RESEARCH DEPARTMENT REPORT SERIES no. 65-2009 ISSN 1749-8775

PLANNING MITIGATION AND ARCHAEOLOGICAL CONSERVATION
RESOURCE ASSESSMENT

Glyn Davies

© Andrew Chopping, Museum of London

ARCHAEOLOGICAL
SCIENCE

ENGLISH HERITAGE

Research Department Report Series 65-2009

PLANNING MITIGATION AND ARCHAEOLOGICAL CONSERVATION – RESOURCE ASSESSMENT

Glyn Davies

ISSN 1749-8775

Requests for further hard copies, after the initial print run, can be made by emailing:
Res.reports@english-heritage.org.uk
or by writing to:
English Heritage, Fort Cumberland, Fort Cumberland Road, Eastney, Portsmouth PO4 9LD
Please note that a charge will be made to cover printing and postage.

SUMMARY

This report aims to assess the current state of knowledge of the impact of construction on the archaeological resource, and the effectiveness of archaeological mitigation practices. The project consisted of desk-based research to explore the known physical, hydrological, chemical and biological impacts of different foundation types, particularly piling, on archaeology. The project also involved research into the results of mitigation schemes designed to allow preservation of the archaeological resource *in situ*. Mitigation methods examined included site burial, piled foundations, shallow foundations and the re-use of existing foundations. The report provides an assessment of our current understanding of the impacts of construction, and identifies areas where further research would be beneficial to the archaeological profession.

CONTRIBUTORS

The work was overseen by a steering group consisting of Ian Panter of English Heritage, James Symonds and Glyn Davies of ARCUS, Adrian Hyde and Charles Hird of the Department of Civil and Structural Engineering, University of Sheffield, and Dave Barrett of Derbyshire County Council. Research and production of the report were undertaken by Glyn Davies.

ACKNOWLEDGEMENTS

The project developed out of an English Heritage funded project undertaken by Jim Williams at the Department of Civil and Structural Engineering, University of Sheffield, which was set up to develop research initiatives on archaeology and engineering. This report represents the results of one of the projects identified by the initiative.

DATE OF RESEARCH

The research was undertaken between March 2004 and April 2005, with the initial report produced in August 2005.

COVER

Andy Chopping/Museum of London Archaeology

CONTACT DETAILS

ARCUS, Unit R6, Sheaf Bank Business Park, Sheffield, South Yorkshire, S2 3EN
Glyn Davies; 0114 2225106; g.davies@sheffield.ac.uk

CONTENTS

1 INTRODUCTION

The aim of the project was to assess the **current state of knowledge** of the impact of construction on archaeology and the effectiveness of current archaeological mitigation practices. The project was undertaken by means of desk-based research and considered the known impacts of different foundation types, particularly piling, on archaeology. Research explored the physical, hydrological, chemical and biological impacts of construction. The project focused on terrestrial archaeology, but the results will potentially have implications for other coastal or maritime archaeological sites.

This report does not provide a quantitative comparison of the impacts of different construction activities, and as such cannot be used to determine suitable mitigation measures. It provides an assessment of our current understanding, and identifies areas where further research would be beneficial to the archaeological profession.

1.1 The urban archaeological resource

It has long been understood by archaeologists that archaeological remains are a finite and non-renewable resource. This resource is being constantly degraded by both natural and human processes. The archaeological resource is not spread evenly across the landscape but is at its greatest concentration in urban areas. As a high proportion of current development takes place in or around the urban environment, the areas with the greatest concentrations of archaeology are those often under the greatest threat; approximately 70% of all construction activities across the EU take place in urban areas (Kjekstad 2002). Urban centres are also more likely to contain greater depths and more continuous sequences of archaeological deposits than rural sites. These areas are of great importance for understanding the socio-economic development of Britain, in particular its mercantile and industrial past and the lives of urban dwellers.

Recent government policy means the government is 'committed to preferring the development of land within urban areas, particularly on previously-developed sites' (DETR 1997). This commitment to the redevelopment of 'brownfield' sites has come about in response to concerns regarding the continuing growth and sprawl of the urban landscape. It is anticipated that 60% of new housing will be constructed on previously developed land by 2008 (DETR 2000).

The commitment to the development of brownfield sites creates a major conflict of interest with other areas of Planning Policy, namely PPG16. The very fact that brownfield sites have been previously developed means that they may contain the remains of previous human activity, and those remains may be archaeologically sensitive. Planning guidance in PPG16 states there is an assumption archaeological remains of significance will be preserved *in situ*, but urban regeneration policy favours brownfield sites for development. Further complications arise when the archaeology itself may be a source of ground contamination. Removal or mitigation of the ground contamination invariably takes priority, at the expense of the archaeology (Durham 2004).

The importance of 'brownfield' archaeology will vary enormously from remains of international significance to sites of very limited local value. The different attitudes of archaeologists and engineers to brownfield land can be demonstrated by a recent classification of 'made ground' by engineers (Rosenbaum *et al* 2003) which describes ground in terms of the pollution or waste it contains, and its risk to development. However, any archaeological layers present on a site will also be contained within the 'made ground' deposits.

The level of archaeological preservation within urban sites can vary enormously and this is a factor in determining significance. The waterlogged anaerobic deposits found in cities like York and London can provide a wealth of information rarely seen on most archaeological sites. These remains can provide a detailed and vibrant insight into the past.

1.2 Archaeology and planning

Although legal protection has existed in Britain since the 1882 Ancient Monuments Act, this only preserved a few upstanding monuments and a small area of associated land around them. The 1979 Ancient Monuments and Archaeological Areas Act was the first legal recognition that buried deposits, often in urban centres, had a cultural value comparable to upstanding physical remains. However, the application of this act was very limited and to a large extent it has been superseded by PPG16 (Archaeology and Planning, DOE 1990). Although PPG16 is not statutory, and relies on local planning authorities to apply it, archaeological remains are now a material consideration within the planning processes. As a result, a wider variety of archaeological remains are now afforded protection, or undergo impact assessment.

Under PPG16 the assumption is that important archaeological remains on a development site will be preserved *in situ*. Preservation *in situ* does not mean that a site cannot be developed, but that any development on a site must minimise the disturbance to archaeological deposits. The development should also minimise disturbance to local environmental factors, such as the water table and soil chemistry, as changes to these can, in some cases, be as detrimental to the archaeology as uncontrolled engineering excavation. This approach has been criticised (Clark 2004) in that the archaeological approach to planning is seen as minimising damage, rather than integrating archaeological approaches and knowledge into the development of overall strategies and understanding of our ever-changing urban and rural environments.

Preservation *in situ* is usually achieved by careful design of the development scheme and its foundations, allied to archaeological monitoring of the construction process. A figure of 5% loss of archaeological deposits to the development has become the accepted norm in Britain when designing schemes for preservation *in situ*. This figure was based on a study of the archaeology of York (Arup 1991).

The concept of preservation *in situ* is not only recognised in British planning but also internationally through the International Council on Monuments and Sites (ICOMOS) Charter for the Protection and Management of the Archaeological Heritage (1990) and the Valletta Convention of the Council of Europe (1992), which was ratified by the British Government in September 2000 and became effective in March 2001. The focus on preservation *in situ* has come about due to changing attitudes in many countries as has been noted by Rubnikowicz (2002) and Teller and Warnotte (2003). Following on from the Valletta Convention the Council of Europe has instigated several projects comparing experiences; one of these, the Archaeology and the Urban Project, led to the drawing up of a code of good practice (Council of Europe 2000). This recognised that preserving the urban archaeological heritage, both buried and upstanding, required a partnership of planners, developers/architects and archaeologists, and identified the role and responsibilities of each partner in this process.

PPG16 recognises that preservation *in situ* is often only possible in cases when the archaeological remains are of national significance, and even in these cases, this is not always possible. In cases where preservation *in situ* is not considered justified or possible, a programme of preservation by record is usually required in mitigation. On many developments, a combination of preservation *in situ* and preservation by record is used to mitigate the impact of the development on the archaeology.

The planning authorities making the decisions on planning applications, and determining what conditions will be required, rely on the advice of the planning officers, who in turn take their advice from the local planning archaeologist. The planning archaeologist (or 'development control' archaeologist) requires evidence to determine the significance of the archaeology on any site. PPG16 outlines how a staged approach should be taken to determine the importance of any potential archaeology on a site; this usually takes the form of a desk-based assessment followed by field evaluation. Developers will commission archaeological consultants to advise them and undertake the work required by the planning authority. Furthermore, advice for both archaeologists and those involved in the construction industry positively encourages communication between the two parties at the earliest possible opportunity (McGill, 1996; Tilly, 1998). However, as Moseley (1998) noted at the first PARIS Conference, it is still common to find engineers working in historic city centres that have not read PPG16, and developers who call in archaeologists after the building has been designed.

The quality of decision making that takes place in the planning process is dependent on the quality of information available; this relates to information on the importance of the archaeology on the site, and to the information available on the impact of the proposed development on the site. In evaluating how a proposed development will impact on the archaeology it is necessary to understand the relationship between different types of construction or construction processes and archaeological deposits. However, much of the information currently available to archaeologists is anecdotal and detailed information is either unpublished or hard to locate. This situation is further compounded by the fact that little accurate scientific testing of mitigation methods has been carried out, and with notable exceptions (see for example, Ashurst *et al* 1989) successful mitigation strategies are rarely published.

