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Pile impacts on Archaeology
Literature Review

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1 INTRODUCTION

Since the advent of the Valetta Convention (European Union 1992) there has been an increasing interest among archaeological and heritage professionals in understanding and assessing the impacts of construction techniques on buried archaeological deposits, structures and artefacts. The implementation of the convention has led to differing approaches across Europe, as outlined by Willems (2008), but throughout, concern has been centred on the development of strategies for preserving archaeological remains *in situ*. Of particular concern has been the impact of piling on buried archaeological remains, deposits and structures during development. In developing preservation strategies, there has been a growing recognition among archaeologists that our understanding of the short- and long-term impacts of piling on buried remains is patchy, at best. This has led to a number of studies and conferences over recent years, aimed at gaining a greater understanding of the impacts of engineering, and piling in particular, on buried archaeological remains. The Preserving Archaeological Remains *In Situ* (PARIS) conferences have had a major impact in developing the study of preservation *in situ* and disseminating knowledge (Corfield *et al* 1998; Nixon 2004; Kars and van Heeringen 2008; and Gregory and Matthiesen 2012).

The principal assumption of preservation *in situ*, as it relates to piling, is that archaeological remains in the ground can be preserved whilst development can proceed. This presumes that the pile foundations will have a limited impact that we can quantify and that this impact will result in a limited and acceptable loss of the archaeological resource. These assumptions are predicated on an overriding assumption that we understand what is going on underground during and after piling. But is this true? Do we understand the impact of piling on the physical, hydrological, chemical and biological processes that act on buried archaeological remains? If not, can we claim to be preserving *in situ* or are we potentially enabling the continuing erosion and degradation of a finite archaeological resource?

Willems (2011) has questioned some of the assumptions behind preservation *in situ*, noting that sites which are preserved and built-over because of their significance become inaccessible until a future unknown date and we are uncertain what will happen to these sites in the future. They could, in theory, be excavated at a later date, if they have survived, although this is based on a number of assumptions. Willems notes that our assessment of the significance of heritage is based on ascribed values which rely on our understanding of the archaeological resource. Additionally, science-based preservation *in situ* is expensive and its results may be limited due to the complexity of the degradation process and our limited understanding of them. The need for reliable and useable data on which to base preservation schemes and to judge their likely effectiveness is essential.

This purpose of this project is to update and build upon previous research, to review existing knowledge, identify gaps in our understanding and provide data with which to inform future revision of Historic England piling guidance. It was originally intended that the project would include a programme of fieldwork but, due to problems identifying and accessing sites, this was not undertaken at this stage. It is hoped that the fieldwork may be undertaken at a later date. This could use an updated strategy, based on the information collated in this report.

2 PROJECT BACKGROUND - PREVIOUS STUDIES

Historic England (formerly English Heritage) have funded a number of studies in recent years that have considered preservation *in situ*. In particular, several assessment of piling impacts have been undertaken over the last 15 years. These studies have included literature reviews of both archaeological and engineering literature and experimental studies.

Mitigation of Construction Impacts on Archaeological Remains

This study (Davis *et al* 2004) described construction processes and their potential impacts on archaeological remains. The review on engineering operations considered what operations were undertaken, how they fit into the stages of construction works for a typical development and how they might impact on archaeology.

- pre-construction ground investigation – test pits, boreholes
- pre-construction activities – site clearance, ground stabilisation
- construction – groundworks, services, foundations
- post-construction – repair and maintenance

Different strategies that can be used in mitigation of impacts were identified: avoidance, engineering solution and monitoring. The study also included an appendix identifying the different engineering processes relevant to the stages outlined and reviewed their potential archaeological impact.

Response of Archaeological Sediments and Artefacts to Imposed Stress Regimes as a Consequence of Past Present and Future Anthropogenic Activity

This study examined the impact of piling on adjacent buried artefacts through stresses on sediments (Sidell *et al* 2004). The study used test cells to study the effect of static and dynamic stresses on buried artefacts. The results suggest that vibro piles produce much greater stresses in sediment and objects while CFA produce negligible vibrations. The study was undertaken to produce hazard charts which show the conditions which will cause failure in different materials.

Piling in layered ground: risks to groundwater and archaeology

This project comprised a laboratory study of sediment disturbance adjacent to driven piles in layered clay soils and a review of sediment disturbance observed on archaeological sites (Hird *et al* 2006).

The deformations observed in the laboratory tests on clay soils indicated that most vertical displacement was restricted to a radius of 1.5 pile widths of the pile centre line provided the particle size of the sediment is small. For stronger clays, the tests indicated that vertical displacements extended for a larger radius around the pile. Previous studies have suggested that vertical displacement in sand soils can be up to 2.5 pile diameters.

Horizontal displacements were not quantified in the tests, but observations indicate they would be within the range of previous tests that suggest horizontal displacement occurs over a wider radius than vertical displacement.

The impact of the piles on groundwater flow was measured. This identified that there can be significant increases in groundwater flow due to piling.

The review also identified archaeological sites where piling impacts had been visually observed through displacement, distortion, drag-down and fragmentation of deposits or surfaces (Table 1).

Location	Pile type	Pile radius or ½ width (m)	Soil Type	Max vertical displacement (m)	Radius of disturbance from centre of pile (m)	Radius of disturbance/ pile radius or ½ width
Northampton	Driven circular	0.24	unknown	1.0	0.6	2.5
Wisbech	borehole	0.06	Cohesive fill	0.2	0.25	4.16
No.1 Poultry London	Augered with metal sleeve	1	Beaten earth floor	?	c. 1.6	1.6
Worcester	Driven square	0.1	Cohesive fill	0.3	0.4	4.0
Lincoln	Driven square	0.125	Compact cohesive fill	?	0.175	1.4
Lincoln	Pre-augered driven square	0.125	Compact cohesive fill	1.0	0.25	2.0
Boston	Driven square	0.13	Limestone gravel over cohesive fill	0.3	0.32	2.46
Boston	Driven steel tube	0.095	Limestone gravel over cohesive fill	0.3	0.15	1.57
Boston	Pre-augered driven square	0.11	Limestone gravel over cohesive fill	?	0.16	1.46

Table 1: Summary of observations in archaeological excavations (Hird *et al* 2006)

Piling and Archaeology: An English Heritage Guidance Note

The Guidance Note (Historic England 2015) provides the current guidance on piling and archaeology in England. The Note reviews current piling practice in England at the time of publication and summarises the available evidence for its impact on archaeological remains. The Note proposes that the impact of new piles should be minimised; impacts from piles should be less than 2 per cent of the site; and the total impact of all construction activity (piles, services, lift pits and so forth) should be no more than 5 per cent of the total site. Specific mitigation recommendations were identified for different types of piles. This clarified the level of ‘acceptable’ loss of archaeological deposits that had previously been based on a figure of 5 per cent, taken from a study of the archaeology of York by Ove Arup (Historic England 2015). However, this has sometimes been erroneously interpreted as 5 per cent loss to piling and not to all disturbance from construction.

Pile type	Mitigation
All piles	Adopt 'avoidance strategy' and avoid use of piles in areas of archaeological sensitivity where possible. Burial grounds should not be piled. Where piling is unavoidable, limit extent of physical destruction as far as possible (consider all ground interventions including ground beams.
Large displacement piles.	Zone of impact is potentially greater than pile diameter, therefore calculate percentage loss of area in building footprint using four times the pile area, unless there is evidence of the impact of past piling activity recovered through excavation.
Small displacement piles	Sheet – if waterlogged remains are present, assess potential impacts on groundwater flow and recharge of deposits. Consider long-term monitoring of water-table and water chemistry. H-section – Not recommended for waterlogged deposits due to possible migration and oxygen ingress
Replacement piles	Consider use of suitable cutting tools where obstructions are likely to be encountered. For secant walls see above for sheet piles. CFA – avoid on sites where structural remains are likely.
Vibro-techniques	Require further investigation but are likely to be extremely damaging to archaeology and should be avoided where possible.

Table 2: Summary of pile mitigation (from Historic England 2015)

Planning Mitigation and Archaeological Conservation - Davies 2009

Planning Mitigation and Archaeological Conservation (Davies 2009) reviewed the character of archaeological deposits, structures and artefacts, and the impacts that can result from construction activities. The study reviewed both archaeological and engineering literature and looked at a range of construction impacts including piling.

The following observations were made:

- the observable impacts that piling has can vary enormously in both scale and nature.
- in some cases, there are no observable impacts at all beyond the footprint of the pile.
- the nature of the impacts can vary from minor deformities in layers to major alterations in the layers adjacent to piles.
- drag-down is a very common impact associated with driven piles. The maximum vertical displacement observed varied from 0.2m to around 1.0m. The radial distance the displacement extended over varied from 0.1m to 1.0m with the extent related to the diameter of the pile.
- cracks and voids in the adjacent deposits were observed in some cases.
- mixing of layers adjacent to piles can take place.
- thin, hard and solid layers can fragment or break up when piled through, however, a pile can also push through thin, hard but fragmented layers with little damage beyond the footprint of the pile.
- artefacts were observed to have been dragged down by piles leading to intermixing of material from different periods.
- the degree of impact depends on the type of pile and the properties of the layers it passes through.

3 AIMS AND METHODS

3.1 Aims

The aim of the project was to gather evidence on the physical impact of a range of pile types in a variety of soils/sediments and archaeological deposit types, in order to add new data and inform future revision of Historic England guidance.

The project objectives were to conduct desk-based research and field investigations to determine the impact of different types of piling on a range of archaeological sites.

