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The use of CPTU for driven piles designed in a backfilled opencast 'marl hole' in an important post-industrial revolution area within the UK

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ABSTRACT: The Etruria Formation has historically been an important resource for the pottery and brickmaking industry in the Stoke-on-Trent area and was mainly exploited using opencast methods – or 'marl holes' as they were commonly known. These 'marl holes' some of which have been reported to be more than 100m deep, have been subsequently backfilled generally with non-organic pottery, brickmaking and domestic waste. This paper explores the redevelopment of land over a backfilled 'marl hole' at a site in Hanley, Stoke-on-Trent, Staffordshire, UK, for residential properties. The development posed a number of challenges for the design of the foundations due to the historical legacy of the site. Driven steel tubular piles were chosen as a suitable system as there is precedent with this foundation solution, which has been frequently adopted for buildings within the area. However, some of the key challenges for this site included the presence of 'high walls' along the edges of the opencast works where driven piles could be deviated off the sides along with the uncertainty regarding socket lengths of piles driven into the underlying solid strata. To establish a 3D ground model for the 'marl pit', underlying strata, piezocone tests (CPTU) were seen as the most cost-effective and practicable method of site characterisation. Using this data, piles were installed, test/production piles were installed, driven to a set/penetration into the bedrock criteria and then compared to this ground model.

1 INTRODUCTION

This paper discusses the use of piezocone tests, CPTU for characterizing a backfilled opencast site for pile design.

1.1 *Site description*

The site is situated to the south of Hanley, which forms one of the six towns that make up the City of Stoke-on -Trent, in North Staffordshire, United Kingdom.

The proposed development is made up of a series of low-rise (2–3 storey) self-contained residential units. While the current topography shows a generally flat ground surface, this conceals the historical legacy of this part of Stoke.

1.2 *Comments on the geology regarding the proposed development*

The geological structure of the North Staffordshire Coalfield, presented in Figure 1, is a syncline, plunging towards the south-south-west, with the productive Coal Measures at the centre of the coalfield and the Etruria Formation forming the outline, particularly along the eastern limb of the syncline (Rees et al., 1998).

It is no coincidence that the six towns forming the city of Stoke (Tunstall, Burslem, Hanley, Stoke, Fenton and Longton) are aligned along the eastern syncline limb above the Etruria Formation.

Unlike the North Staffordshire coal mining, the Etruria was generally exploited by opencast methods – or 'marl holes' as they were called. The outcrop of the Etruria, along the eastern limb of the syncline forms a line of many marl excavations of varying sizes. At Fenton, less than 10 km south-south-east of Hanley, the marl pit is reported to have been more than 100m deep.

The British Geological Survey (BGS) no longer recognises the term 'marl' and so now the Etruria Marl is officially known as the Etruria Formation.

Published information from the BGS suggests this proposed development site is underlain by Glacial Devensian deposits and in turn Carboniferous bedrock. These are mainly formed of a sequence of the

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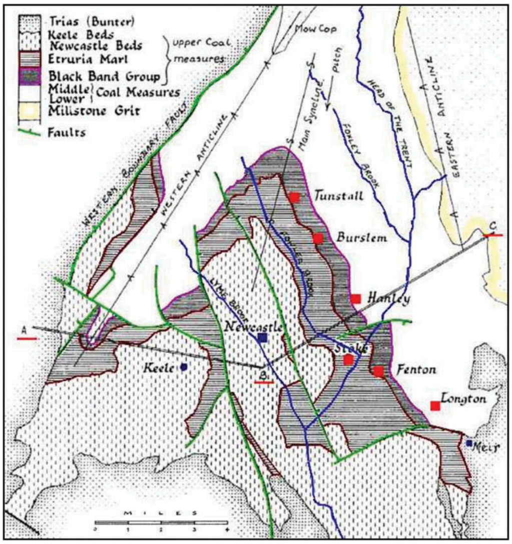

Figure 1. Geological map of North Staffordshire, modified from Millott (1937).

Etruria Formation, which is of Middle Carboniferous age, from 308 to 319 million years ago. It comprises of mudstones, siltstones and sandstones that overlay part of the North Staffordshire productive Coal Measures (Pennine Upper Coal Measures).

Reference to historical data indicates the site sits partly over an old marl pit. Data for an adjacent site indicates that the main extent of this old pit, known as the Mousehole Marl Pit, was to the north-east of the current development. The remainder of the site considered in this paper also appears to straddle the side of this old pit.