The APPEAR programme (Teller and Warnotte 2003) is a pan European study to identify ways to preserve and enhance archaeology in urban centres while making it more accessible. Although not wishing to prejudge the results of this programme it is encouraging to see that archaeologists are beginning to look beyond preservation *in situ* as a means of preserving an academically interesting data set, to seeing archaeology as a cultural resource that is of interest to the population of the urban centre and one that can be used to enhance the historic identity of the city. This can be seen in cases such as the London amphitheatre where the remains have been put on display as well as preserved (Nixon 1998).

1.3 Archaeology and civil engineering

As previously stated, archaeologists and engineers are now expected to cooperate in aiding the preservation of archaeological remains on development sites. However, while engineers identify the importance of undertaking geotechnical surveys early in the planning process, reference to archaeology is rarely made at this stage and is often only considered alongside natural and man-made hazards (eg Paul and Chow 1999). Likewise too few archaeologists consider (or fully understand) the geotechnical and engineering implications of archaeological recommendations.

The need for engineers to have an understanding of cultural heritage was recognised in a TEMPUS-Phare project 'Civil Engineering Curriculum Development', jointly undertaken by Gdansk University of Technology, City University of London and Hanzehogeschool van Groningen (Affelt 2002). This led to the development of a course at Gdansk on the 'Cultural Aspect of Buildings' within the Faculty of Civil Engineering.

In 1996, English Heritage commissioned a 'study of engineering techniques for the mitigation of the impact on archaeological remains of construction causing ground disturbance during the development or redevelopment of sites in England' (Davis *et al* 2004). This study has evaluated the many possible construction impacts on archaeology from the pre-construction ground investigation through to the post-construction remedial and maintenance activities. For each activity, the potential impact on archaeology is assessed and potential mitigation solutions given. However, these solutions do not take into account the particular depositional environments and stratigraphic sequences of specific sites, and lack detailed information in areas where advice is often most needed.

There is, then, a requirement for more detailed information on the impact of construction activities that can be related to specific site conditions. There is also an urgent need for the full dissemination of this information. Some local authority planning archaeologists involved in the mitigation process find it hard to find the time to locate further relevant information, even when they are aware that the information exists. Similarly, because of the recent impetus that has been given to this subject, new research findings and new mitigation solutions and problems are continually being identified.

2 METHODOLOGY

2.1 Aims and objectives

The overall aim of this project is to assess the current state of knowledge of the impact of construction (particularly piling activity) on archaeology, and the effectiveness of current mitigation practices. Specific objectives are:

- to raise awareness and understanding of the processes affecting the preservation of archaeological remains;
- to produce a synthesis of current knowledge;
- to identify gaps in current knowledge and make recommendations as to how this could be rectified;
- to assess the potential for producing mitigation guidelines and make recommendations as to how this should be undertaken.

2.2 Method statement

The assessment was undertaken by means of desk-based research. The assessment was concerned with identifying how foundations impact on four main aspects of the archaeological resource:

physical	compaction and distortion of deposits, fracturing and cracking of artefacts;
hydrological	dewatering of deposits and artefacts;
chemical	changing the chemical environment of deposits and artefacts;
biological	altering the hydrological and chemical environment and changing the nature and extent of biological activity.

2.3 Data sources

The sources listed below were examined during the desk-based research to identify information pertinent to the project.

Archaeological sources

- English Heritage regional archaeological science advisors and local authority curatorial archaeologists;
- published literature and English Heritage reports;
- 'grey literature' client reports in Sites and Monuments Records (SMRs), the National Monuments Record (NMR) and archaeological contracting units;
- schemes devised for the management of archaeological resources on ranges owned or operated by the MoD and the Defence Estates.

Engineering sources

- Consultation with C Hird, A Hyde and S Barnwart of the Department of Civil and Structural Engineering, University of Sheffield;
- published literature;
- geotechnical companies (identified through consultation and the published literature).

Other sources

- Environment Agency (through contacts with ARCUS and Civil and Structural Engineering);
- Nuclear industry (studies following up work of Bill Miller in PARIS 1).

3 THE NATURE OF THE ARCHAEOLOGY

3.1 Soils and sediments

Archaeological soils or sediments are a matrix containing structures and artefacts but are also an artefact in themselves, being a product of human activity. Soil is made from mineral and organic components; the character of the soil depends on the origin of these components, and on how they have been transported to the site and combined to make the soil.

The preservation of archaeology within a deposit is dependent on the nature of the deposit and the environmental condition within which it lies, particularly the hydrological regime within the soil, oxygen activity in the soil, and the pH of the soil which results from the interplay of the mineral and organic components in the soil and the hydrological regime. Archaeological remains within soils can be divided into three main groups, artefactual, structural and biological. However, it should also be remembered that the deposit itself is an artefact of natural processes and human activity and understanding its development may be of great archaeological interest in itself.

The soil action plan for England 2004-2006 (DEFRA 2004) recognised that soils are part of our cultural landscape that have developed as the result of human environment interaction and that they contain the physical remains of our cultural heritage. The plan recognises that threats to soil and soil quality endanger this cultural heritage component in soils, but it also notes that soils are dynamic entities that are constantly developing and measures to conserve them and their contents cannot 'freeze' soils in time. There is, however, an implicit understanding in the plan that the soils it is concerned with are rural agricultural soils, and that soils in the urban context are of little consideration. This is regrettable from an archaeological perspective as urban deposits, including soils, often contain the densest concentration of archaeological remains.

In his work on palaeosols in rural Scotland, Simpson (1998) has highlighted the importance of understanding the process and speed at which they are buried. Physical, chemical and biological interactions occur between buried palaeosols and their overlying sediments, and if one wants to understand how the palaeosols formed one must understand the changes that occurred when the palaeosol was buried. This would also hold true for urban deposits. In this case the overlying deposits have the potential to have major impacts on the buried deposits, changing their appearance and physical and chemical properties. This could alter the conditions for any archaeology incorporated in the deposits and affect the preservation of that archaeology.

In contrast, when engineers consider a soil or deposit they are usually concerned with its strength and load bearing capabilities rather than any other properties (Shilston and Fletcher 1998). Geotechnically, soils may be generally divided into cohesive soils and granular soils.

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. 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 than cohesive soils, depending on the packing of individual grains. Granular soils are more permeable than cohesive soils.

Under loading, granular soils settle almost immediately while cohesive soils generally 'consolidate' over a period of weeks or months. Organic-rich soils such as peat continue to deform long after consolidation has ceased; this process is known as 'creep', or secondary compression.

3.2 Artefactual remains

Due to the wide range of materials which are used in the manufacture of artefacts, the conditions that preserve them vary enormously. However, the most important factor is the stability of environmental conditions; most artefacts can be preserved in a range of environments, if they are stable, but changes in environmental conditions will invariably result in damage to the artefacts (Nardi and Schneider 2004). **The idea of preservation *in situ* is therefore predicated on the (sometimes erroneous) belief that environmental stability can be maintained during any construction processes that take place.**

Stone

Stone artefacts recovered from archaeological sites include chipped stone artefacts (eg knives, arrowheads and spear points), ground stone artefacts (eg axes and whetstones) or carved stone artefacts (eg bowls, statues and architectural fragments). The preservation of a stone artefact is less dependent on the type of artefact than the type of stone from which it is made, and the environmental conditions within which it is buried. As the range of stone types that have been used to manufacture artefacts in the past is extensive there are no specific environmental conditions that are conducive to the preservation of all stone artefacts. Stone that has been commonly used to make artefacts includes flint, chert, sandstone, limestone and various igneous rocks commonly used to produce stone axes. Physical damage can result from penetrative foundations such as piles and applied stresses which can break or chip artefacts, particularly fine artefacts such as chipped flint artefacts, as was noted by Garfinkel and Lister (1983), in their study of site burial. Chemical damage can also occur to stone artefacts, particularly limestone or calcareous sandstones which are susceptible to acid damage. In general, biological or hydrological activity does not damage stone, or only does so slowly, for example in surface weathering and the development of surface patinas.

In general stone artefacts are resistant to damage and survive well on archaeological sites although there are certain conditions that can result in damage to certain types of stone artefacts, eg shale.

Ceramics

Ceramics are one of the most common artefact types found on archaeological sites from later prehistory onwards. In themselves ceramics are fairly robust materials although this does vary due to the quality of clay used in production and the firing temperature. Generally, the higher the firing temperature, the harder the ceramic produced. Some earlier prehistoric ceramics fired at lower temperatures are much less robust, more susceptible to damage and more likely to degrade. A glaze on a ceramic vessel can add protection to the fabric of the ceramic as it will help to waterproof the surface. Vessels are the most common ceramic artefacts, and these can come in a wide range of shapes and sizes. More elaborate vessel forms do occur (eg teapots and teacups) as do figurines and other ceramic forms. Resistance to physical damage due to stress is dependent on the quality of the ceramic and the form, with thin walled and elaborate forms more likely to break. Acid soils will degrade low-fired prehistoric ceramics to the point that they will break up under even gentle handling or soil movements. Well-fired ceramics are generally not damaged by water and biological activity, but damage can be caused to porous fabrics and low fired ceramics by water and roots.

Generally ceramics survive well on archaeological sites; soil moisture content is not normally an important factor and usually only the most acid soils are destructive.