This report describes the results of the first stage of the project, the desk-based research. The second stage field investigations have not been undertaken due to difficulties in identifying appropriate sites with access.

3.2 Methodology

This literature review updates previous work, but concentrates primarily on works that have been produced since the first publication of Historic England's *Piling and Archaeology* in 2007. Published sources on archaeology and engineering and unpublished archaeological reports (grey literature) have been examined.

The review is specific to impacts from piling and does not review the extensive literature on the preservation and decay of archaeological remains in general. However, attempts have been made to identify the impacts that piling can have on ground conditions that could affect the preservation and survival of archaeological remains.

Engineers have undertaken many studies on the interaction of piles with the surrounding sediments, both during insertion and afterwards and these studies have formed the basis of this review. Most of these studies have examined individual types of piles rather than comparing the impacts of different types. However, it is clear from the literature that different types of piles interact with the sediments around them in very different ways and the aim of this study is to identify the potential impacts that may be relevant to the preservation of buried archaeological remains.

4 PILING AND TYPES OF PILES

4.1 Piling

Piles have been used for foundations for thousands of years. Through most of history driven wood piles were the main, if not only, option available. The development of new materials, such as steel and concrete, increased the range of materials available but also led to the development of more varied techniques for the insertion of piles. The different properties of piles (material, construction method and load-bearing capacities) have different potential impacts on buried archaeological deposits. The design of a piling scheme, and choice of piles, is based on an assessment of the ground conditions, load-bearing requirements, design life expectancy, cost and impact on adjacent structures. Any piling scheme is therefore based on the site- and construction-specific requirements of a development. There is an extensive engineering literature on the basic principles of piling and geotechnical engineering (for example Fleming *et al* 1992; Knappett and Craig 2012).

Archaeologically, the major disadvantage of piles is that they are inserted blind and their archaeological impact is not observable. All archaeology within the pile footprint will be destroyed, but archaeologists have been concerned for some time as to how far the impact of the pile will extend beyond the pile itself.

One consideration of interest to both engineers and archaeologists are the properties of the deposits to be piled through. In the terminology of engineering and soil mechanics 'soil' is used to mean 'any uncemented or weakly cemented accumulation of mineral particles formed by the weathering of rocks' (Knappett and Craig 2012, 3). 'Soil' thus includes what archaeologists and geologists would refer to as topsoil, subsoil and superficial geology. Engineers are concerned mainly with the strength and load-bearing capacity of the deposit and classify 'soils' as cohesive or granular, based on their engineering properties:

- cohesive soils include clays and silts. These are often weak and compressible but their properties vary and are dependent on the water and clay content. In general, a higher water and clay content gives a weaker and more compressible soil.
- granular soils include sands and gravels. These are generally stronger and less compressible depending on the packing of individual grains and the homogeneity of grain size. Granular soils are more permeable than cohesive soils.

A third group of soils are organic-rich soils, such as peat. These have limited load-bearing potential and are thus of less interest to engineers designing foundations, except as something to be passed through to reach load-bearing deposits.

Of primary concern in engineering terms are the soils' characteristics under loading. Granular soils settle almost immediately under loading, while cohesive soils tend to consolidate over time, weeks or months. Organic-rich soils continue to deform long after consolidation has taken place, a process referred to as secondary compression or 'creep'. The mechanical properties of soils will therefore have an impact on the choice of pile design and the long term impact of the piling process can continue after pile construction has ceased.

4.2 Related engineering techniques

Related to piling are stiffening columns (vibrated stone columns, soil stabilised columns, jet grouted columns and vibro-columns) used for ground improvement. Although similar to piles they have two primary differences. They are often formed of a compacted fill rather than solid material and they are not directly load-bearing, post-construction. Despite these differences, reference will be made to studies of the impact of stiffening columns, where applicable to our understanding of piling impacts.

4.3 Types of piles

It is possible to classify piles based on a number of attributes although from an archaeological point of view the most useful classifications relate to the means of insertion and the load bearing properties. The different properties and construction techniques associated with these piles lead to different potential impacts on deposits during insertion.

Piles are inserted as either displacement piles or replacement piles. Displacement piles are inserted into the ground displacing sediment, resulting in the compression of deposits around the pile with increased lateral stresses extending beyond the pile. Replacement piles are inserted into holes from which the sediment has been extracted, this shouldn't result in lateral stresses being imposed during insertion of the pile although this will depend on the method by which the sediment is removed.

The load bearing capacity of piles results in stress transfer to the surrounding soil. Based on how piles transfer these stresses to the ground they are classified as friction piles or end bearing piles. Friction piles transfer their load to the ground through friction acting between the pile and the soil, while end bearing piles are supported by the strength of the deposits beneath them.

4.4 Displacement piles

During the insertion of displacement piles displacement is primarily lateral, although vertical displacement (compaction below the pile or ground heave) can occur in some cases.

The potential impacts on buried archaeological remains of displacement piles include compaction of deposits, dynamic and static stress, drag-down of sediment and artefacts, distortion of deposits, creation of water pathways, fracturing and cracking of artefacts, and alterations to the soil chemistry and biology from the introduction of new materials, changes to water flow, oxygen levels, pH and soil redox.

Types of displacement piles include:

- Driven piles - precast concrete, closed or hollow steel tubes, steel H-sectioned, driven cast-in-place and timber,
- Rotary auger displacement piles,
- Screw piles.

4.5 Replacement piles

Replacement piles are inserted into a hole in the ground that has been made for them. A temporary or permanent metal casing can be used to supports the pile hole during construction. This stops the migration of concrete into the surrounding soil or voids in the soil as it is pumped in. Permanent casings can also stop the pile concrete interacting with the deposits the pile passes through.

Replacement piles can be undertaken with a rotary cutting head attached to the auger. This enables the pile to pass through buried obstacles, such as former foundations or buried structures.

Types of replacement piles include:

- Open hole auger piles
- Continuous flight auger
- Odex piles (overburden drilling eccentric)
- Plunge piles or columns

4.6 Mini piles

Mini piles, also called micro piles, are small-diameter piles that can be used where lower load-bearing capacity is required or where access is limited. Mini piles have the same potential impacts as larger piles, but little published research has been undertaken on the impact of mini piles. It is therefore uncertain if the impact of mini piles is proportionate to their size relative to large piles.

4.7 Pile loading-bearing characteristics

During pile installation and use, forces will be applied to the surrounding deposits and structures. The peak forces will be applied during installation, particularly for displacement piles, but forces are continually applied post-installation through the weight of the pile and the structure it supports. The impact of forces during pile installation is discussed below in Section 5 (physical impacts) but a brief summary of the long-term forces is worth considering.

The load of the pile and the structure above applies stresses to the surrounding deposits that leads to strain developing in the deposits. The forces that are applied to the surrounding deposits are dependent on whether they are end bearing or friction piles.

End bearing piles apply the load acting on them to the base of the pile. Loading post-installation is limited to the pile base.

Friction piles use the friction between the pile and the deposits it passes through to hold the pile in place. Loading post-installation is on the sides and base of the pile.

The nature of the stresses that occur between completed piles and the sediment around them depends on how the pile bears its load. Drag load is the compressive force on a pile caused by the settling of the sediment around, while the down-drag is the settlement of the pile due to the drag load. End-bearing piles have high drag load and low down-drag, while friction piles have low drag load and high down-drag.

Different types of soils have different load bearing capacities. Pile capacity in weak breakable sands (for example calcareous sands) is generally accepted to be lower than in strong sands (for example quartz). This is thought to be related to particle crushing and the migration of finer particles produced by crushing. This was investigated by Zhang *et al* (2013), who identified that crushable (for example calcareous) soils have lower bearing capacity than conventional theory because grain crushing helps to accommodate the new volumetric intrusion of the pile. The 'crushing influenced zone' was found to extend for approximately half the pile radius from the shaft.

There are differences in the load-bearing capacity of different types of piles. Tolooiyan and Gavin (2013) noted that the recommended bearing capacity of bored and cast *in situ* piles is typically assumed to be 50 per cent of those for driven piles. This was investigated by Brown and Powell (2012), who compared the load-bearing capacities of CFA and driven piles in field trials. The trials showed that in London Clay, driven piles had a better loading capacity than CFA piles, with CFA piles displaying only 70 per cent of the capacity of driven piles for a given cross section of pile. These differences have archaeological implications, as significantly different total areas of pile cross section may be required depending on the type of pile used.

In general, the loading of piles on the adjacent soil can be summarised as:

- end bearing displacement piles have high loading during installation but low loading post-installation, except at the base.
- end bearing replacement piles have low loading during installation and low loading post-installation, except at the base.
- friction displacement piles have high loading during and post-construction.
- friction replacement piles have low loading during construction but high loading post-construction.

4.8 Pile structures

Pile can be used in different arrangements to form different types of structures below ground.

Pile layouts can be based on a regular or an irregular grid and are usually tied together at the surface by ground beams or pile caps. The latter can be supported by a single pile or groups of piles.

Pile layout can be designed to avoid archaeological remains, thereby enabling them to be preserved *in situ*, although this may require additional or larger piles to support the above-ground structure and larger ground beams to span areas without piles.

A specific form of pile structure is a pile wall, such as a continuous line of piles that can form the outer wall of a basement. This is usually constructed of either interlocking steel sheet displacement piles or augered concrete replacement piles. The augered concrete replacement piles overlap with each other to create a continuous concrete wall. When a pile wall is created around a basement, the pile wall is constructed first and then the basement is excavated within the area enclosed by the wall.