The Etruria Formation has a few unique properties that have made it a very important resource for the pottery and brickmaking industry. Firstly, it has a relatively high natural carbonate content common with non-marine semi-lacustrine 'marl' deposits. However, the source material for the Etruria was eroded material from an older Midlands volcanic sequence. Therefore, it has a relatively high iron content that gives rise to the natural colour variations. While the formation is mainly of clay and silt grain size, the Etruria also includes regular sandstone layers termed 'esplays'. These are laterally discontinuous with few recognised as named horizons.

No published records are available for the Mousehole Marl Pit, which is known to extend beneath the proposed development. Following the exploitation of the Etruria Formation, the marl holes were backfilled with non-organic pottery and brickmaking waste. Much of the backfilling was undertaken during the 1960s, 1970s and 1980s (or before), when domestic waste was largely ash, glass and metal goods and it is expected that these products are also present.

Furthermore, there have been many anecdotal reports of industrial waste being dumped within the marl holes during times when the controls on waste disposal were less rigorous than now.

The following photograph presented in Figure 2 shows the nature of the excavations from a nearby well documented marl hole at Daisy Bank. While these pits were active, the high walls were steep probably between 45° and 50° overall, but locally up to 60°.

Figure 2. Air photos depicting the full extent of the Daisy Bank Brickworks, English Heritage (1927).

In respect of future development over the marl holes, probably the worst case is construction over the marl hole sides, often termed the 'high walls'.

2 INTERFACE DELINIATION BETWEEN THE MADE GROUND AND MUDSTONE

2.1 *Ground conditions*

Field work was undertaken in two phases. The first phase took place in September 2019 where 9 boreholes were performed, six to shallow depths to nearly 6m and three deeper boreholes to a maximum of nearly 24m. On the deepest borehole, groundwater was encountered at 16.5m. Ground conditions at the borehole locations comprised a layer of made ground overlaying natural strata considered to be Upper Coal Measures Formation.

Most of this initial investigation terminated in the made ground and no Glacial deposits were found. The made ground was mainly granular loose to medium sandy gravel with occasional cohesive material present in thin layers, typically soft to firm clay. Mudstone was only encountered in a couple of boreholes found below the made ground and was described as very weak rock.

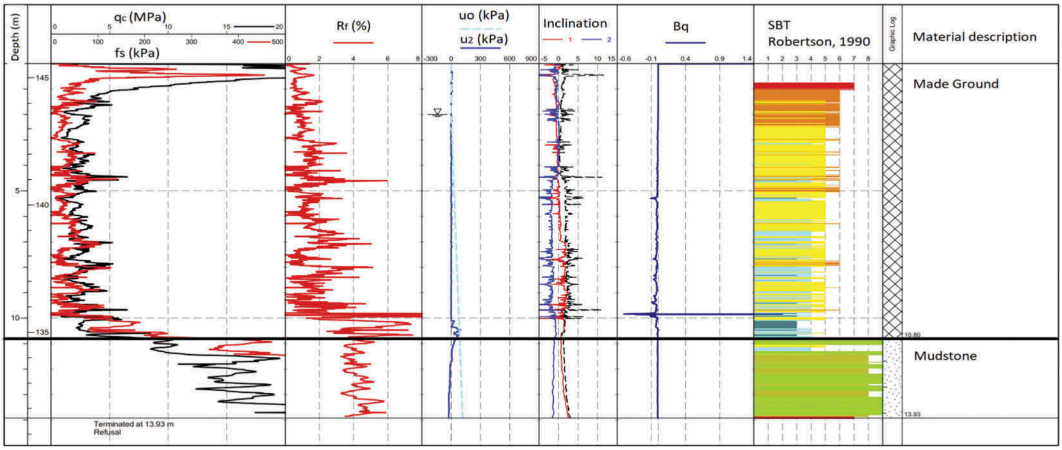

Figure 3. Typical CPTU profile for this site.

During the second phase of site investigation, 52 CPTUs were carried out to a maximum depth of 31.5m.

2.2 *CPTU interpretation*

The delineation of the interface between the made ground and the mudstone was assessed by the cone resistance, q_c, friction sleeve, f_s, porewater pressure, u_2 and inclination. Figure 3 represents a typical CPTU profile from this site.

The typical site level was 145.5mAOD. CPTU results indicate bedrock from between 3-30m depth. Although CPTUs provided a site coverage, it was found that there is no evidence for bedrock between 128 and 124mAOD.