Glass

Glass is usually found on Roman and later British sites. Glass beads are known from later prehistoric sites but these are extremely rare. Glass is susceptible to various types of damage due to its properties and attributes. Physical damage is easily sustained, as glass is fairly fragile and vulnerable to both static and dynamic stress; under excessive stress it will shatter. Deterioration of glass is primarily related to its composition and its environment.

Of environmental factors, water is the most important although others such as soil pH and temperature also play a part (Newton and Davison 1989).

Metals

A wide variety of metals and metal alloys have been used in the manufacture of artefacts in the past including copper, bronze, iron, lead, tin, silver and gold. Although the metals used are all quite different in their physical and chemical properties, they all share certain factors that govern their survival, with the exception of gold which is chemically extremely stable. Chemical damage is probably the greatest problem for metals; all metals, excluding gold, corrode in the presence of oxygen and water. The corrosion products produced depend on impurities in the metal and the surrounding chemical environment (Stoffyn-Egli *et al* 1998). The development of patinas or corrosion crusts on the surface of metals can inhibit further chemical activity as these patinas tend to be stable in the environment in which they have formed and act as barriers between the artefact and the surrounding environment. However, if the environment changes the patina loses stability and chemical activity will increase (Edwards 1998). Physical damage to these patinas, which can be caused by stress or abrasion, will also enable chemical activity to increase. Whether corrosion reactions occur depends on the chemical reactivity of the metal in its environment, and the speed with which corrosion occurs will depend on such factors as surface area exposed and the local environmental conditions, which can be difficult to determine in a natural system (Barnwart 1998). Attempts have been made to use archaeological analogues to calculate corrosion rates in the nuclear waste industry but problems have been found due to the complexity of the environmental systems involved and the difficulties of determining the variables involved (Miller 1998). At Inchtuthil (Miller *et al* 2000) it has been identified that the outer nails in the large pit of nails acted as a redox buffer protecting the nails at the centre, which were much better, preserved.

All metal will dissolve in acid, thus metals do not generally survive well in acid soils (Ullen, *et al*, 2004). Resistance to physical damage varies between metals: cast iron will fracture under excessive stress while lead will deform. Water in itself is not damaging to most metals, although in conjunction with oxygen it can have extremely corrosive effects. Biological activity has low impact on metals in good condition.

Metalwork can be found on many archaeological sites in Britain, but the state of preservation varies greatly. Generally, dry, non-acidic sites or anaerobic, waterlogged, non-acidic sites provide the best preservation conditions.

Wood

Wood was probably one of the most commonly used materials to make artefacts in the past, but it is not found on most archaeological sites in Britain, except in the form of charcoal. This is simply because wood degrades in most environments, with biological activity being the primary cause. Once wood starts degrading its strength is significantly reduced and it becomes much more susceptible to physical damage. Wood only survives long term in buildings, in extremely dry environments, or in waterlogged anaerobic environments. The dry desert conditions that can preserve wood do not exist in Britain but waterlogged anaerobic conditions do occur. Anaerobic waterlogged conditions in Britain can be quite acidic but this does not generally have a destructive effect on wood. Waterlogged wood is known from sites in Britain and has been found in historic urban centres such as London, York and Carlisle. This is due to the location of these towns and cities in valley bottoms adjacent to rivers and large depths of archaeological deposits below the water table. In addition, perched water tables can develop over impermeable layers such as clay, and these, as well as water-retaining, organic-rich deposits, can raise the level at which anaerobic conditions exist.

Wood in waterlogged conditions is very susceptible to any changes to the hydrological regime. Even archaeological evaluations which are designed to assess archaeological potential with minimal damage can adversely affect the local hydrology, as was amply demonstrated at Sutton Common (Van de Noort 1998). Here, wood preservation was significantly inferior in reopened trenches than in new trenches when the site was evaluated for the second time, five years after the initial assessment. This seemed to be due to a combination of disturbance to the hydrology and increased biological activity.

Leather

The processes that preserve and degrade leather are very similar to those that act on wood, because both are organic materials. Anaerobic waterlogged conditions are the only conditions in which leather survives for long periods in Britain.

Textiles

Textiles found on archaeological sites in Britain are made from natural organic materials. Textiles from synthetic fibres only started to be manufactured in the twentieth century. The range of materials used in making textiles includes wool, cotton, silk, flax (linen) and hemp. Generally textiles do not survive well on archaeological sites in Britain as they are all subject to degradation through a combination of biological and chemical action. Textiles generally survive only in waterlogged anaerobic conditions in Britain, but even in these conditions they are fairly fragile, and will degrade with time. The speed with which waterlogged textiles decay depends on the material they are made from in combination with the local environmental conditions. Textiles may also be preserved through the proximity of metal corrosion products, by mineral replacement, and through desiccation in dry environments.

Bone

A study by Nielson-Marsh and Hedges (2000) identified that the main environmental factors related to bone preservation were soil pH and site hydrology. A detailed discussion of the properties and decay of bones is given by Millard (1998). A simple summary of the main points is given here. Bone is made up of two components, a protein (collagen) and a mineral (carbonate-hydroxyapatite). It is the combination of these two components that gives bone its properties. As these two components are very different, the conditions that aid the preservation of one may be detrimental to the other. The mineral component is susceptible to physical or chemical damage, while the collagen is primarily subject to biological or chemical damage. Physically, bone is strong but will fracture under stress, and loss of the collagen will make the bone more brittle. Acid soils are detrimental to bone as the mineral component is easily eaten away by acids (Millard 1998), and even the humic acids in roots can etch the surface of bones. Generally bone preservation is better in dry environments or wet anaerobic conditions with neutral or slightly alkaline pH.

3.3 Structural remains

This project is primarily concerned with buried rather than upstanding structural remains and the comments below only consider buried structural remains. The type of construction used in the past depended on the period and on the available resources. Until modern transportation networks were available the majority of materials used in construction were locally sourced. Although timber was traded across Europe from the thirteenth century (Tyers pers comm), heavier materials such as stone and brick were generally of local origin (except in a few notable cases). This has resulted in regional variations in vernacular building styles and materials. All structural remains would be susceptible to damage from penetrative foundation techniques which could cause extensive damage. Foundations can also be subject to water damage by flooding or by fluctuating water tables, which may arise from the impact of human activities.

Stone

The remains of stone walls or wall foundations are often found on archaeological sites. Stone structures are known from the Neolithic period onwards. As was noted in the section on stone artefacts, stone is generally a robust material that is resistant to most forms of damage, although some types of stone can be subject to salt damage. Limestone does dissolve in acid and the surface of limestone blocks can become very eroded in acid soils; however, in limestone areas soils are generally not acidic, though there are exceptions such as peat bogs on limestone moorland.

Ceramic building material

Ceramic building materials (bricks and tiles) have been used in Britain since the Roman period. As with all ceramics they are generally robust and survive well although they can be damaged by very acid soils if poorly fired, or by the deposition of salts in certain hydrological conditions.

Wood

Wood has been a common building material from the prehistoric period onwards. As was discussed in the section on wooden artefacts, buried wood will only survive for long periods on British archaeological sites in waterlogged anaerobic conditions.

3.4 Biological remains

As well as studying artefacts and structural remains, archaeological research is also concerned with the reconstruction of past economies, diets and environments. Various types of biological remains are therefore studied to research these issues.

Bone

As has been noted previously, bone does not survive in acid soils and is best preserved in either dry or wet anaerobic conditions.

Wood and plant macroscopic remains

As was noted in the sections on wooden artefacts and structures, wood (and plant macroscopic) remains are generally only preserved in waterlogged anaerobic conditions in Britain. However, where wood and plant macroscopic remains are charred as a result of burning, they are resistant to chemical and biology attacks and survive on nearly all archaeological sites. Mechanical damage to these remains may occur, eg through wetting and drying.

Pollen

Despite their small size, pollen grains are remarkably robust and can survive in a range of conditions. The most important factors in preserving pollen appear to be soil acidity, preferably an acidic (low pH) environment, and soil moisture content. Although pollen is best known from recovery in waterlogged and acidic soils such as peat bogs, it can be recovered from a range of environmental conditions, including limestone caves.

Seeds

Seeds on archaeological sites can survive either in their natural state or in a carbonised state. Seeds in their natural state are like other plant remains in that they only survive in waterlogged anaerobic conditions. When they are carbonised, seeds are much more likely to survive. This is because they are no longer subject to biological activity, are much more tolerant of environmental conditions and therefore survive in a wider variety of deposits. As with wood and plant macroscopic remains, mechanical damage to seeds may occur, eg through wetting and drying.

Molluscs

The shells of snails and shellfish are found on archaeological sites of all periods. Different types of shells have different physical properties based on their structure, with some being resistant to physical damage while others are much more fragile. However, with all shells the greatest impact on their preservation comes from soil environmental conditions, particularly pH. This is because all shells are made of calcareous material and dissolve in acid. Shells are therefore only recovered from sites with alkaline or neutral soils.

Insects

The hard exoskeleton of insects can survive on archaeological sites. As with most biological remains this normally only takes place when the remains are buried in waterlogged anaerobic conditions, or through mineral preservation and replacement. The degradation of insect remains is primarily from biological action although chemical and physical factors are involved.

4 GENERAL IMPACTS FROM SITE WORKS

There are four types of impacts that may result from construction site activities. This section discusses the effects of these impacts on various aspects of the archaeological resource, citing examples from case studies where available.