A specific impact related to pile walls is the potential to create a barrier or underground dam to groundwater flow. The archaeological implications of this are that groundwater levels may rise in some areas and become lower in others. In London, major changes are known to have occurred to the water table; historically, this has lowered due to water pumping, but has recently been rising by around 1m per year in some areas as impermeable basements, cut into the impermeable London clay, impede groundwater flow. Such changes will have significant impacts on chemical and biological activity in soils and the preservation of archaeological remains.

The effects of pile walls are complex; in one case (Richards *et al* 2007), the impact of a pile wall on soil pore water pressure was examined. This identified that, following excavation in front of the wall soil pore, water pressure reduced dramatically on both sides of the wall and that, over the long term, the soil pore water pressures were consistent with the wall acting as a drain rather than as an impermeable barrier.

4.9 Re-use of piles

The re-use of old piles has received considerable interest in recent years. Tamura *et al* (2012) noted that when brownfield sites are redeveloped there can be advantages in re-using old piles, through reduced costs and shortened construction periods. Re-use of existing foundations reduces construction impacts on archaeology, has environmental and sustainability advantages and reduces the problems of ground congestion due to existing below-ground structures, services, tunnels, basements and old foundations.

From an engineering viewpoint, there are two main problems in re-using old piles: a lack of detailed knowledge on the condition and load capacity of old piles and potential limitations on the design and structure of the new building (Tamura *et al* 2012).

These problems led to the development of the Re-Use of Foundations for Urban Sites (RuFUS) Project. The RuFUS handbook (Butcher *et al* 2006) provides guidance on the re-use of foundations now and in the future. Although the RuFUS study was not undertaken with archaeological remains in mind, it identified that the increasing speed of redevelopment and more substantial foundations have the potential to have a greater impact on buried archaeological remains.

Other assessment tools have been developed to assess the potential re-use of existing foundations. Laefer and Farrell (2014) undertook a review of the three common assessment tools. The review identified that the SPeAR (Sustainable Project Appraisal Routine) method was good for a preliminary assessment approach. The RuFUS flowchart provided a staged approach to conclude whether re-use, re-use with supplemental foundations or new foundations are appropriate, but does not clearly define the site-specific constraints. The CIRIA (Construction Industry Research and Information Association) five-point method, which is based on a modified version of the RuFUS flowchart, determines the applicability of foundation re-use to a particular project.

4.10 Evidence for pile impacts

Evidence and data on the impacts or potential impacts of piling on archaeological remains are derived mainly from engineering sources, as engineers have studied the interaction of piles and soils in much greater detail than archaeologists. However, engineers are concerned mainly with the stability and load-bearing potential of the pile and how this is affected by the soil, not with the impact of the pile on archaeological remains within the soil. Engineering studies have therefore concentrated on the physical impact of piling on soils and to a lesser extent on hydrological impacts. There have, however, been a few collaborative studies between engineers and archaeologists on the impact of piling, such as Hird *et al* (2006) and Williams and Butcher (2006).

There are three main sources of potential evidence for the impact of piles on archaeology: field data, laboratory tests and computer modelling.

Field data

Field data can provide good data on real world conditions but data collection in the field can be costly and accessibility can be difficult, particularly below-ground access to monitor and observe the impacts of piling during construction. However, field observation can record the long-term impacts of piling through observations of old piles when sites are redeveloped. Also, real world conditions can limit the potential for repeatability, while variation between natural ground conditions can make the applicability of the results to different sites difficult to assess.

Laboratory testing

The use of test rigs in laboratories can provide good data as tests can be controllable, repeatable and comparable. However, there can be boundary effects caused by the limits of the testing chamber, scale effects due to the size of the models and the sediment used, and an idealised world cannot completely model reality and its complications.

Computer modelling

As with laboratory tests, computer modelling can provide good, controllable, repeatable and comparable data. However, any computer model simplifies reality and there can be issues with modelling surface conditions.

Laboratory tests and computer modelling have mostly focused on the physical or hydrological interactions between piles and the ground, while field observations have been able to look at a wider range of impacts with observations also made on chemical impacts.

4.11 Impact type and duration

The potential impacts of piling on buried archaeological remains fall into four basic groups: physical, hydrological, chemical and biological. In reality, these are all interrelated; for example, the physical compaction of soils can change soil moisture which can in turn lead to changes in chemical and biological processes. The presence of a large concrete body can impact on soil chemistry, resulting in the precipitation of minerals that can alter soil porosity and soil waterflow. The impacts of piling can be temporary or long term.

Temporary impacts are those that take place during or immediately after pile installation, prior to a new equilibrium being reached in soil conditions. Such impacts include the loss of deposits, stress, vibrations, increased soil pore water pressure, concrete migration and chemical reaction between the pile and the adjacent deposit during concrete setting.

Long-term impacts are those that continue and are ongoing for the lifetime of the pile. These include loss of deposit, ground loading, changes to hydrological flow paths, changes to local soil chemistry through the introduction of new materials and changes to soil properties that may impact on biological activity. The effect of concrete decay on soils chemistry could be a long term impact that increases with time as the decay products are produced, however, studies to confirm or counter this are lacking.

In addition to the impacts in the immediate vicinity of the piles, there can be impacts on the wider buried archaeological landscape. For the large buried archaeological landscapes, such as urban centres, the development of individual plots can degrade the wider buried landscape and can separate and isolate the formerly continuous remains into a patchwork of isolated fragments.

In recent years, there has been a growing interest in the potential value of the long-term monitoring of impacts of development. Monitoring has the potential to determine whether impacts have occurred and how great they have been. If post-development impacts are identified, however, it may not be possible to rectify them in many cases, eg. a new building cannot be demolished to enable excavation. Monitoring may therefore be more useful to collect data that can be used to assess which impacts result from construction and which mitigation methods work in the long term. These lessons can then be applied to other sites.

Attempting to predict the impact of construction activities is not easy, but in the Netherlands concern over sensitivity of archaeological deposits to compression led the Dutch to produce a predictive map of the compression sensitivity of the Netherlands (De Lange *et al* 2012). The compressibility of sediment is dependent on its properties, including lithology, grain size and previous loading history; this work enabled a 3D model to be produced which provides a tool with which to asses potential compression impacts of future developments on archaeological remains.

Chang *et al* (2010) used 3D modelling to evaluate the relative effects of pile-loading, as opposed to construction using pile-casing methods, on Taiwan's Tapei Rapid Transit underground railway. The 3D model showed that, where the pile foundations of two sub-surface tracks overlapped, with the piles driven between the tunnels of each line, the effects of construction using pile-loading methods were greater than those using casing methods (Chang *et al* 2010).

5 PHYSICAL IMPACTS

The most obvious physical impact on archaeological remains is the loss of a proportion of the site, which can also lead to the disconnection of features and loss of spatial coherence due to the distribution of piles across the site. This is the case with all types of piles.

There are other physical impacts, including displacement, deformation, compaction and crushing that relate to the type of pile used. The physical impacts will therefore be considered separately for displacement and replacement piles.

Physical impacts during piling occur due to the insertion of the pile and related activities, such as the movement of heavy vehicles and loads across the site. Studying the impact of pipeline construction, Shi *et al* (2014) identified that loading and compaction occurred over the whole working area, not just on the pipe route, and that flatter areas suffered greater disturbance from the movement patterns of heavy machinery and traffic routes than did hillier areas (Shi *et al* 2014).

5.1 Physical impact of displacement piles

Displacement piling does not remove material from the ground, but it does displace it and any archaeology on the vertical line of a pile will be effectively lost. The discussion below is mainly concerned with the impacts beyond the line of the pile and how they might affect any buried archaeological remains.

5.1.1. Stress, strain and vibrations – displacement piles

Whether applied by a hammer, jacking rig or vibro hammer, force is applied to a displacement pile when it is driven; this force applies stress to the soil that the pile is penetrating and results in the development of strain (deformation) within the sediment. The strain characteristics and the effects that they have on the sediments in the ground are dependent on the stress levels and the properties of sediment that make up the ground. Two concepts, shear strength and soil pore water pressure, are key to understanding the impact of the stresses applied to the soil when piles are driven through it.

Soil shear strength is a measure of the ability of soil to resist applied forces without failing. The forces applied during piling lead to increased shear stress and, when the shear strain in the soil exceeds shear strength, the soil fails and particles slide past each other. Shear strength is dependent on soil particle size and grading; well-graded soils contain a range of particle sizes and have greater strength than uniformly graded (single sized) soils.

Soil pore water pressure is a measure of the pressure of the water filling the voids between solid particles in a soil. Soil pore water pressure increases when a soil is under pressure and compaction. Increases in soil pore water pressure can lead to a decrease in shear strength (Shen *et al* 2005).

The basic forces that develop due to hammer-driving a displacement pile were investigated by Jardine *et al* (2013a and 2013b) in laboratory experiments:

- extreme stress and strain developed close to the pile during insertion
- stress in the sand increased as the pile tip approached and declined sharply as the tip passed deeper
- soil stress varied due to loading during the pile driving cycle, increasing during penetration and reducing between strokes
- radial stress after installation is at a maximum approximately 3 radii from the pile centre

As a pile tip passes there is a reduction in stress levels accompanied by a reversal in shearing direction, while particle breakage and rearrangement, which can occur in some soils, reduces stress and lowers resistance to pile penetration. Associated with the increase in stress caused by piling are increases in soil pore water pressure in moist or wet soils particularly clay Different soils will react differently to the loading associated with pile driving cohesive soils (clays) are generally considered to have greater resistance to cyclic loading than granular soils which may be liquefied under cyclic loading

Tan and Lan (2012) investigated the vibration effects of pile driving on structurally sensitive adjacent buildings and buried pipes. This was undertaken following reports of pile driving causing severe damage to buildings between 15m and 100m from the construction sites. The study recorded the effects of inserting concrete pile piles using a heavy press-in machine. They identified that ground vibration is attenuated by dampening, with a reduction in vibrations as distance from the pile increases. During pile driving, vibration waves travelling across soil boundaries reflect and refract which can cause interference and amplification of vibration waves. Lateral ground movements in pipes were greater near the piles (9-13mm) and lower (3mm) in pipes distant from the piles. Further piles had little effect due to the blocking effect of the earlier piles. Vertical ground movements showed a similar pattern, with cooling towers that sat on pre-existing piles showing small settlements (2-4mm).

