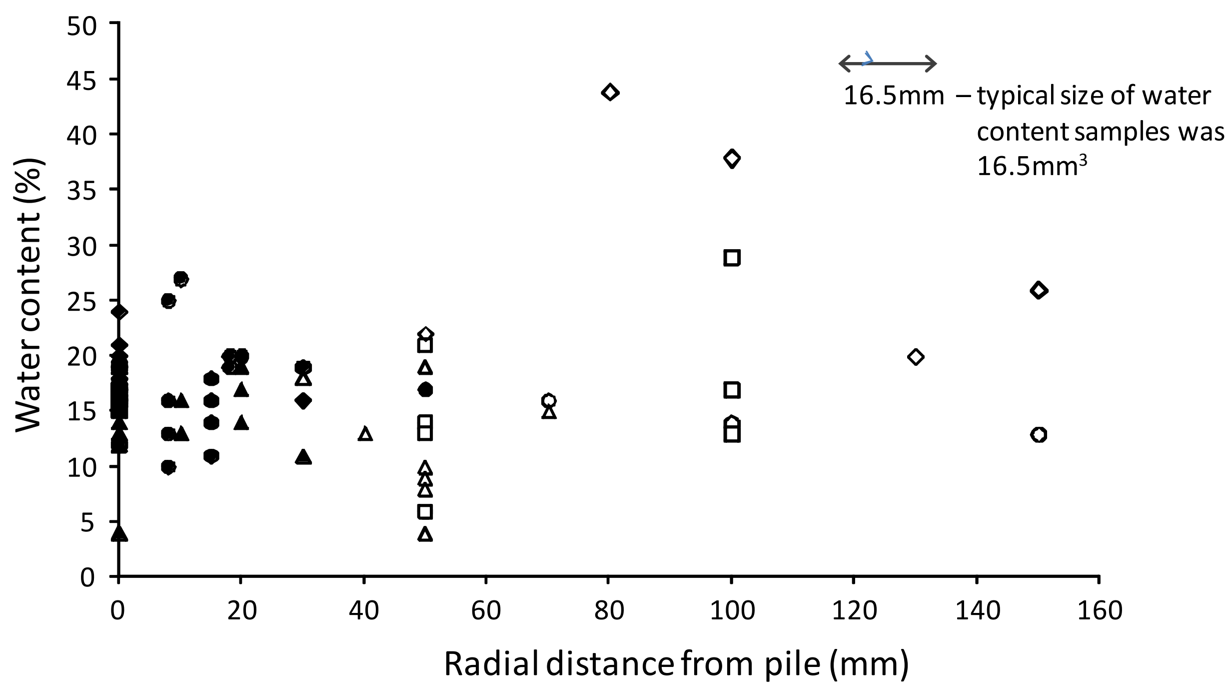


Figure 11 Abundances of minerals within the whole rock undisturbed soil outside remoulded zone and remoulded soil adjacent to the piles. Data is from samples from all piles. Error bars give maximum and minimum values measured.



(a)



(b)

Figure 12 Variation in water content with (a) depth and (b) radial distance from the pile. Data from all piles, remoulded and undisturbed soil