The increase in q_c and f_s with greater depths were immediately noticed when cone was penetrating the mudstone. Results from 42 CPTUs with a penetration of more than 1m into this strata suggest that within mudstone $q_c > 5.5$ MPa, $f_s > 250$ kPa and u_2 has a significant drop to negative measured values. The negative porewater pressure indicates suction. Smoother inclination measurements are another indication that Mudstone is a uniform deposit.

To allow further review of the CPTU results within the mudstone, the data points recorded were plotted in the Robertson 1990 soil behaviour type, SBT chart, as presented in Figure 4.

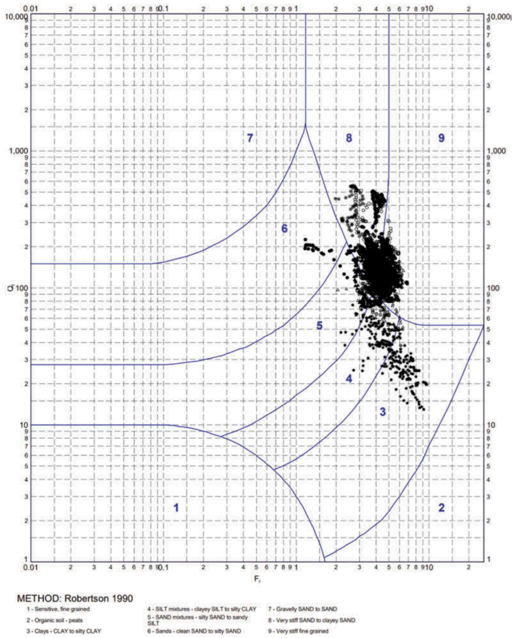

Figure 4. Mudstone results plotted on Robertson 1990 SBT chart.

The majority of results for Etruria Formation fall in zones 8-9, sand to clayey sand and very stiff fine grained, respectively. It is also noticed that some results plot in zones 3-4, which represent clay and silt mixtures.

Figure 5 presents a typical CPTU cross section for this site. The data shows that the rockhead was encountered at shallower depths in the south west of the site. In the eastern boundary of the site, mudstone occurs at greater depths. These results are used to develop the ground model for this site, which is also included in the paper.

A simplified graph of friction ratio, R_f (%) for mudstone to show the variation of results is presented in Figure 6. Black graphs present the minimum and maximum R_f within the deposit, meanwhile the red graph presents the averaged results. It is seen that this parameter may vary greatly in mudstone and cannot be trusted as the main parameter to interpret it.

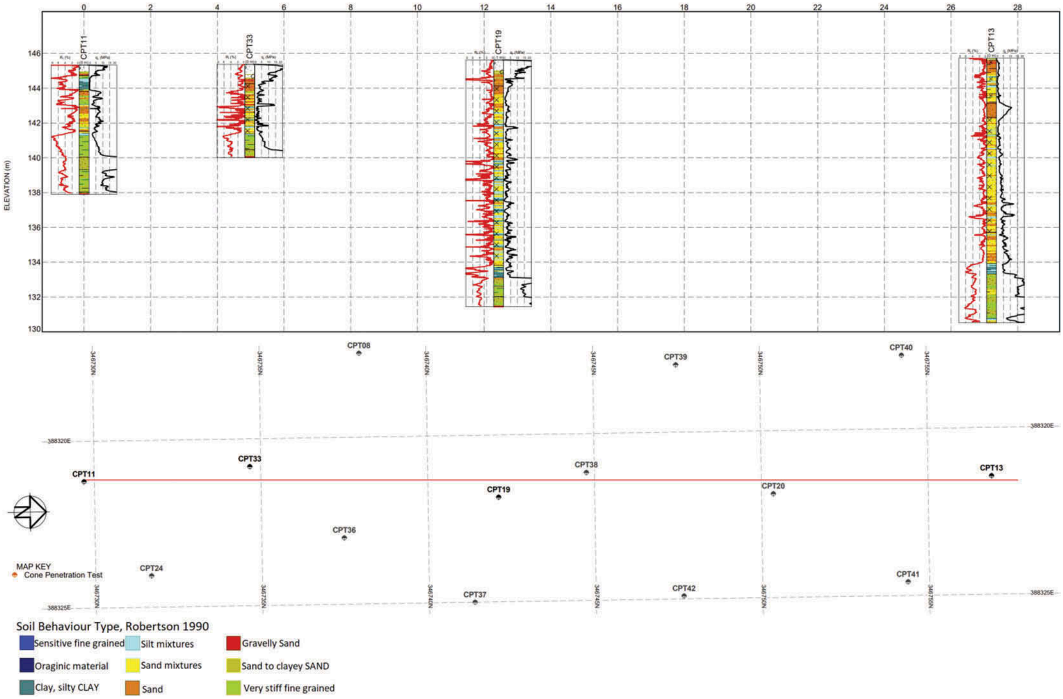

Figure 5. Cross section showing the mudstone coming in at a shallower depth to the south and much deeper to the north of the site.