In order to investigate the impact of pile driving on ground vibration, Khoubai and Ahmadi (2014) modelled the effects. Below-ground soil particle velocity increased as the pile end approached the measuring point and decreased as it moved away. For points close to the pile, particle velocity was larger at greater depths. The level of vibrations were dependent on pile, hammer and soil properties; an increase in pile diameter, impact force and soil–pile friction was found to increase particle velocity.

Laboratory testing by Vogelsang *et al* (2017) investigated the effect on stress of monotonic or cyclic penetration during vibration piling. Monotonic loading led to higher stress around the pile, while cyclic penetration reduced stress. The beneficial effect of cyclic loading regarding driving is most pronounced in medium dense sand in combination with large pile displacement amplitudes.

The California Department of Transportation monitored the potential impact of vibrations on a buried prehistoric site in order to address concerns regarding the possible impact of vibration-induced settlement altering stratigraphy (Brandenberg *et al* 2009). In layered soil profiles, waves of different wavelength mobilise different soil layers, potentially mixing different stratigraphic units. Geophones and accelerometers were used to measure vibrations caused by driving steel pile during bridge construction. Previous studies have identified that vibrations from pile driving can induce shear strain in soil which can cause granular soil particles to slip past one another, thereby inducing settlement. Previous studies have recorded settlements of between 8-250mm. The test results showed that, in the conditions on this site, small-scale settlement could occur at distances of up to 40m from pile driving and was higher closer to the piles. Settlement reduced rapidly with distance from the pile and, at 100m distance, ground strains were such that the probability of settlement was small. In this case, settlement varied smoothly from the point of piling.

The different techniques used to insert displacement piles can result in different effects on the soil. In the case of vibratory piles, the stresses from vibratory piles can be greater than those from hammer driven piles. The increase in soil pore water pressure for jacked piles is less than for driven piles (Liu *et al* 2012).

The forces required to insert piles are related to the type of pile and pile design. Gorasia *et al* (2014) investigated the design of pressed in sheet piles in London Clay. The study compared plain, shoed and horizontally ribbed piles to assess differences in the required driving forces. Shoed piles (3mm and 5mm) were shown to require greater force to overcome initial base resistance, but this quickly reduced with a 30-40 per cent reduction in driving force as the pile penetrated. This was probably due to a reduction in the friction between the faces of the pile and the soil. The ribbed piles also showed higher initial forces, but this also soon reduced and saw a 15-20 per cent reduction in required driving force. The design of the pile and the resulting reduction in friction can significantly reduce the force that is needed to insert them and also the potential impact on the soil.

5.1.2. Soil displacement - displacement piles

Soil displacement from pile insertion can occur in a number of directions. Vertical displacement can occur downwards as soil is pushed down by the tip of the pile or upwards due to ground heave. Horizontal displacement can result as soil is pushed away from the pile as it passes through the soil. In addition, displacement can result in drag-down of material next to the pile which can be observed as downward deformation of deposits next to the pile. The extent of soil displacement is highly variable, depending on the type of pile and the character of the soil it is passing through.

Soil displacement is often most easily observed through the deformation of soil layers and this is the piling impact that has most often been observed by archaeologists. There have been a number of recent studies on soil displacement due to displacement piling.

Ni *et al* (2010) observed that displacement contours plotted for soil displacement in piles driven through clay in a laboratory test rig showed general agreement with theoretical predictions. They also observed that soil heave was reduced adjacent to the pile, probably as a result of friction causing drag-down.

Laboratory based experiments on the impact of driven displacement piles in sand identified that radial displacement of sand crushed beneath the pile led to the formation of concentric zones with successively lower proportions of crushed sand (Yang *et al* 2010).

The formation of a soil cone has been observed when driving a flat-ended pile. Ni *et al* (2010) observed this in clay during laboratory, while Paniagua *et al* (2013) have observed this in silt. The soil within the cone or 'contact bulb' (Paniagua *et al* 2013) would be pushed down for a considerable depth, with material transferred down the stratigraphic sequence.

Open-ended concrete or tubular steel piles are driven into the ground as displacement piles, but as they are open-ended, the soil displaced by their driving should be much less than for a similar diameter closed-ended pile. However, plugging can occur in open-ended piles and, depending on how complete the plugging is, this can effectively convert them to closed-ended piles.

Studies of open-ended piles have been undertaken in Asia, where they are commonly used. Liu *et al* (2012) examined the effects of soil plugging in jacked open-ended piles. Plugging occurs when the sediment in the pipe forms a blockage that stops the passage of further sediment up the hollow centre of the pile. The study identified that open-ended piles can either fully core the sediment or partially or fully plug with sediment. The test cases showed that plugging was dependent on the deposits/stratigraphy being passed through and the roughness of the pile pipe which depended on its material, concrete or steel. The plugged soil became highly compacted and was displaced down with the pile.

Xu *et al* (2006) studied displacement and stresses in the vicinity of steel pile pipe installation in soft clay, driven with a vibratory driver. Lateral displacements were found to be lower in coarse grain sediments and higher in clay. They also determined that models for closed end piles can be used to calculate displacements if a closed-end pile of radius equivalent to the pile's tip area is used.

Adjacent buried structures, such as old piles, can interact with new piles as they are inserted. Such interactions can result in additional ground movements, both horizontally and vertically. For new jacked piles, the primary effect on existing adjacent piles was increased settlement, although this related primarily to the force exerted by the weight of the jacking rig on existing piles. In the cases studied, this resulted in ground settlements of around 6mm in clay and 15mm in sand and settlement of up to around 4mm for existing piles adjacent to the rig. Bryson *et al* (2010) identified that existing structures had a stiffening effect on the soil, thereby reducing lateral ground movement, although in this case the new piles were augered replacement piles.

Auger displacement piles are common across Europe but there are few reported studies of their use in Britain. These piles are screwed into the ground and displace soil laterally, but do not generate arisings at the surface despite the auger head. Hird *et al* (2011) undertook laboratory tests with artificial soil to investigate the effects of auger displacement piles. They identified that soil was transported upwards on the flights away from the tip and that displacement around an auger depends on the rotation speed of the auger itself and the extent to which the flights carry soil upwards. The displacement around the rotary displacement auger was observed to extend over an area of around four to six times the pile radius.

Screw piles have been used since the 19th century, but have been used mainly in marine contexts in Britain. Recently, they have been used on land as an alternative, potentially less destructive, pile in archaeologically-sensitive areas but no recent studies were identified in the literature. Screw piles do not produce spoil, are easy to remove and should have minimal impact beyond the pile, resulting in negligible disturbance. Different designs of screw pile are used in different soil conditions.

5.1.3. Soil deformation and smearing - displacement piles

Soil deformation and smearing are specific soil displacements that can be observed visually. Drag-down is often observed as deformation in layers adjacent to the pile, while smearing is observed as a thin mixed layer of material adjacent to the pile incorporating material from layers above. Engineering studies have identified that the severity of smearing increases with decreasing clay layer thickness.

Ni *et al* (2010) undertook laboratory experiments to investigate the impact of flat-tipped pile penetration in clay; these identified that friction between the soil and the pile resulted in the soil being dragged down close to the shaft.

A study of three square-sectioned driven piles (Huisman 2012) assessed the impact of piling on buried archaeological deposits based on field observation. Visible effects were soil drag-down and disturbance of structure. Soil micromophology was used to examine soil layers for disturbance associated with piling. This identified very limited disturbance in clay and peat layers, where the disturbed zone was limited to an area within 7cm of the pile and often much less. However, in a sand layer disturbance could be identified up to 1.5m from the pile although this disturbance was small scale draw-down and microtechtonic features. These disturbances are much less than have been recorded elsewhere, but the differences in the sand and clay and peat layers demonstrates the importance of the type of deposit being piled through.

5.1.4. Soil compaction - displacement piles

During pile driving, the soil being penetrated can be compacted. The level of compaction will be determined by the properties of the soil. Cohesive and granular soils will react differently while deposits with uniform particle size are less compressible than deposits with variable particle sizes. Key factors in soil compressibility are its soil water content and porosity. As compressive forces are applied to soil, both soil water and porosity can be reduced as the soil particles are forced together, enabling the deposit to compress. One result is increased soil pore water pressure.

Evidence for the processes that may contribute to compaction was provided by Huisman *et al* (2011), who used soil micrmorphology to observe the impact of driven piles on soil structure. This identified a number of effects in clay soils, including pore closure, tilting of clay rich parts (possibly indicating they functioned as slide-planes) and fragmentation of charcoal. In sand, spherical voids were observed, probably caused by soil liquefaction during piling and redistribution of the sand around gas bubbles.

Ni *et al* (2010) compared surface heave with the pile volume during pile driving in clay in a test rig and identified an overall reduction of soil volume of 0.3-0.4 per cent in the model.