4.1 Physical impacts

The ultimate physical damage is the removal of the archaeology by excavation and, in general, all archaeology should be assumed to be destroyed in an area that has been excavated. However, as many archaeologists have experienced on watching briefs, artefacts recovered from the buckets of excavators can still have archaeological value even though they have been removed from their context. On most developments engineering excavation will result in horizontal or vertical truncation of the archaeology. This can be made worse by slumping of sections if they are not supported.

As well as physically removing archaeological deposits, construction activities on any site will result in forces being applied to the deposits on the site. These forces will create static or dynamic stresses on the deposits and the archaeological remains buried within the deposits. This can cause compaction and distortion of deposits, and fracturing and cracking of artefacts or structures buried within the deposits. Loading of the deposits may impact on the soil structure, compacting it or causing physical alterations to the particles or grains that make up the deposit, the most obvious alteration being crushing of the grains in friable deposits.

As was noted above (Section 3.1), in geotechnical terms soils are divided into two main groups, cohesive soils and granular soils (Shilston and Fletcher 1998), and the different characteristics of each type of soil will impact on the way they compact and how the stresses on the deposit are applied to any artefacts within it.

Hyde (2004) has studied the damage to particles under one-dimensional compression. Studies were undertaken on sand samples, including uniformly graded (single sized) and well graded (range of sizes) sand samples. It was found that levels of damage were related to particle size distribution and compression levels, with damage increasing with greater compression. For archaeological artefacts in sediment under one-dimensional compression, damage will depend on the grading of the sediment and the relative size of the artefact with smaller artefacts being more susceptible to damage. The worst case for damage to the artefact will occur when the artefact size approaches the matrix particle size. This research also has implications for interpreting archaeological sediments, because many of the particles in deposits that have been subject to excessive loads will have been damaged. This in turn could affect the results of particle size analysis, or other analyses, which could alter the interpretation of how a sediment formed.

Sidell *et al* (2004) and Allison and Higuchi (pers comm) have recently undertaken a study on the impact of piling on buried artefacts. This was based on laboratory tests to study the effect of static and dynamic stresses on buried artefacts. The artefacts used were glass, bone and wood which exhibited a range of brittleness. Tests were undertaken with sands and gravels as a deposit medium. The study has reached the following provisional conclusions:

- for a given stress level, dynamic stresses are more damaging than static stresses;
- continuous flight augur piles appear to set up lower vibrations that driven piles;
- vibro-piles, which are often used in developments today as they are quieter, produce much greater stresses in sediments and artefacts than hammered piles;
- experiments have been carried out to determine what stress conditions cause material failure;
- the transmission of stresses in the ground will be affected by buried structures and soil moisture.

Using the above findings Allison and Higuchi aim to draw up hazard charts that show under what conditions different materials fail.

Ultimately Allison and Higuchi's study was aimed at producing predictive models that could be used in determining the impact of piling on buried archaeological artefacts. They concluded that the analysis of site sediment characteristics can be used to assess what stresses will be produced by different piling techniques and, by reference to the proposed hazard charts, the threat to buried artefacts from different piling techniques could be determined.

Negueruela's (2000) study on managing maritime sites highlighted the problems with coastal developments and some of his conclusions may be applicable to the wider environments such as riverside sites. He noted that the construction of ports, marinas and breakwaters could cause direct physical damage to deposits but that construction can also cause changes in currents, resulting in the scouring of the seabed deposits.

4.2 Hydrological impacts

Dewatering of deposits and artefacts can aid biological and chemical degradation as well as causing shrinkage of deposits which can impact on structures built in or on the deposits. The potential impacts of deposit shrinkage on artefacts buried in the deposit does not appear to have been studied. Dewatering a waterlogged anaerobic soil can cause a rapid increase in biological and chemical activity. Raising the water table can destabilize structures and increase chemical and biological activity when the ground has been very dry. Changes in the water table can also result in the leaching of salts on, or in, deposits and structures. Generally a stable, unchanging water table provides the best preservation conditions for most artefacts, biological remains and structural remains. Perforation of impermeable layers can cause major changes in the water table as can pumping down the water table in ground adjacent to the site.

Welch and Thomas (1998) have described the water flows that exist within the groundwater, deposit surface flows, inter-deposit flows, and intra-deposit flows. They have also considered the effects changes to these flows may have on waterlogged deposits and the preservation of archaeological remains. It has been noted (Caple 1998) that although efforts have been made on some sites to preserve the water table to protect archaeology in the face of development, this has rarely been combined with monitoring of the oxygen content of the water. It is possible, therefore, that although the water table has been preserved, other activities have enabled oxygen to enter the system thereby removing the anoxic conditions. Flag Fen, which is now above the water table, is kept wet with water pumped up from drainage ditches; however, this is allowed to stagnate in a lake before percolating through the site, with the stagnation process removing dissolved oxygen from the water. Caple (1998) has also identified that the water pH and conductivity need to be monitored if all environmental conditions on a waterlogged site are to be kept unchanged.

The technology now exists to undertake regular monitoring of waterlogged sites through either fixed or mobile water monitors. Davis (1998) described the technology used to monitor waterlogged deposits to determine if conditions are stable (ie staying waterlogged and anaerobic). This technology has been used to monitor water levels and properties on the Marks and Spencer site in York (Oxley 1998; Davis *et al* 2001). This was undertaken after archaeological evaluation identified that there were highly productive waterlogged deposits on the site and that significant changes in the water table appear to have occurred in the last 30 years which have reduced the ground surface by 200mm.

Changes to water table levels are known to have occurred in other cities. In the last 200 years pumping has significantly lowered the water table in London, by up to 70m in some parts of the city. However, recently it has been rising by around 1m per year; this is in part due to deep, impermeable basements acting as dams to stop water flow over the impermeable London Clay. These major changes will have had significant impacts on the preservation of organic remains (Nixon 1998).

Pumping is undertaken as a temporary measure on many construction sites to make groundworks easier to undertake; however, little information is available on the impact of such pumping and the area that will be impacted. Some studies have been undertaken on the impact of pumping on rural gravel extraction sites to examine the area impacted by dewatering. French and Taylor (1985) monitored the water table and preserved organics on a site adjacent to a gravel pit. Once pumping started the water table in adjacent land dropped by 1m. Following pumping the wood on site was showing signs of deterioration, with surfaces becoming degraded and the wood being less robust. French *et al* (1999) looked at the impact on the water table of pumping associated with quarrying. The study identified that after four months of pumping the groundwater 200m away from the quarry had dropped by 1m.

A study undertaken in conjunction with an archaeological excavation has also examined the impact of pumping on the surrounding area. This was undertaken by Matthiesen *et al* (2004) where they examined the effect of pumping during an excavation at Nydam Mose, Denmark. Although the area of excavation only measured approximately 10m x 10m, pumping impacted on an area of at least 3000m^2, and water levels were observed to have dropped up to 35m away from the excavation. Once pumping stopped the water levels took several months to recover, although this may have been exacerbated by low rainfall figures during and after the period of excavation.

Pumping is not the only cause of dewatering. Cox *et al* (2001) studied part of Abbot's Way trackway in Somerset Levels. This area was well preserved in 1982 when birches were planted on part of it. In 1992 trial trenches examined this area to determine the impact of the birches extracting water from the ground. Desiccation cracks up to 1.3m deep were found in the peat and the trial trenches showed that the biological remains, wood and insects had been degraded by the desiccated conditions. This study gives an idea of the significant damage that can result from dewatering and the time period over which it can occur. Even temporary dewatering can cause problems, as was evidenced by Van de Noort (1998). In his study of Sutton Common he examined the results of two programmes of trial trenches five years apart. He showed that wood preservation was significantly inferior in reopened trial trenches than in new trenches, this was attributed to a combination of disturbance to the hydrology and increased biological activity.

Further study at Sutton Common by Van de Noort, Chapman and Cheetham (2001) looked at attempts to rewater the site that had been recently partially drained. Following re-watering it was found that the water table could be reinstated but that redox conditions (see Section 4.3) on the site were variable. However, without monitoring prior to dewatering, it is not known if the redox conditions had originally varied. In general, deeper deposits and remains appeared to have more stable preservation conditions, but there could be variations due to local deposit conditions.

Van de Noort (2004) has also used Sutton Common to highlight the problems of preserving wetland sites *in situ* without active management strategies. With a wide range of threats to wetland sites, benign neglect is not a viable option as has been shown by the study of dewatering around a gravel pit (French and Taylor 1985). Human activities carried out at some distance from the site can still impact upon it, while natural erosional processes can also be destructive. In some cases, such as Sutton Common, a combination of monitored preservation *in situ* and some preservation by record has to be employed.

The need for wetland sites to be managed as a resource has also been advanced by Chapman and Cheetham (2002). They have examined the potential to use GIS to aid in monitoring wetlands and have argued that this can be done.

Re-watering has one major side effect, beyond making the ground wetter, and that is ground heave (see Glossary). Crilly and Driscoll (2000) examined ground heave at Chattenden, Kent, which resulted from tree felling that allowed the water table to rise. Ground heave at the site of the former trees was 160mm over 10 years, and 60mm over 10 years at a distance of approximately 30m from the site. This can have major implications for the development of a site. This causes restrictions on the types of foundations that can be used.

Although not currently a problem in Britain, changes to soil hydrology in very dry conditions can also have severe impacts. Three studies have shown how human activities can impact on the water table in dry environments.