Although CPTU provided a good site coverage, it was found that there were no probes relating to datum levels of between 128 and 124mAOD. Consequently, CPTU data were provided within two zones and between approximate levels of 141 to 128mAOD and 124 to 115mAOD. These are referred to as the upper and lower zones. The stratigraphic plots indicate distinct differences between the upper and lower zones. Although the results show some consistency several distinct layers can also be seen. In particular a more cohesive layer, with typical R_f = 6-8% between 140-138mAOD, and then some more sandy horizons averaging R_f =1% between 133-130mAOD. The lower zone indicates significantly more variation with values of R_f varying from as low as 1% to as high as 9%.

After reviewing the scatter in these results it is suggested that the big variation in R_f results within the deposit can be mainly explained by lithological variations within the marl.

2.3 *Discussion of CPTU results*

Findings from CPTU tests regarding the delineation of the interface between the made ground and the mudstone for this site are in line with historical facts and previous experiences from investigations of backfilled opencast 'marl holes'.

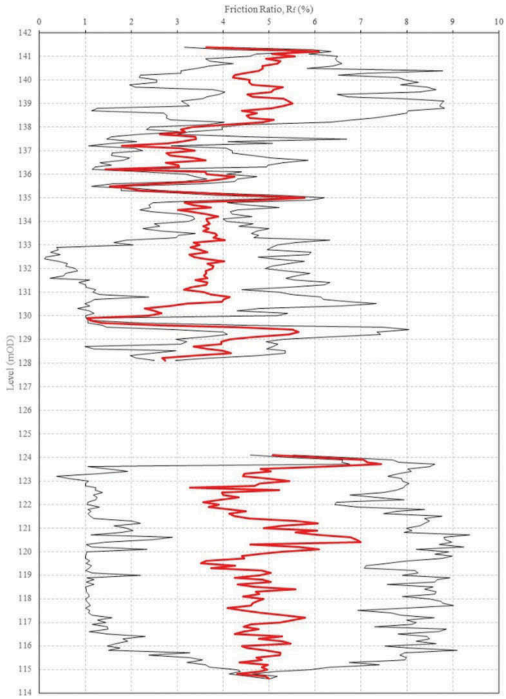

Figure 6. Friction Ratio (Rf) variation.

Among 52 tests carried out in total, only a few tests were refused at shallow depths, due to obstacles encountered in the first meters of backfilled material. 42 CPTU tests penetrated through the mudstone, 18 of which with a penetration of more than 2m into this material, which allowed us to review the results and the findings of this paper were crucial for the ground model and foundation design. Etruria Formation, interpreted as mudstone behaves as very stiff fine grained material, plotting in zone 9 in Robertson 1990 SBT when q_c>5.5 MPa and f_s >250 kPa and as sand to clayey sand when q_c >15 MPa and f_s >500 kPa, plotting in zone 8.

Porewater pressure can be another important measured parameter to interpret Mudstone, due to the sudden drop in the interface with made ground and large suction developed as the penetration continues. Another important indication of the penetration in mudstone is the inclination in both directions, which becomes uniform soon after the start of penetration through this deposit.

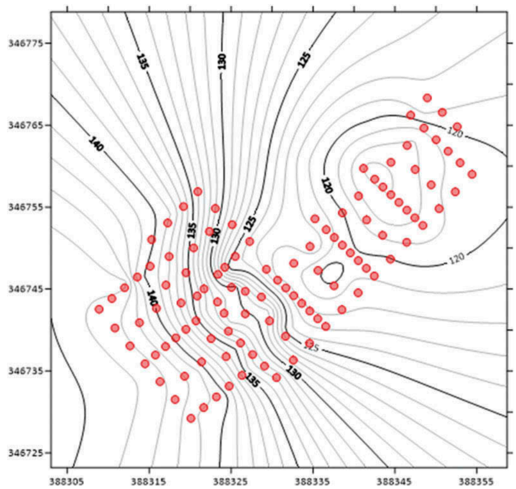

Figure 7. Marl Hole Contour Profile 2D.

3 GROUND MODEL

The ground model for this site was developed based on CPTU results that had penetrated into the natural strata beneath the made ground.