Yang *et al* (2010) identified that sand penetrated by driven piles in laboratory experiments formed three concentric zones around the pile due to radial displacement of the sand and that the zones had different properties. The first zone was highly over-consolidated and compacted by up to 15 per cent. The thickness of this zone appeared to relate to particle size and was approximately 2.4 times the mean particle diameter size on the sides and up to four times the mean particle diameter size beneath the pile tip. The outer zones did not show the same compaction.

Post-piling, soil compaction and settling is related to the dissipation of excess water pressure while, with auger displacement piles, the soil adjacent to the pile was consolidated. This is likely to be due to compaction caused by the compression of the soil during.

5.1.5. Soil crushing - displacement piles

The extent of crushing experienced by a soil during pile driving is dependent on the nature of the particles that make up the soil. Stress due to piling results in the development of strain within the particles that make up the ground and it is the particles' resistance to strain that determines whether crushing takes place. Some materials, for example weak calcareous sands, are more prone to damage from crushing than strong silica sands (Lobo-Guerrero and Vallejo 2005).

Mathematical modelling of the behaviour of sand under stress suggests that particles are only crushed or broken beneath the pile, not adjacent to it (Simonini 1996). Laboratory experiments on the impact of driven displacement piles in sand appear to confirm this, with the sand below the pile crushed by intense compression before being displaced laterally (Yang *et al* 2012). The radial displacement of crushed sand as the pile was driven led to the development of concentric zones around the pile shaft, with different degrees of particle crushing (Yang *et al* 2012). Zone One had a different colour, possibly due to particle surface abrasion, and adhered to the pile shaft. This zone varied in thickness from approximately 2.4 times mean particle diameter up to four times mean particle diameter beneath the tip. Zone Two was thicker, with 6-8 per cent broken fine sand. Zone Three, the outer zone, had a lower proportion of fine broken sand.

Zhang *et al* (2013) suggested that the crushing influenced zone extends for approximately 0.5 times the pile radius from the shaft.

A study by Ngan-Tillard *et al* (2015) assessed the impact of mechanical loading on charred organic matter, wood, hazelnut shells and seeds. The tests included individual particle strength tests and one-dimensional compression tests on charcoal assemblages and charcoal embedded in a sand matrix, using an oedometer. For charcoal assemblages without a matrix all tests identified damage, splitting and loading at stresses below 320kPa. This corresponds to stresses applied beneath the pile foundation level of a high rise building. The samples of charred wood in sand matrix showed a very different response with no damage observed except when the charcoal formed a layer separated from the sand.

In addition to damage to buried artefacts, the stresses applied by piling can lead to crushing or fragmentation of archaeological deposits. Two photographs in the Museum of London show these effects. In one case, piles had passed through Roman mosaic floors without apparently disturbing the tesserae beyond the footprint of the piles. In the second case, extensive damage could be seen around a pile sleeve that had passed through a thin beaten earth floor. The floor had disintegrated for a radius of about 0.3m around the pile sleeve. A comparison of the two floors, mosaic and beaten earth, may help to explain the different results. Both floors are thin and hard, but the beaten earth floor is in one continuous layer, while the mosaic is made up of numerous small pieces that are held together with mortar, which often degrades over time. When the piles pass through the beaten earth floor, the impacts spread out through the continuous layer. With the mosaic floor, the mortar must have failed and the mosaic tiles stayed *in situ* just beyond the footprint of the pile.

5.1.6. Grout migration - displacement piles

Auger displacement piles are the only displacement piles that use liquid concrete and so have the potential to produce grout migration. No cases related to the study of grout migration were identified in the literature review, so this remains an area of uncertainty. The migration of bentonite could provide an analogy but no record of cases were reported in the literature review.

5.1.7. Related engineering structures stiffening columns

Stiffening columns are used as a means of ground improvement and to improve the load bearing properties. As noted previously, these do have some similarities to piles in their methods of insertion that can make comparison useful.

McCabe *et al* (2009) reviewed the literature on the impacts of stone columns in soft cohesive soils. This identified that:

- ground heave and excess soil pore water pressure with long dissipation times can result, particularly if excess stone is used, to create an enlarged base to the stone column
- permanent lateral stress increases should be expected from stone columns similar to those from pile driving. Studies of stone columns showed that maximum lateral stress at installation was at its maximum at 4-5 pile diameters from the pile and minimal at 9 pile diameters from the pile. Lower values closer to the column were attributed to remoulding of the clay by the poker and excitation caused by vibrations
- soil pore water pressure is at a maximum as the poker tip passes a level
- soil pore water pressure is cumulative as successive columns are installed, dependent on column proximity and the duration between installations
- excess soil pore water pressure dissipates much faster in stone columns than piles as the columns provide a drainage benefit

Studies by Castro and Sagaseta (2012) and Juneja and Mir (2012) examined the effect of stone and sand columns on soil pore water pressure. Castro and Sageseta (2012) identified that excess soil pore pressure was much lower in their study than theoretical models predicted, which they suggested was probably due to the presence of sand layers increasing permeability and clay fracturing. Juneja and Mir (2012) identified that initial drilling created smear zones adjacent to the sand pile and that the smear zones impeded water flow into the sand leading to a slower dissipation of excess soil pore water pressure.

5.1.8. Physical impacts of displacement piles - summary

A range of physical impacts can result from the use of displacement piles:

- displacement piles cause static and dynamic stresses and strains
- long-term loading of soil
- compression and compaction of deposits
- vertical and horizontal displacement of sediment and any incorporated inclusions
- soil cones or bulbs can be pushed down by the pile
- drag-down of sediments around pile leading to distortion of soil layers
- crushing of sediment particles and development of crush zones
- crushing can also affect inclusions within a sediment and cause cracking of corrosion crusts
- mixing of layers from screw piling

5.2 Physical impact of replacement piles

Replacement piles due to their different insertion method have very different physical impacts on the ground being penetrated. As replacement piles are inserted, often as liquid concrete, into a pre-prepared hole it is the excavation of the hole, often by augering, that has the greatest physical impact.

The excavation of the pile hole removes material and, although artefacts can be recovered from the slurry produced by augering, these are unstratified and out of context.

5.2.1. Stress, strain and vibrations – replacement piles

Replacement piles are inserted into prepared holes, which are usually made by an auger. The loading, vibration and ground stress effects produced by an auger are much less than those induced during the driving of displacement piles (Allison and Higuchi pers. comm.).

With replacement piles, the changes to ground loading are primarily derived from the removal of material. This reduces lateral loading in the ground adjacent to the pile hole. In order to reduce the risk of collapse, bentonite slurry may be used to fill the hole as it is excavated and provide support to the sides, thus maintaining lateral pressure and loading. This is usually required with a granular soil, but may not be needed for cohesive soils.

There is less published research by engineers on the stress and vibrations caused by replacement piles. This is probably due to the perception of replacement piles having lower impact than displacement piles.

Two studies have investigated the stress and soil pore water pressures associated with the construction of pile walls. The stresses on an overlapping drilled shaft pile wall and existing adjacent structures were investigated by Bryson *et al* (2010). Measurements were made of lateral deformation between the pile wall and an adjacent structure and away from the pile wall into open ground. Lateral movements between the wall and the adjacent structure were lower than those in open ground. There are two conclusions from this: drilling the shaft for the pile wall was causing stress in the surrounding deposits and the existing structure had a stiffening effect on the soil. Richards *et al* (2007) studied soil pore water pressure following excavation in front of a bored pile wall. Soil pore water pressure was monitored and found to have reduced dramatically on both sides of the wall. This suggested that the pile wall was acting as a drain, post-construction, and that the change in the soil pore water pressure did not reflect any changes during installation.

5.2.2. Soil displacement - replacement piles

Huisman's 2012 review of pile impacts discussed anecdotal evidence from foundation engineers. This suggests that replacement piles may have a greater effect than is generally believed (Husiman 2012). The use of a pre-placed casing, with the soil removed from inside and concrete pumped in, would appear to reduce the risk of ground displacement, but groundwater levels are often lowered to aid this and this can cause mixing and disturbance of deposits at the pile base due to water flow.

The stresses induced by the construction of an overlapping drilled shaft pile wall caused lateral ground displacements (Bryson *et al* 2010), although they were not large, between 10mm and 17mm. The maximum displacement was at a depth of around 10m.

5.2.3. Soil deformation and smearing - replacement piles

The augering of displacement piles shouldn't lead to deformations such as drag-down, if undertaken correctly. Laboratory test modelling demonstrated that deformations around CFA piles were relatively small, compared to the deformations around driven displacement piles (Hird *et al* 2006). The tests did not involve the use of casings and no other studies were identified where the impact of casings was recorded. It is not known if the use of casing would affect the development of deformation or smearing. If a casing tube was pushed in advance of an auger, this could act in a similar manner to a hollow displacement pile.

Deformations around replacement piles are generally perceived as being of minor significance, but anecdotal evidence from foundation engineers suggest the impact may be greater than is believed. This evidence suggests that augering for replacement piles may result in damage to the surrounding deposits through drag from the auger, particularly when obstacles such as stones are encountered (Huisman 2012). Similar anecdotal suggestions have been made that the auger head could get stuck in large buried timbers, spinning them around and churning up the surrounding deposits. Casings for augered piles have dragged timbers down and created voids which collapsed when water entered them (Nixon 1998).

5.2.4. Soil compaction and crushing - replacement piles

No studies were identified which researched compaction or crushing caused by replacement piling. The impact of replacement piling techniques is therefore uncertain.