Mavlyanova and Ismailov's (2004) study on hydrology and preservation of buildings at Kiva in the Central Asian Desert showed rapid degradation of buildings in recent years. This was shown to be linked to changes in the water table. The local soils on which the town is built are stable when dry but become unstable when wet, causing cracking of buildings. Salts have also been leaching out of bricks used to build many of the structures in the town, which has resulted in their degradation. This has been caused by changes in the water table brought about by human activity, including leaking sewers and the creation of large areas of tarmac which has reduced evaporation.

Similar problems have been encountered in Cairo (Sheehan 2004) where the ground water level has risen by 2m in the old city due to unregulated development without infrastructure, and changes to the hydrology of the Nile Valley associated with the Aswan High Dam. The rise in water level has had serious impacts on ancient buildings and monuments. Measures to mitigate the impact has required the construction of new sewers to take away the excess water.

Moenjodaro, Pakistan, has been subject to many studies and proposals regarding water damage and the precipitation of salts on the brickwork. The local environment is very harsh with large temperature and water table fluctuations. Dams downstream and increased rice cultivation appears to have contributed to a rise in the water table (Hughes 1998).

4.3 Chemical impacts

In his review of soil chemistry, Pollard (1998) noted that it is the chemistry of the water contained in the soil that is of paramount concern, as it is through the water that any buried object interacts with its environment. The water content of a soil varies with depth, season, land use and the weather. Water in the saturated levels of a soil (ie below the water table) is known as groundwater while water above the water table is known as soil water. To understand the chemical activity of a soil/sediment one must understand its acidity or pH, its redox conditions or reactivity, and the speciation of the soil solution. Although standard chemical analysis reports the chemical content of material within a solution as weight of elements per volume, this is a gross oversimplification. In a soil water solution most elements will occur in combination with others, often several others at once; this is known as speciation. It is these combinations that are of concern as they determine the likely chemical activity of the elements involved. Some are stable while others are reactive and it is only by understanding what species are present that one can predict the likely chemical activity of a soil. To achieve this level of understanding requires geochemical modelling of the water and its associated minerals. This approach was promoted further in Wilson and Pollard (2004), who argued for the use of geochemical modelling to understand artefact diagenesis.

The redox potential of a deposit, measured as its Eh, is usually seen as being related to the oxygen content of the deposit, but work by Smit (2004) has demonstrated that some soils have much higher redox potential than would usually be expected from the oxygen content. This, he suggests, may be related to the presence of other oxidising agents, probably nitrates and sulphates. However, he notes that it is only if the redox potential is high that further investigations may be required to determine what oxidising agents are responsible and to develop appropriate action to remedy this.

Reed (2004) identified problems with the measurement of redox potential in the field. During the study at Tønsberg in Norway technical problems resulting in inconsistent readings were encountered, as was the potential for differences between dipwell water and soil water, a factor that had been noticed previously by Caple and Dungworth (1998).

Matthiesen *et al* (2004) have monitored changes in soil water chemistry associated with lowering the water table in peat at Nydam Mose, Denmark. This resulted in increases in sulphate, potassium, nitrate, nitrite and ammonium levels and a reduction in pH. These have probably resulted from oxidation of compounds in the peat when the water table is lowered.

In the complex stratigraphy of urban sites it is possible for major chemical changes to occur in relation to development and the placing of large concrete structures in contact with archaeological deposits. The results of this have only been observed on the Marks and Spencer site in York (Carrott *et al* 1996 and Davis *et al* 2001). Here the deposition of calcium sulphate crystals in the upper archaeological levels was observed. They suggest that these have been deposited through an interaction between calcium ions leaching down from above with sulphides in the archaeological layers. The calcium ions are thought to have originated in the overlying concrete slab, having been leached out of the concrete by the downward movement of acidic water. They have also suggested that this chemical activity may be a factor in the relatively poor preservation of organic remains in the upper layers on the site.

Corrosion of metals takes place spontaneously in the presence of oxygen and water; it is an electrochemical process whereby the metal reacts to reach its thermodynamically stable state (Edwards 1998). The rate at which corrosion occurs is dependent on the metal and the local environment. Corrosion takes place through two separate reactions: an anodic reaction involving oxidation and a cathodic reaction involving oxygen reduction (or rarely hydrogen evolution), and the likelihood of corrosion taking place can be assessed by means of a Pourbaix diagram (Edwards 1998). Corrosion usually leads to the development of patinas or corrosion crusts on the surface of the artefact. The composition of these patinas is dependent on the environment surrounding the metal. The patinas formed are thermodynamically stable in the environment in which they form and will retard further corrosions by acting as a barrier as long as the environment does not change (Edwards 1998).

Published archaeological studies of soil chemistry and artefact preservation have mainly focused on metal artefacts. These studies have rarely examined the impact of development on soil chemistry and the subsequent artefact corrosion; however, some studies have produced information which may be relevant to this study.

Ullen *et al* (2004) studied the impact of acid rain on soil acidity and degradation of bronze artefacts. They compared material from museum collections with recent excavations on the same or similar sites and discovered that bronze artefacts are now recovered in a much more degraded condition. Sites with thin soils showed the greatest damage to the artefacts. The increasingly degraded state in which artefacts were being recovered was attributed to increasing soil acidity due to acid rain. It is possible that similar results could come from any changes to soil chemistry that increases soil acidity. A similar study in Denmark by Madsen, Andersen and Andersen (2004) showed a similar deterioration in bronze finds over a similar period although they did not suggest a cause.

The importance of the impact of microenvironments on corrosion was highlighted by Fox (1994) who studied metal corrosion on a costal site in Israel. The study identified that coastal microenvironments are saturated with seawater and therefore act as a marine environment chemically, despite being on land.

Both archaeologists and engineers have looked at the rate at which corrosion of metals occurs. MacLeod's (1995) study of metal corrosion on an Australian wreck site identified that when metal objects are sunk (or buried), initially there is rapid corrosion until a protective coating of corrosion product covers the surface; the rate of corrosion then slows down as dissolved oxygen no longer has direct access to the surface of the metal.

There have been two studies of the corrosion of steel piles undertaken by engineers. The first, undertaken by Ohsaki (1982), looked at corrosion on steel test piles driven on a number of sites in Japan. These were examined two, five and ten years after driving to assess the corrosion. The study concluded that corrosion was generally light, corrosion rates were faster at first then slowed down, and corrosion rates were higher near the surface where water and oxygen were present. Neither the type of soil nor groundwater fluctuations appeared to have had any discernable impact on the rate of corrosion. However, low pH soils (ie acidic soils) had a slightly increased corrosion rate.

The second study, by Wong and Law (1999), looked at piles that were exposed on the demolition of a 22-year old building in Singapore. The piles were steel H piles that had been in a decomposed granite soil. They identified that the average corrosion rates were low and that temperature did not appear to be a factor as rates were similar to those that had been identified in a temperate climate by Romanoff (1969). The study also found that corrosion rates were similar above and below the water table; this appears to contradict Ohsaki's (1982) study where he identified that corrosion rates were higher near the surface. Varying soil chemistry and redox potentials may have been a factor in the different results, but further research would be required to determine the cause.

In general, it would appear from the two studies that chemical interaction between steel piles and the surrounding soil is limited and slow acting. However, these studies were on modern, high quality steels, which will probably contain far fewer impurities than archaeological objects, and compositional variations, particularly impurities, may result in more rapid or extensive corrosion on some archaeological samples.

The International Atomic Energy Agency (IAEA 2002) looked at the potential use of archaeological analogues for studies of nuclear waste disposal. These studies have focused on demonstrating that metals and glasses can survive for long periods with only limited corrosion. However, there are limits to the usefulness of these studies as it is difficult to produce quantitative measurements from such data, since variations in soil chemistry and hydrology over time are not known.

A more detailed analysis was undertaken by Miller *et al* (2000) looking at archaeological analogues for nuclear waste disposal. This was primarily concerned with the conditions under which artefactual remains can survive for long periods buried in the ground. Their case studies included Inchtuthil Roman nails (iron), the Kronan Cannon (bronze), Hadrian's Wall (cement), Dunarobba forest and Chinese tombs (organics). These studies were all concerned with sites where constant burial conditions have prevailed, not at sites where burial conditions have changed over time. This limits their value to this study as this is concerned with sites where burial conditions may have been changed by construction activities.

Other studies that have been undertaken on archaeological analogues for nuclear waste disposal have included Stoffyn-Egli, Buckley and Clyburne (1998) who looked at brass shells in Halifax Harbour, Nova Scotia, that had been buried for 52 years. This study identified that corrosion varied for partially buried shells. The buried parts were much better preserved than the parts that were not buried. This demonstrated that different preservation conditions in different microenvironments can result in variable corrosion. Any changes in these microenvironments could have major and detrimental effects on the preservation of artefacts.

King (1995) undertook a detailed study of the corrosion processes operating on a bronze cannon at the base of the Baltic Sea. He identified that the corrosion products were the result of complex chemical interaction with the local environment, with an interchange of materials between the cannon and the clay in which it lay. The rate at which chemical exchange occurred was found to vary due to the degree of compaction of the clay.

Other than metal, one material that has been studied is glass (Kaplan 1980). The study identified the weathering products of glass and related these to the chemical composition of the glass. The weathering observed was found to relate to the chemical composition of the glass and the environmental conditions acting on it.