For some tests where sensible assessment of this rockhead boundary was unclear, or the CPTU test appeared to have deviated or refused on an obstruction within the made ground, a repeat test was carried out.

Based on the CPTU results a model of the pit was constructed using the contouring package Surfer. Surfer interpolates irregularly spaced XYZ data into a regularly spaced grid. The grid data can then be interpreted using gridding and mapping modelling tools to produce 2D or 3D maps such as contour, shaded relief and surface maps. In addition, calculations such as bilinear interpolation can be carried out where the Z value at the XY location can be calculated from the nearest four grid nodes. In Figures 7 and 8 the marl hole contour profiles is shown, including the pile positions, shown in red.

The initial Surfer plots in Figures 7 and 8 provide a profile of the western high wall of the marl hole. This model was used to check that installed piles have a suitable penetration into the natural strata.

In reviewing the updated ground model, the data shows that rockhead occurs at 144-143mAOD along the western boundary of the site. There is a fairly shallow gradient towards the east until typical rockhead falls to 141-140mAOD. Thereafter the plot shows a steeper incline representing the western edge of the marl hole. Rockhead falls to about 123-122mAOD and then thereafter the gradient is more gradual towards the eastern site boundary.

Nearer the eastern site boundary rockhead levels are typically 120mAOD although with some further reduced levels. Reviewing the steeper part of the western edge of the marl pit the average gradient appears to be about 50 degrees although locally this is indicated as increasing to almost 65 degrees. These back analysed gradients are comparable with those previously indicated for marl pits in the area.

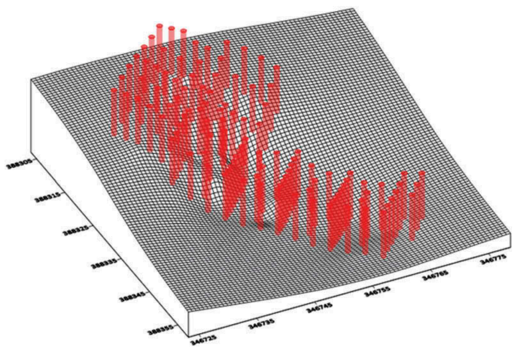

Figure 8. Marl Hole Contour Profile 3D.

From the results of the CPTU tests a suitable ground model showing the profile of the made ground/bedrock interface across the site has been established in relation to the proposed pile locations. The CPTU testing has provided data which indicates a good profile for the interface, and which looks reasonable when comparing all the available information. Where CPTU results looked anomalous, they have been discounted.

In reviewing and analysing the CPTU data, at least 1-2m bedrock penetration was typically considered sufficient to provide confidence that the probe attained a suitable penetration into the natural material.

This surfer ground model has been used to review the toe depths of the installed piles against the interpolated mudstone levels. It may be noted that the surfer ground model has been considered as more reliable than particular pile driving records.

4 FOUNDATIONS

The foundation proposal was to adopt top driven tubular steel piles with a 178mm diameter tubular steel section considered. The driving system employed was using a 5.5 tonne hammer. It may also be noted, based on experience, that it was expected that the proposed newly installed piles would achieve a penetration at least comparable to the CPTU tests.

From the piling works a typical penetration of approximately 3 to 4m into natural strata was achieved. This was considered appropriate as it is anticipated that for the proposed piles, using an efficient energy input, a greater penetration compared to the CPTU tests, should be achieved.

As noted in monitoring the installation data all piles used within the foundation system showed reasonable penetration into the mudstone. Only one pile indicated an anomaly, taken as possible deviation, and which was subsequently replaced.

5 CONCLUSIONS

CPTU tests were used to provide a cost effective method to profile and establish a ground model for the backfilled opencast marl hole in Stoke on Trent. There was an initial concern on using CPTU to get to depths due to equipment limitations to penetrate through hard strata and rocks.

At the end of the site investigation program, CPTUs provided effective information for the ground model, which allowed a suitable piling solution to be installed for the site.

From reviewing 42 CPTUs, it may be suggested that Robertson 1990 normalized SBT chart is a good classification method to interpret the mudstone in an accurate way. It provides more consistent results, indicating the behaviour of the deposit as overconsolidated cemented weak rock, plotting data points for this deposit in soil zones 8-9.

Possible inconsistencies in CPTU based classification should be attributed to physical complexity, which may affect the overall behaviour of the deposit especially in the upper zone, where some soils show a more clay-like behaviour and some others a more sand-like behaviour.

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