5.2.5. Grout migration and heating during setting – replacement piles

Replacement piling normally uses liquid concrete ('grout') much more frequently than displacement piling and there is therefore a much higher potential risk of grout migration. With CFA piles, a hole is bored by an auger and, as it is withdrawn, concrete is pumped in to form the pile. The rate of pumping needs to be matched to the withdrawal of the auger. If too little concrete is pumped, voids can be left; if too much is pumped, this can migrate or dissipate into surrounding voids or the soil.

No observations or studies were identified that had considered the potential physical impact of the heating of adjacent soil during concrete curing, which is an exothermic reaction. How this could influence soil moisture levels, chemical and biological activity is therefore unknown.

5.2.6. Physical impacts of replacement piles – summary

A range of physical impacts can result from the use of displacement piles:

- static and dynamic stresses are significantly reduced in comparison to non-displacement piles
- long-term loading of soil
- horizontal displacement of sediment and any incorporated inclusions should be minor compared to displacement piles
- churning of deposits possible, if debris trapped in auger head
- smearing possible in sediments around the edge of the auger or casing
- potential voids created, if the auger is incorrectly used during installation - this may lead to soil movements and mixing
- liquid concrete or grout may migrate into voids or dissipate into soils, particularly granular soils

5.3 Summary of physical impacts

5.3.1. Factors influencing physical impacts

The main factors that influence the impact of piling on buried archaeological remains are the type of pile used and the properties of the deposits through which the pile passes.

The potential impacts of different types of piles have been reviewed above and this has identified that displacement and replacement piles can have very different effects.

The properties of the deposits being piled through that can influence the physical impacts of piling are:

Soil type – cohesive (clays) or granular (sands) soils have very different reactions under stress. Cohesive soils are less permeable and compressibility depends on water content, granular soils more permeable, stronger and less compressible depending on packing and grading.

Soil moisture – and, in particular, soil pore water pressure which when increased can weaken cohesive soils and lead to failure

Layering in soil – layering in soil can result in different properties with associated different responses under stress. In addition, the transfer of stress and vibration can be influenced by layering, which can lead to different impacts.

Poulos (2005b) reviewed of impact of geological conditions on piling from the perspective of engineering. This viewed geological stratification and the water table as imperfections in the real world and considered their effects on piling. Archaeologically, the opposite is true - it is the impact of piles on an imperfect world that is of interest. The main geological imperfections identified as being of concern were:

- clay seams below the pile toe
- compressible layers below the pile founding level
- soil layers of uneven thickness
- differences in founding conditions
- pile or pile group founded on a large boulder

From the point of view of engineering, the first two can reduce load capacity. The latter three, of greater concern, can result in uneven settlement and induce bending moments and shears in piles. All five imperfections identified could result in increased loads and stresses on the soil during piling and could results in impacts on archaeological remains.

5.3.2. Intensity of impact

A summary of the potential intensity of physical impact for displacement and replacement piles is provided below. This considers the type of pile and its method of insertion. Based on the literature review, a qualitative assessment has been made with impact levels assigned to one of three categories: high, medium or low. It should be noted that this is a provisional assessment and is likely to be modified by further research.

Pile type	**Displacement**					**Replacement**
Piling method	***Driven***	***Vibrated***	***Jacked***	***Auger displacement***	***Screw***	***CFA/auger***
Excavation	low	low	low	low	low	high
Displacement	high	high	high	high	medium	low
Compaction	high	high	high	high	medium	low
Drag-down	high	high	high	low	low	low
Vibration	high	high	?	low	low	low
Particle crushing	high	high	high	low	low	low
Construction loading	high	high	high	high	low	low
Foundation loading	high	high	high	high	high	high
Grout migration	nil	nil	nil	variable*	nil	variable*

* depending on soil type and correct auger operation

Table 3: Provisional summary of pile impact intensity by pile type

6 HYDROLOGICAL IMPACTS

The hydrological impacts of piling can be short term, acting during the duration of piling activities, or long term, acting post-piling.

6.1 Short term hydrological impacts

6.1.1. Soil pore water pressure

Soil pore water pressure can rise during displacement pile driving, due to the stresses on and compaction of the soil. Increases in soil pore water pressure can reduce the shear strength of a soil (Pestana *et al* 2002 and Shen *et al* 2005). The relationship between soil pore water pressure shear stress in the ground is noted above, in Section 5.1.1.

Hwang *et al* (2001) summarised the observed stress in ground deposits and soil pore water pressure during the driving of displacement piles, it was identified that, at a distance of three times pile diameters from the pile centre:

- water pressure began to rise when the pile tip reached between four to seven pile diameters above the measuring point and reached a maximum value when the pile tip passed four pile diameters below the measuring point.
- maximum excess pore water pressure build up decreased rapidly with an increase in distance from the pile.
- excess pore water pressure declined to stable conditions rapidly in a granular soil, whereas in a cohesive soil layer it required much longer.
- If excess pore water pressure exceeds effective overburden pressure, ground heave would be expected.

The method of pile driving can have an impact on soil pore water pressure. The applied ground stress has less impact on pore water pressure and increases in pore water pressure are lower for jacked pikes than hammer driven piles (Liu *et al* 2012).

Less research has been undertaken on the impact of replacement piles on pore water pressure, although the lesser loading and reduced stresses of replacement piles should result in smaller changes in soil pore water pressure. One case where soil pore water pressure was measured in association with replacement piles, was on a bored pile wall (Richards *et al* 2007). In this case, following excavation to one side of the wall soil pore water pressure was found to have reduced dramatically on both sides of the wall. This was interpreted as being consistent with the wall acting as a drain rather than as a barrier. This is an atypical case, but it does show the complexity of outcomes that can result from piling.

In general, short-term increases in soil pore water pressure would not be expected to have major impacts on archaeological remains in themselves. It is the associated soil displacements and ground heave that are likely to have greater consequences.

6.1.2. Temporary dewatering

During construction works, on-site groundwater levels can be lowered by the contractors to aid in their works. Huisman (2012) recorded this can be done to aid piling operations.

The primary risk from de-watering relates to the loss of waterlogged anoxic conditions. This will lead to an increase in biological activity, as more oxygen is available to biological organisms. This can then lead to rapid degradation of buried organic archaeological remains. Following construction, the re-watering of the site post-construction works should alleviate the problem by re-establishing waterlogged conditions. However, it is only when anoxic conditions are re-established that the degradation of organic remains will, in theory, return to the rate prior to construction works.

6.2 Long term hydrological impacts

The primary long-term hydrological impacts on the *in situ* preservation of buried archaeological remains relate to changes to water-table levels, drying out and changes to water oxygen levels.

6.2.1. Changes to water table levels and drying out

The main long-term risk to preservation relates to changes to the water table. While this is often focused on the de-watering of organic rich deposits, this is not the only risk. In all burial environments, corrosion products will form on the surface of materials such as metal, thereby creating a corrosion crust. This will provide a partial barrier that can slow down and inhibit further corrosion. Any changes in the burial environment that change soil chemistry will enable the reactivation of the chemical processes that lead to corrosion, possibly creating new corrosion products. This can be detrimental to artefact preservation.

Piling can impact on water-table levels by creating new groundwater flow paths. The creation of such flow paths can result in the lowering or raising of the groundwater level depending on local conditions. The creation of flow paths is primarily due to the puncturing of impermeable layers, usually cohesive soils. If the impermeable layer and the pile form a seal during and after construction this should stop water flow. Water flow is most likely to take place where smearing or drag-down has left a permeable skin of material, including granular material, around the pile. New flow paths can cause the ground water to lower, particularly in the presence of perched water tables, or to rise where the pile punctures an aquifer with excess water, which can cause water to flow up through a flow path.

The puncturing of impermeable layers can occur with both displacement and replacement piles.

For replacement piles, the penetration of impermeable layers will create a possible flow path when the hole for the pile is excavated. During piling, this is an open hole that creates a temporary flow path. Bentonite slurry can provide a barrier to restrict groundwater flow during excavation. After excavation of the pile hole, liquid concrete is pumped in and this should come into contact with any impermeable layer, assuming a casing is not used; however, it is uncertain how good the seal between the pile and impermeable layer will be.

The case of the bored pile wall acting as a drain, reported by Richards *et al* (2007), demonstrated the complex interplay between piling and groundwater flow that makes predicting the outcome very difficult.

6.2.2. Changes to water oxygen levels

The creation of water flow paths discussed above does not have to lead to dewatering to have an impact on archaeological deposits. If the flow path is created between anoxic ground water and oxygenated groundwater this could lead to an increase in oxygen levels in formerly anoxic deposits, thereby enabling increased biological activity. The direction of flow between different areas will depend on soil pore water pressures and the relative heights of the water table in each area. Although theoretically possible, no such scenarios were identified in the literature.

7 CHEMICAL IMPACTS

Buried objects interact chemically with their burial environment through soil water above, and groundwater below, the water table (Pollard 1998). Chemical activity in a soil is related to its pH, redox potential and the speciation of the soil solution.

Potential chemical impacts of piling come about due to two factors:

- the introduction of pile material
- changes to local environmental conditions that can cause a change in ongoing chemical processes or prompt the initiation of new processes

One factor that is fundamental is soil moisture levels; this is because water in the soil is the medium in which most soil chemical activity takes place.

7.1 The introduction of pile material

Whether displacement or replacement piles are used, piling involves the penetration of significant quantities of foreign material into the burial environment. Modern piles are mainly made from concrete or steel although wood is occasionally still used.

There are a few studies that have relevance to the potential interaction of piles and soils.

7.1.1. Steel piles

Previous studies have examined the interaction of steel piles and soil (Ohsaki, 1982, Wong and Law, 1999 and Romanoff, 1969) but more recent studies were not identified in the literature review. In general, these studies suggest that chemical interaction between steel piles and the surrounding soil is limited and slow-acting.