One engineering study by Tedd, Charles and Driscoll (2001) looked at brownfield site risk management. This identified one of the risks on a development as the possibility of chemical attack on building materials in chemically aggressive ground. In such chemically aggressive soils archaeology may not survive well, but some materials may have survived and reached equilibrium with the local environment. However, if the building is being damaged by interactions with the soil there must be major chemical reactions taking place and these will be changing the soil chemistry of the site. In these circumstances corrosion to the archaeological artefacts will recommence or increase until equilibrium between them and their environment is re-established, if this is possible.

4.4 Biological impacts

By its nature, biological activity in soils is mainly detrimental to buried organic remains. There are a range of biological organisms that live in soil. Bacteria, fungi, protists, viruses, animals and plants were listed by Hopkins (1998) although, as he noted, there is some debate as to whether plants are true soil organisms as they are not wholly resident in the soil. He also identified that the rate of decomposition of organic remains in soil is dependent on a number of factors:

moisture	water is required for biological activity, however, in waterlogged 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, but nitrogen may;
temperature	at 0°C there is virtually no biological activity, Above this temperature biological activity increases with rising temperature to around 40°C;
clay content and physical accessibility	biological matter encased in solid matter, particularly clay, is in part physically protected from microbial attack

.

The relationship between biological activity and the hydrological and chemical properties of soils means that altering the hydrological and chemical environment changes the nature and extent of biological activity. Many of the biological impacts are related to, or increased by, changes in the hydrological regime. Waterlogged anaerobic conditions retard biological activity and any activity that dries out an anaerobic waterlogged site will result in rapid and detrimental increase in biological activity.

Hopkins (1998) also noted that soil disturbance is generally associated with an increase in biological activity, but that this may be followed by a decrease in activity in some cases (such as storage bunds) due to compaction of the soil and increased waterlogging.

In a review of soils, biological activity and archaeological preservation, Ritz *et al* (2004) noted that the current strategy of *in situ* preservation assumes that archaeological evaluations and construction activities do not alter the degradation processes on a site. However, there is a large body of non-archaeological data on soil that suggests that soil disturbance invariably results in changes in the soil environment that almost always results in increased biological activity. This can come about through environmental changes and ingress of fungi into excavated trenches, increased biological activity and associated release of nutrients in stockpiled soil which fertilises the ground on backfilling, and inappropriate backfilling changing the site hydrology with attendant changes in physical and biological activities.

Bronze Age timbers at Bramcote Grove in Southwark were temporarily reburied under plastic and peat in 1992 but when re-exposed after eight months fungal blooms and growths were seen on the surface of the wood. Further excavation demonstrated that biological activity had been restricted to material near the edge of the evaluation trench (Nixon 1998).

Fungal activity can be very damaging to biological remains and, although soil contains a range of fungi, one study (Heaton and Cleal 2000) suggested a different source for fungi. In the study they examined remains in Beaker pits where they found poor organic preservation which they related to fungal activity. They also suggested that the fungal activity was related to an adjacent coniferous plantation; it is known that coniferous leaf litter supports a large range of fungi which can attack other organic materials.

It has been suggested that burial of sites can lead to an increase in temperature but, as Reed (2004) observed, that was not the case at Tønsberg in Norway. Here temperature levels were found to drop slightly following burial. However, this suggestion is of concern, as it is known that increasing temperatures lead to increasing biological activity (Hopkins 1998).

An example of the impact of temperature on biological activity is the study of Pournou, Jones and Moss (2001) which looked at wreck sites in British and Greek waters. Comparison of sites demonstrated that variations in salinity and in temperature affected bio-deterioration. In the warmer waters off Greece wood-boring crustaceans and molluscs were much more active, increasing the decay of the site. This also demonstrates how changes in only one or two factors, in this case temperature and salinity, can significantly change biological activity.

There have only been limited studies on the rate at which biological activity in soils occurs; however, two studies have demonstrated it can be very fast in the right conditions. A study of the bones from Aartswoud (Kars *et al* 2004) demonstrated the speed at which biological activity can cause decay. The work revealed that there was a major change in bone preservation between samples collected in 1997 and 2000. The histological index for 1997 was 5 while for 2000 it was 3. The histological index, graded from 0 (poor preservation) to 5 (good preservation), 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. In cases like this only rapid action will avert significant loss to the archaeological record. Hopkins (2004) examined the biological remains recovered from the 33-year excavation at the Wareham experimental earthwork. This identified that substantial degradation had occurred to the biological remains buried, and indicated how quickly a range of biological materials can decay and how little will survive after even a short time on many sites.

Studies in York have started to suggest that some archaeological deposits have been suffering rapid decay to organic remains in recent years. Kenward and Hall (2000) have argued that the current state of preservation of organics in near-surface sediments at York is not stable. Evidence for why this may be was identified at the Marks and Spencer site, where the ground surface has dropped by 200mm over 30 years due to drying out (Oxley 1998). Kenward and Hall also noted that, as organics decay rapidly when not waterlogged, the material in these sediments must be undergoing decay at the moment. This decay of organic materials will be primarily biological. They suggest that modern development in towns has upset the balance of the environment, particularly the water table, and that although further research is needed to confirm this, extensive archaeological deposits are now under threat. Taking this argument further Kenward and Hall (2004) considered if it was possible to determine when organic remains in a deposit had been subject to biological decay and how to identify if decay was ongoing. They argued that although it is impossible to be sure, examination of the varying components of the assemblage may give some guidance as to the likely taphonomic history of the deposit and suggest if decay is ongoing. They also considered if re-watering can stop decay once it has started and noted that the decay that has occurred may have changed conditions in the deposit making it more vulnerable to further decay.

Some organic remains can be protected from biological activity by fossilisation. McCobb *et al* (2004) looked at how insect remains become fossilised, reviewing the evidence as to how calcium phosphate or calcium carbonate replacement takes place. Carbonisation, although not true fossilisation, can provide similar protection from biological activity for seeds and wood remains.

Arnott *et al* (2004) are investigating the potential for using changes in the acoustic properties of wood to monitor the condition of wood on maritime sites using high frequency acoustic sources. This would be very useful as it offers the potential to monitor sites without disturbing them.

5 DEVELOPMENT ACTIVITIES RESULTING IN IMPACTS

Williams and Corfield (2002) reviewed the main types of site works that can impact on buried archaeology, and the stages of the development where these types of work take place. Detailed discussion of site development activities and their potential impacts on archaeology have been described in Davis *et al* (2004). More detail on the engineering activities on development sites, and how they are undertaken, can be found in standard engineering texts such as Tomlinson (1995). The types of activities that are often undertaken on construction sites will be summarised here as an introduction to the assessment of their potential impact.

The construction process for building on an urban site will involve the following three stages of works that could impact on the archaeology:

ground investigation	test pits and boreholes;
enabling works	site clearance (removal of vegetation or demolition of site buildings), soil stripping, remediation of land contamination, ground improvements;
construction activities	foundation construction, services construction, landscaping.

In Sections 6-12, the different types of construction site activities are subdivided and discussed, based on a combination of the types of activities and impacts they have rather than when they take place in the construction timetable. Each section includes a short summary of relevant research that has been undertaken to date. Each section also presents a summary of the known impacts of the activity and current or possible mitigation practices; these latter have not necessarily been proven to be the most suitable measures.

The discussion of construction impacts on archaeological remains is divided into the following sections:

small-scale excavations	ground investigations, service trenches and shallow stripping (Section 6);
large-scale excavations	remediation and deep excavations (Section 7);
piles	screw piles, push piles, open-ended piles, boreholes (Section 8);
shallow foundations	pads and rafts (Section 9);
ground improvements	densification and stiffening columns (Section 10);
site burial	long-term burial and temporary burial (Section 11);

foundation reinforcement/underpinning	compensation grouting, steel underpinning rods, soil extraction (Section 12).

6 SMALL-SCALE EXCAVATIONS

For the purposes of this study, small-scale excavations include test pits for pre-construction geotechnical ground investigations, service trenches for cables and pipes, and shallow strips for car parks, minor roads, site compounds and landscaping.

There is a specific problem with ground investigations, including both test pits and boreholes. The problem is that this work is carried out well in advance of planning applications being submitted, and is often undertaken before archaeological consultants are appointed to projects. This means that they are often undertaken with no consideration of the archaeological implications, and without archaeological monitoring or other mitigation being conducted. Many sites are investigated several times with engineers undertaking geotechnical investigations, geochemists testing for contaminants and archaeologists evaluating the archaeology. All three require intrusive ground works, and cooperation between the different specialities could reduce this as the same test pits or boreholes could serve several purposes (Davis 2004). For this to be achieved all the different specialists would need to be appointed before site investigations start, and would have to agree on a common strategy.

Other small excavations are usually undertaken during the site set up or construction stages. In these cases activities should only be undertaken once a mitigation strategy has been agreed for the site. Unless an open area archaeological excavation is undertaken prior to the development proceeding, these shallow works are often covered by a watching brief. When these engineering works are carried out there is often an implicit assumption that anything within the excavation is lost but that there is no disturbance of, or damage to, archaeology beyond the area of excavation. Excavations can result in the truncation of archaeological deposits or structures. The scale of these operations are such that significant loading and unloading forces are probably not created. However, as Ritz *et al* (2004) have identified, there is a large body of non-archaeological data suggesting that soil disturbance invariably results in changes in the soil environment causing increased biological activity. This comes about through environmental changes and ingress of fungi into excavated trenches. If the excavated area is backfilled with material taken from it, increased biological activity and associated release of nutrients in stockpiled soil fertilises the ground on backfilling. Inappropriate backfilling can change the site hydrology, creating water barriers or pathways depending on the material used for the backfilling. All of these activities can result in changes in site hydrology and chemical and biological activity.