7.1.2. Concrete piles

The chemical interaction between soil and concrete piles will vary depending on soil chemical composition, water content, pH and redox.

Brueckner *et al* (2013) examined the chemical interactions between concrete piles and clay. They noted previous studies which showed that interaction between concrete piles and clay is due to calcium and hydroxyl ions in pore water. Conventional sulphate attack causes expansion and eventually cracking of the cement matrix and can cause the following soil changes:

- reduction of plasticity
- reduction in volume change

- flocculation (aggregation) of soil particles making them more friable
- increase in optimum water content allowing compaction under wetter conditions (soils dry out more rapidly)
- some increase in soil strength and stability

Other studies showed an initial (over seven days) increase in clay moisture content near the surface interface, although this decreased with time. A similar trend was seen in soil pH. Both effects appeared to be restricted to within about 25mm of the interface of the pile with the soil, In addition, increased concentrations of calcium ions have been observed within 75mm of the interface.

Bruecker *et al* (2012) undertook a more detailed study of thaumasite sulphate attack (TSA), which targets calcium silicate hydrates, the main binding agent in Portland Cement binders. TSA transforms the cement matrix into an uncohesive mass, from the surface inwards. During TSA attack, the following have been observed in surrounding soils:

- increase in moisture content towards the concrete
- increase in pH towards the concrete
- increase in calcium concentration towards the concrete
- water-soluble magnesium decreased closer to the concrete and had an inverse relationship with pH
- pyrite and indirect sulphide concentration decreased with increasing attack
- sulphates and total sulphur increased with increasing attack
- gypsum values were highest where there was partial attack
- pH value and magnesium increased and decreased respectively with increasing attack

Laboratory tests were used to test the concrete clay interfaces during which the following was observed:

- clay within 10mm of the surface was more friable
- within 10-15mm of the surface, moisture content increased, although this increase decreases with time
- pH increases towards the surface, but the zone effected and the level of increase decreased with time
- a relationship between moisture content and pH was not apparent
- the mineralogical composition of the reaction product changed close to the interface; this was due to old reaction product, next to the clay, degrading to gypsum
- the pH gradient continues in the reaction product up to the unattacked concrete

- changes to clay mineralogy due to TSA were not detected in the clay adjacent to the surface.

Williams *et al* (2008) attempted a study to assess the chemical impact of leaching from cast *in situ* piles. Borehole samples were collected prior to, and after, piling on a site in Winchester. Samples were tested for chemical characteristics, electrical conductivity and pH. The results did not demonstrate any significant changes or clear trends, but it was felt that this was due to the methodology being too coarse to identify any changes. In particular, it recommended that any future studies would have to undertake more detailed pre-piling characterisation of the geochemistry and groundwater conditions to allow for existing variability and would require *in situ* measurements during pile installation.

Huisman (2012) noted another archaeological observation of the chemical interaction between a concrete pile and soil; this observed the formation of pyrite in peat directly adjacent to driven concrete piles.

Due to the complexities of soil chemistry, it is difficult to generalise about soil and concrete chemical interactions. Much more research is needed in this area.

In addition to the direct reaction between the soil and piles, such process may cause changes to the local environmental conditions by altering the background soil chemistry.

7.2 Changes to environmental conditions

Changes to local environmental conditions can cause a change in ongoing chemical processes or prompt the initiation of new processes. The main environmental changes that are likely to alter chemical activity are:

- changes to soil moisture levels,
- changes to soil pH and redox potential,
- physical contamination or mixing of different deposits.

These factors are interrelated and could derive from the physical and hydrological impacts of piling. Changes to soil moisture levels could result from the drying out or wetting of deposits due to changes water flow and water table levels. Contamination or mixing of deposits could result from soil displacement and disturbance processes, such as drag-down and deposit fluidisation. Changes to pH and redox potential could result from both changes to water flow and physical contamination. Previously undisturbed archaeological deposits with stable soil chemistry will normally reach a condition with minimal or slow chemical activity. Any changes to the local environment could therefore initiate changes in the chemical activity. How such changes will operate will depend on the initial chemistry of the soil and on the nature of the changes. These changes could initiate chemical activity in the short or long term, but will normally reach a new stable condition with minimal or slow chemical activity - however, in the process, degradation of artefacts in the ground may have taken place.

8 BIOLOGICAL IMPACTS

The impact of construction on biological activity in the ground is currently poorly understood. The main concern with biological activity in the ground is its impact on organic remains. Hopkins (1998) identified a number of biological organisms that live in soil: bacteria, fungi, protists, viruses, animals and plants (roots), the actions of which can lead to the degradation of organic remains. Additionally, worms, insects and roots rework the soil mixing material which can lead to the blurring of the boundaries of archaeological contexts and the movement of artefacts.

The rate of decay of organic remains due to biological activity is determined by a range of factors. These were identified by Hopkins (1998) as:

Moisture	Water is required for biological activity; however, in waterlogged anoxic soils biological activity may cease due to an absence of oxygen
Oxygen	Required for biological processes, absence is usually due to waterlogging
Nutrients	Inorganic nutrients do not usually limit biological activity in soil, although nitrogen may
Temperature	At 0°C there is virtually no biological activity. Above this temperature, biological activity increases with rising temperature up to around 40°C
Clay content and physical accessibility	Biological matter encased in soil matter, particularly clays, is in part physically protected from microbial attack

One further factor that could be added is light. Certain biological processes are light sensitive, particularly with regard to plants, so any ground disturbance that increases light access to the soil could change biological activity.

The oxygen, nutrient and moisture levels in a soil are related to the chemical and hydrological properties of the soil, therefore any changes to the hydrological and chemical environment may change the nature and extent of biological activity. Ritz *et al* (2004) noted that the strategy of *in situ* preservation assumes that construction activities do not alter the degradation processes on a site, although soil disturbance is generally associated with an increase in biological activity (Ritz *et al* 2004; Hopkins 1998).

The engineering literature contains little on the impact of ground works associated with construction. Shi *et al* (2014), in their study of the impact of pipeline construction, noted that within the excavated area there was an increase in biological and chemical activity and loss of organic content. This study evaluated disturbance to the physical-chemical properties of soil caused by pipeline installation, using two soil-quality indices to identify the scale of disturbance and the restoration cycle. The results showed that the adverse effects of pipeline construction on soil properties occurred mainly in the right-of-way and working. The results showed that while disturbed areas of a pipeline was still recovering from the disturbance two years after restoration, the soil restoration cycle was almost 100 per cent after six years (Shi *et al* 2014).

Archaeologically observations have been made regarding changes in biological activity due to changes in soil properties, although none were specifically related to piling. In Southwark, the temporary exposure of Bronze Age timbers in a trench led to the growth of fungal blooms, near the edge of the trench, which were observed when the timbers were re-exposed eight months later; (Nixon 1998). The decay of organics when not waterlogged is primarily due to biological activity. Bones from Aartswoud showed major changes in preservation between samples excavated in 1997 and 2000 (Kars *et al* 2004). Bones were recorded as 5 on a Histological Index in 1997 and 3 in 2000 (the Histological Index is a measure of microbial attack on the bone). This rapid decline in bone preservation is indicative of oxygen entering into what had been an anoxic system.

The effects of construction that can result in increased biological activity in the soil are related to a number of factors:

- Temporary increases in light during construction
- Increased oxygen availability in the short and long term
- Changes to soil moisture levels in the short and long term
- Changes in compaction and porosity due to changes in soil loading
- Temporary and long term temperature changes
- Changes to soil chemistry that could alter nutrient availability

The impact of piling is effectively unknown when considering these factors. However, informed estimates can be made as to possible risks. In many cases, the effects are likely to be small and limited in duration, but there is a lack of hard data on which to base these assumptions.

Light - displacement pile insertion should not enable increased light below the ground surface, but replacement pile could enable light to increase for short periods if an unsleeved open hole auger is used. Additionally, the excavation for pile caps and pile beams will temporarily increase light levels to the upper layers.

Oxygen – in this case, the potential for increased or decreased oxygen ingress will probably relate to the type of deposit being piled through. Cohesive deposits are unlikely to allow increased oxygen ingress during piling, but the impact of piling on granular deposits is less clear. One factor that will enable oxygen ingress is de-watering, if undertaken even temporarily, during the site construction activities. Changed groundwater flow could also mix oxygenated water with anoxic water, increasing the oxygen available for biological activity. Soil loading is important as this can affect soil compaction. Changes in compaction will change soil porosity and permeability, which will influence the movement of oxygen and water. During piling, soil loading can increase, particularly with displacement piles.

Soil moisture – here, a combination of piling technique, sediment type and stratigraphy will probably interact to determine if soil moisture conditions will change temporarily or permanently. Displacement piles often increase pore water pressure temporarily during piling. Replacement piles probably have a more complicated impact depending on whether sleeves are used. If replacement piles are sleeved, the impact should be minimal. However, if they are unsleeved, inserting replacement piles could reduce pore water pressure and soil moisture as water migrates into the void created during excavation of the pile hole. Soil moisture can increase in close proximity to a poured concrete pile due to water migration from the concrete as it sets. Groundwater movements and soil moisture levels vary depending on the soil type, cohesive or granular, and changes to these could be expected in relation to piling. As discussed in the section on hydrology, a specific risk with regard to piling relates to the presence of water-permeable and impermeable layers. If piles puncture impermeable layers, they could create new flow paths if the pile does not seal with the impermeable layer. If a flow path is created, this could result in change to the water table. Groundwater could lower as water flows away or increase if an aquifer with excess water pressure causes water to flow up through a flow path.

Extensive waterlogged deposits at Nantwich were investigated during the redevelopment of the town's Lamb Hotel. A monitoring programme identified areas of active decay in previously waterlogged deposits, with the process of desiccation feared to be accelerating as a result of modern intrusions and management of the town centre (SLR 2016). The upper levels of the organic deposits had been seriously de-watered in some areas and were found to actively decaying. These deposits required monitoring, as only those deposits at greater depths appeared to be stable and unaffected (SLR 2016). The use of sleeved mini-piling may have prevented the creation hydraulic pathways and have prevented the dessication of the waterlogged deposits (SLR 2016).

Temperature – daily temperature changes are more extreme above ground than below ground. Changes to temperature could be either short term or long term. In the short term, the primary factor in significant temperature changes will relate to the type of pile used. Poured concrete piles, replacement or augered displacement piles will heat the adjacent ground as concrete setting is an exothermic reaction which can give off heat for some time. Long-term changes in soil temperature could result from the presence of a new construction. The structures may insulate the soil from environmental fluctuations or increase the temperature through conduction or radiation of excess heat in the building

Nutrient availability – the accessibility of nutrients in the soil to biological organisms varies according to how the organisms take them in and to their accessibility. Changes to soil chemistry could alter the availability and access to nutrients by fixing them in inaccessible compounds. This is unlikely to have a major effect, however, as nitrogen is the only inorganic nutrient that tends to be a problem in most soils (Hopkins 1998). On brownfield sites, the presence of high levels of contaminants which may be toxic to some organisms might be a problem and this may restrict or alter the range of organisms active in the soil.

One new field in construction that is not specific to, but could be used in conjunction with, piling relates to the manipulation of soil biology. Engineers are looking to use soil biology to aid engineering in fields such as ground improvement, remediation and soil stabilisation DeJong *et al* (2013). Current research is mainly on the use of soil microbes to precipitate products such as calcium to bind soil particles. This would have impacts on soil density, porosity, stiffness, compressibility, permeability and chemistry, among others. Other research is being undertaken on the production of biofilms around the soil particles which can reduce hydraulic conductivity (water flow). This has implications for archaeological deposits; whilst these processes can be undertaken with minimal physical disturbance they could have significant chemical impacts on soils that contain archaeological remains.

9 MONITORING IMPACTS

One area where there is a lack of information relates to the monitoring of the impact of piling on *in situ* preservation. Although there have been a number of *in situ* monitoring projects on archaeological sites, few have been undertaken with particular regard to the impact of piles.

Davies (2013a and 2013b) reviewed previous monitoring projects undertaken in England as an aid to developing guidance on monitoring redox and soil moisture measurements. Most were concerned with the monitoring of waterlogged sites buried in urban and, occasionally, rural contexts. While these provide useful general information on monitoring, they often lack specific references to the impact of piles.

There are two data-recording stages involved in monitoring construction impacts such as piling. The first involves the establishment of baseline conditions, while the second is concerned with identifying changes in conditions during and post- construction. If baseline conditions are not established, any monitoring programme will be compromised, as it will be difficult to establish if any changes are due to the impact of piling or to natural ongoing processes and seasonal variations. The duration of monitoring required to establish baseline conditions will vary significantly, from a few days to months or even longer. Soil water, moisture and groundwater levels, can vary over an annual cycle as the seasons change and it would, therefore, take a year to fully establish baseline conditions. The duration of the monitoring programme during and after construction will depend on the programme's aims, but should generally last until the monitored conditions are stable. It is at this point that comparison can be made between conditions before, during and after construction. The work at Bryggen in Bergen (Matthiesen, *et al* 2008) has been one of the most extensive and detailed programmes undertaken in Europe. This has demonstrated the need for establishing baseline conditions and multiple monitoring points, as the work has shown that different preservation conditions and degenerative processes are in action in different parts of the site.

There are various parameters that can be monitored as part of monitoring programmes and normally more than one parameter is monitored. The choice of parameters to be monitored depends on the site-specific conditions, the particular concerns with the site, the costs and the access available to undertake monitoring. The most commonly monitored parameters include:

- redox
- soil moisture
- groundwater levels
- pH
- temperature

- oxygen content
- soil or soil water chemistry

Redox and Soil Moisture are the two parameters that have most often formed the focus of monitoring programmes, although they are often monitored in conjunction with other parameters.

Redox, shorthand for reduction and oxidation, is used as a proxy indicator for sediment geochemistry. Redox potential indicates whether oxidising or reducing conditions predominate within the sediments. Low redox potentials suggestive of reducing conditions are optimal for preservation of organic materials. In contrast, higher redox potentials, indicating oxidising conditions, are bad conditions for organic survival. Redox potential can be measured via permanent probes in the ground or on water samples extracted from the ground and passed through a flow cell. Long-term monitoring is thus possible through the use of permanent probes or dip wells. Further information is available from a recent review of redox potential monitoring (Panter and Davies 2014a).

Soil moisture and ground water are of particular interest to archaeological monitoring programmes; this is because preservation conditions for organic materials are best where oxygen-free conditions exist. This is usually when soils and sediments are fully saturated, with soil pores water-filled. Oxygen diffusion in water is slow. Therefore, once residual oxygen has been used up by aerobic bacteria, reducing conditions will be established and these will prevail as long as oxygen is used up at a faster rate than it can enter.

The measurement of groundwater levels can be undertaken at dip wells. Soil Moisture can be measured through a number of techniques, both *in situ* and on collected samples, and these have been reviewed by Panter and Davies (2014b). As with Redox, such systems can be permanently installed for long-term monitoring programmes.

The range of other parameters included in monitoring programmes varies due to the specific aims of the monitoring programmes, but can include physical, chemical and biological properties, the condition of organic and non-organic materials and variations within a site. In order to understand and interpret redox potential values, other measured parameters (pH, groundwater levels and temperature) are required. Of these, pH is the most important. This is because measured redox potential varies according to pH and a data calibration is required to take account of the pH value.

With regard to the monitoring of biological decay, Kenwood and Hall (2004) considered whether it was possible to determine if organic remains in a deposit were undergoing biological decay. They suggested that examination of the various organic components of the assemblage may give some guidance as to the likely taphonomic history of the deposit and suggest if decay is ongoing. This would require sampling, post-construction, and assessment by specialists.

Soil micromorphology has been used a few cases, notably in the Netherlands (Huisman 2007, 2012 and Huisman *et al* 2011) to characterise the impact of piling. This has enabled a much greater understanding of microscopic impacts of piling on deposits and greatly aids our understanding of the processes observed at a larger scale, for example compaction, changes to porosity, the alignment of clay minerals and the generation of slip-slides. There could be problems with obtaining samples post-construction because, as noted previously, difficulty of access is a fundamental problem when seeking to monitor archaeological deposits buried below a newly-constructed building. While this can make monitoring difficult, it also means that if degradation of the archaeological remains is identified, the potential to remedy this is limited. Access would be required either to undertake action, for example re-watering, to stabilise ground conditions or to excavate a site that cannot be stabilised.

Monitoring projects, therefore, have to consider the requirements of potential access to the archaeological deposits if effective action is to be taken. An example of how this can be done is provided by the Rose Theatre, where the building's design was adapted to provide access to the archaeological remains, post-construction. Where this is not possible, monitoring projects can still have value in developing a database of case studies of the impacts of piling on *in situ* remains. This information will enable better informed choices of pile type and piling layouts for future sites.

10 GAPS IN KNOWLEDGE

Our understanding of the potential impact of piling on the preservation of *in situ* archaeological remains is variable and can be summarised as follows:

Physical impacts – there is an extensive literature on the physical effects of piling. This provides a good understanding of the major physical impacts of displacement and replacement piles, although in the case of the latter, some of our understanding is based on assumed knowledge.

Hydrological impacts – there is extensive literature on some aspects of hydrological impacts. This provides good understanding of the potential risks, but our ability to predict possible dewatering scenarios relating to piles penetrating permeable layers is less certain. It would require detailed stratigraphic knowledge of the site under consideration and more generally how drag-down and smearing operated to create flow paths.

Chemical impacts – some literature exists on the potential interactions between piles and soil, which provides a basic knowledge for interactions between steel and concrete piles and local soil chemistry, although the details and the variations caused by different soil chemistries are less clear. The changes to soil chemical activity that may result due to piling-induced changes to wider environmental conditions are less well-documented or understood.

Biological impacts – little literature exists on the biological impacts of piling and the degree to which piling can influence biological activity in soil is not well understood. The basic factors that may influence this are known, but variations that exist in soil biology makes identification of the details of potential impacts difficult to predict.

11 GLOSSARY

Cohesive soil – in soil mechanics, cohesive soils include clays and silts. These are often weak and compressible, but these properties vary and are dependent on the water and clay content

Flocculation – the process by which small particle aggregate into larger particles

Granular soil – in soil mechanics, granular soils include sand and gravels. These are generally stronger and less compressible depending on the packing of individual grains and homogeneity of grain size.

Loading – the application of force to an object or material.

Porosity – the ratio of volume of voids in a rock or soil to its total volume.

Soil - in soil mechanics, soil is any uncemented or weakly-cemented accumulation of mineral particles formed by the weathering of rocks.

Soil shear strength - is a measure of the ability of soil to resist applied forces without failing.

Soil pore water pressure - is a measure of the pressure of the water filling the voids between solid particles in a soil. Increases in soil pore water pressure can lead to a decrease in shear strength .

Strain – deformation due to stress.

Stress – the ratio of force upon which it acts.

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