As an alternative to service trenches, shallow microtunnels are now being used. So far these have primarily been used abroad but they are likely to become more common in Britain. Ulitskii and Alekseev (2002) describe the techniques used to set up shafts/chambers to use microtunnel technology to lay underground utilities. This technique has been extensively used in Europe, US and Japan, and in Berlin 55% of all pipelines were constructed by this technique by 1994.

An obvious advantage of this technology is that service trenches do not need to be excavated, and only the route for pipe or cable is disturbed. However, it is impossible to observe what the microtunnel is cutting through and if it is impacting on buried archaeology, which it could easily damage.

In Moscow, Petrukhin, *et al* (2002) looked at the different types of tunnelling machinery being used to create service tunnels under the city. These tunnels are not microtunnels, but vary in size from 2m to 4m in diameter. They are constructed at different depths depending on various factors, but 6% are at 20m plus, 50% at 10 to 20m and 44% less than 10m. This means that a significant proportion are located at depths where they could impact on archaeology. Also, all the tunnels will need connections to the surface which will further disturb archaeology.

Badly constructed pipes for water or sewage can lead to water leaking into areas that would otherwise be much drier, leading to soil expansion and the deposition of salts (Mavlyanova and Ismailov 2004). As well as water, leaking sewer pipes could also introduce material into the soil which could change biological or chemical activity.

Summary – small-scale excavation

Table 1: Summary – small-scale excavation

Impact type	Comments/keywords	Key Refs
Physical	Ground disturbance. Truncation of archaeology.	
Hydrological	Temporary dewatering from pumping. Permanent dewatering or altered routes of water flow. Soil expansion due to leaking pipes, and long-term salt deposition detrimental in dry environments.	Mavlyanova and Ismailov 2004
Chemical	Changes in soil chemistry, especially from inappropriate backfill material.	
Biological	Localised increases in biological activity (tends to be limited to area of excavation).	Ritz *et al* 2004 Nixon 1998

Current mitigation – small-scale excavation

Table 2: Current mitigation – small-scale excavation

Mitigation	Comments/keywords	Key refs
Physical	Co-ordinate site investigations between professions. Careful choice of backfill material.	Davis 2004
Hydrological	Co-ordinate site investigations between professions. Careful choice of backfill material. A groundwater flow model could be used to assess potential changes.	
Chemical	Co-ordinate site investigations between professions. Careful choice of backfill material.	
Biological	Co-ordinate site investigations between professions.	

In current practice there are some implicit assumptions behind the decision-making used in drawing up mitigation schemes. However, these assumptions may not be justified, particularly in reference to the impact of excavations on biological activity. Other potential problems should be dealt with through the mitigation strategy; physical, hydrological and chemical issues should be addressed by careful choice of backfill material. Potential problems with enhanced biological activity are probably not serious as long as the excavation is not cutting into archaeologically sensitive layers. This is because it has been identified that enhanced biological activity appears to be limited to zones just adjacent to the excavation (Nixon 1998).

7 LARGE-SCALE EXCAVATIONS

Any development that involves the excavation of a large hole or the large-scale removal of deposits will destroy all the archaeology in the area excavated. This is a problem that may be increasing. Chow (2002) has argued that underground development is a way to reduce pressure on limited urban space and even suggests that it can have environmental gains in terms of conservation of energy and improvements to the visual environment by hiding unattractive structures, car parks, roads and shopping malls. This position fails to consider the impact upon buried archaeology.

Large-scale excavations are undertaken on construction sites for four main reasons: the construction of deep foundations, ground remediation, the construction of basements and the construction of tunnels. Where excavations are undertaken in areas containing archaeological remains some form of mitigation will usually be undertaken through the planning process; however, where excavations take place adjacent to archaeological remains no mitigation will normally be undertaken.

7.1 Ground remediation

Ground remediation can take place on a development due to the presence of loosely compacted ground, to remove contaminated material, or to remove organic or compressible material.

Many brownfield sites contain areas of uncompacted ground, including deposits of loose brick and stone rubble, cellars, voids, ducts, etc To remediate these deposits the material may be excavated, crushed and relaid in compacted layers. Excavations of this nature will result in the total destruction of any archaeology in the area of excavation, and will also result in stress being applied to the unexcavated deposits below the excavation during the compaction of the relaid material. In cases where this work is undertaken post-planning permission, mitigation for the areas excavated should be covered by PPG16-determined requirements. However, remediation can be undertaken prior to planning permission being granted and in these cases the excavation would not be subject to any archaeological mitigation and the archaeological resource would be lost.

Major excavations may take place on development sites to remove contaminated material and dispose of it in an appropriate contaminated waste landfill site. Excavations of contaminated material of this nature will result in the total destruction of any archaeology in the area of excavation. As Durham (2004) has identified this can be in conflict with the aims of PPG16 to preserve archaeology *in situ*. In the cases he describes, the conflict between the desire to preserve the archaeology, and the need to remove ground contamination prior to development, invariably results in the removal of the ground contamination. This should result in further mitigation measures, including preservation by record, but there can be serious health and financial implications to the excavation of contaminated ground that can make it difficult to implement. The refilling of any holes left from the removal of contaminated material brings in all the problems that can be encountered if the incorrect material is used for backfilling; this should be chosen to avoid changes in soil chemistry, hydrology or biology.

In some cases the ground contaminants form part of the archaeological record; this could be the case on industrial sites such as metal works, gas works, tanneries and chemical works.

In all types of ground remediation, ground disturbance could result in an increase in biological activity and changes to the hydrological regime on the site if inappropriate backfills are used or if the backfilled area creates areas with increased or retarded water flows. During the excavation pumping may be employed to lower the water table, and this has all the potential problems that were identified in Section 4.2.

7.2 Deep excavations

Large excavations are often undertaken under the footprint of a building either for floating/compensated foundations or for basement car parks, plant rooms and lift pits. Similar large-scale excavations can take place to change site levels as required by the development. Excavations of this nature will result in the total destruction of any archaeology in the area of excavation. This activity should be mitigated through preservation by record. In the case of large underground basements there are also potential problems with the introduction of large quantities of concrete impacting on the soil chemistry, and changes to the hydrological regime resulting from the creation of a barrier to water flow. Also, biological activity is likely to increase during and immediately following the excavation; once the basement is constructed this may decrease, as the structure acts as a barrier to oxygen.

7.3 Areas adjacent to deep excavations

On many developments underground basements for car parks, etc, will only cover part of the site. This may come about due to limits on the area of basement needed for the development, or because part of the site was determined to be worthy of archaeological preservation *in situ*. In these cases there is usually an implicit assumption that the archaeology outside the excavated area will not be subject to damage from the development. However, this assumption is likely to be over-simplistic; removal of loading will result in some movement of deposits and stresses within them and it may also impact on the site hydrology, particularly if the excavation is associated with pumping. Chemical and biological impacts may also result.

Large-scale excavations can involve the removal of hundreds, if not thousands, of tons of material. The removal of such quantities of material will significantly change the forces acting on the remaining material. The material below the excavated levels will have had a large weight removed from above, while the material to the side will have had lateral support removed which could lead to collapse unless support is provided. The stress operating on the surrounding sediments will change as the excavation continues, and will be dependent on the size and shape of the excavation as well as the material excavated and left behind. Stresses acting on the soil around the excavation are further complicated by the type of support provided to the sides of the excavation and how this is installed. All the stresses caused by the excavation result in lateral and vertical movements in the ground. Although the potential impacts have been little considered by archaeologists, the potential problems for the adjoining ground, foundations and structures have been extensively considered by engineers. If these impacts can be damaging to modern foundations and structures there must be the potential for them to damage buried archaeological structures and foundations.

One of the few studies that has looked at the impact of large excavations on archaeological preservation was by Suh *et al* (2004), who looked at a sixth century AD tomb in Korea which had been excavated and left open for display. Unfortunately, the partial removal of overburden had changed the forces on the structure and this, combined with changes to the temperature and moisture, has resulted in severe structural instability requiring remedial work to make the tomb safe.

In a study on the installation of foundation pits in Moscow, Astrakhanov (2002) describes various methods for installing support, including diaphragm walls. In one case the remains of wooden structures were found 4m below the ground surface. He notes that these were removed, without specifying what they were, but that engineering problems remained due to deformation of the trench sides resulting from the removal of the remains. Unfortunately, he does not specify whether these deformations resulted in greater ground movements than would otherwise have been expected.

Engineering studies of the impact of large excavations have primarily focused on ground movements, particularly ground settlement, and the subsequent impact on adjacent structures. The two main movements that take place are lateral movements towards the excavation and ground settlements around the excavation. The studies have included field observations and modelling studies.

Hsieh and Ou (1998) looked at ground settlement adjacent to deep excavations. They identified two types of settlement behind retaining walls. These were *spandrel*, which has a downward curve towards the wall with the maximum settlement adjacent to the wall, or *concave*, where the greatest settlement is in a depression behind and separated from the retaining wall. They identified that the type of settlement that forms depends on soil conditions, the nature of the ground support, and when the settlement occurs in the excavation sequence. The depth of settlement depended on the type of retaining wall and the depth of excavation. Modern diaphragm walls tend to have less settlement than sheet pile walls. The impact of the depth of excavation can be offset by the use of braces or props, which span the hole to support the side walls and reduce lateral movements and subsequent settlement. In nine case histories Hsieh and Ou (1998) examined, with excavations of between 10m and 20m, the depth of settlement varied from 6cm to 20cm, and this was observed to impact over an area of influence of between 30m and 50m, although the maximum settlement would only impact on a small part of this area. Maximum settlement for excavation with concave settlement occurred 10m from the wall; with spandrel settlement the maximum settlement was adjacent to the wall.

Long (2001) undertook a survey of 300 case histories of ground movements due to deep excavations with retaining walls. He compared the results of this study with standard mathematical models of ground movements developed by Clough and O'Rourke (1990) to determine the applicability of the model. Long (2001) identified that the lateral and vertical movements can be divided into five groups depending on the nature of the soils.

For retaining walls in stiff soils with a large factor of safety against excavation base heave[1]:

- lateral movements are frequently between 0.05% and 0.20% of excavation depth;
- vertical settlements are usually between 0% and 0.20% of excavation depth;
- there is no discernable difference in the performance of propped, anchored or top-down systems of side support;
- the values recorded are somewhat less than those predicted by Clough and O'Rourke (1990).

For retaining walls that retain a significant thickness of soft material (>60% of excavation depth) with stiff material at base level and with a large factor of safety against excavation base heave:

- lateral and vertical movements increase significantly over stiff soils;
- the values are very similar to those predicted by Clough and O'Rourke (1990).

For retaining walls embedded in a stiff stratum with a significant thickness of soft material (>60% of excavation depth) with soft material at base level but with a large factor of safety against excavation base heave:

- lateral and vertical movements increase significantly over the situation with stiff soils at base level;

---

[1] The factor of safety against excavation base heave is determined by the depth at which a retaining wall is embedded in the ground; for a large factor of safety the retaining wall is deeply embedded in the ground, while for a low factor of safety the retaining wall is only shallowly embedded. The factor of safety also depends on the soil strength profile.

- the values are considerably underestimated by Clough and O'Rourke (1990).

For retaining walls with a low field of safety against excavation base heave:

- large horizontal movements have been recorded up to 3.2% of excavation depth.

For cantilever walls the maximum lateral movements normalised by excavation depth:

- are relatively modest and average 0.36% of excavation depth;
- are independent of excavation depth and system stiffness.

Computer modelling was also undertaken by Ng and Yan (1998), to examine ground settlement associated with diaphragm wall installation around a large excavation. They concluded that the influence zone resulting from diaphragm wall installation normally falls within a distance of one panel depth (D) from the panel, and that maximum settlement behind the panel occurs at a distance of 0.2D behind the wall, and settlements beyond the influence zone are insignificant.

Il'ichev, Konovalov and Nikiforova (2002) compared the different types of methods used to shore deep excavations in Moscow, to determine how settlement varied between the different methods used and which resulted in the least settlement. The four commonly used supporting systems are:

- anchored walls;
- dividers;
- interstory ceilings (a braced structure);
- sheet piling.

The greatest settlements were found to occur with anchored structures, while the smallest settlements occur with interstory ceiling structures which, being braced, have the greatest resistance to lateral movements and subsequent ground settlements.

A study was undertaken in Singapore on four large excavations retained by diaphragm walls (Poh, Goh and Wong 2001). Comparison of these sites allowed the authors to reach the following conclusions:

- in the stiffer zone near the base of the wall, lateral soil movements varied from 3.0 to 21.7mm near the wall. In the upper softer soils movements were more complicated and larger;
- maximum inward lateral movements appear to increase with the increasing longitudinal cross-sectional area of wall panels;
- if bentonite or slurry is used to support the construction of the diaphragm walls this should be maintained at a high level above the water table to minimise lateral movements;

- soil movements caused by wall construction decrease with increasing distance from the wall. Maximum settlement decreased from 25mm (3m from the wall) to 4mm (24m from the wall). The largest soil settlement represented 0.12% of trench depth.

Two recent sites demonstrate the variability that can be found in ground settlement. Ng and Yan (1999) looked at stresses in ground and ground deformation on land adjacent to an excavation at Lion Yards, Cambridge, where the retained ground was supported by a diaphragm wall. Maximum settlement was 3mm with small depressions or settlement bowls behind each diaphragm wall panel for a total excavation depth of 20m. However, Ou, Liao and Cheng (2000) describe recorded ground responses next to a deep excavation supported by a diaphragm wall in Taiwan. Here two holes were excavated: a 19.7m deep hole had a maximum of 106mm of lateral movement and 78mm settlement, while a 8.1m deep hole had a maximum of 250mm of lateral movement and 180mm of settlement. These large variations show how great the differences can be between sites and even within a site due to variations in soils.

These lateral ground movements and settlements may appear small in general but their influence on the stability of surrounding deposits and structures within them can be significant. Engineering studies have naturally focused on the impact on adjacent foundations and standing buildings, but some of the consequences observed may well be applicable to buried archaeological structures.

Mathematical modelling has been undertaken on the impact of vertical and lateral movements on piles caused by adjacent excavations (Poulos and Chen 1997). This reached the following conclusions:

- pile response increases with increasing stability number[2] due to larger lateral soil movements;
- pile response decreases with stiffer excavation support conditions as this results in smaller soil movements;
- pile bending moment increases with increasing pile diameter, due to its larger stiffness (for a solid pile), pile deflection tends to decrease slightly with pile diameter but generally follows the soil movement unless the pile is very stiff.

Wong and Chua (1999) examined the ground movements recorded next to a 3.7m deep excavation in soft clay shored by steel sheeting; settlement of 70mm and lateral movement of 30mm were observed. Precast concrete piles were then driven into the base of the excavation and this increased ground movements next to the excavation with settlement increasing to 117mm, and lateral movement to 91mm. Buildings adjacent to the site on steel H piles showed no signs of damage but an adjacent concrete apron settled by up to 150mm and cracked.

Recent work in Russia has examined the impact of large construction site excavations on adjacent historic buildings in Moscow and St Petersburg. In Moscow (Il'ichev *et al* 2001)

---

[2] **The stability number is the ratio of geostatic stress to soil undrained strength.**

large excavations have resulted in average settlements of around 20mm on adjacent buildings, but in extreme cases settlements of up to 60mm have been recorded. Cracks have been recorded in up to 23% of historic buildings adjacent to large excavations. Fadeev, Inozemtsev and Lukin (2001) looked at settlement on old buildings, on weak soils, in St Petersburg. In one extreme case adjacent buildings had suffered from a settlement of 70mm at one end causing major damage. Many of these old buildings can be very susceptible to damage from the stresses imposed upon them due to the poor construction of their foundations. Skal'nyi *et al* (2002) have described the problems of monitoring poor foundations while adjacent excavations are being undertaken. The problems include difficulty of access, variable construction and load bearing potential.

One site where detailed monitoring of ground movements has been undertaken was Plantation Place, London. This was undertaken during the redevelopment of the site and observed ground movements related to the demolition of old buildings, construction of the secant pile wall, excavation of the basement and construction of the new building (Hughes *et al* 2004b). At this site 50% was given over to a new basement in the centre of the site and 50% to preservation *in situ* of archaeology around the basement. A perimeter wall from the old buildings on the site ran around the site within the area of *in situ* preservation. During demolition of the old buildings on the site ground heave of between 2mm (at the periphery) and 7mm (at the centre of the site) was measured. Further ground heave was measured as the secant wall was inserted, although this may have been due to continuing heave resulting from the demolition unloading. There were small (1-2mm) lateral movements on the perimeter wall of the old buildings during secant piling, resulting from the release of the support from the concrete base slab of the old building which had been cut through by the secant piles. Excavation of the basement for the first 3m was undertaken archaeologically and resulted in a further 3mm of ground heave and a further 3mm of lateral movement, towards the excavation, on the perimeter wall. Further basement excavation, down to 15m in total, was ongoing when the article by Hughes *et al* (2004b) was published. Monitoring of ground movements is continuing and further, probably more substantial, movements are expected, although none that were expected to severely impact on the archaeology.

The impact on the water table of large-scale excavation will depend on local hydrological conditions and whether the excavation is accompanied by pumping to lower the water level. If pumping is used to lower the water table during excavation the site will be subject to the same impacts as have been identified previously. French *et al* (1999) identified that the impacted area can be very large, with the water table dropping significantly (by 1m) 200m away from a quarry where pumping was occurring. French and Taylor (1985) also identified that lowering the water table can result in rapid degradation of waterlogged organic remains. Temporary lowering of the water table may also change the chemical environment as the water that recharges the water table during and after pumping may contain greater oxygen levels, changing the redox environment. Longer term changes to the water table can result from the construction of impermeable basements. In London this has created underground dams interrupting water flow over the impermeable London Clay (Nixon 1998). This has stopped underground water flow, contributing to a rise in groundwater of up to 1m a year in some areas. Although not noted in any publications, interruptions to water flow could also result in the lowering of the water table in certain areas depending on local conditions. It is also possible that flow paths for water could be created adjacent to basement structures, but again this has not been recorded.

Lowering the water table can also impact on the ground movements associated with large excavations. Ng, Leung and Lau (2004) modelled soils next to deep excavations. They compared anisotropic sediment (properties are directionally dependent) with isotropic sediments (uniform properties in all directions). This identified that lateral deflection and vertical settlement from dewatering were respectively 8% and 19% greater for anisotropic than isotropic sediments, and were respectively 15% and 10% greater for combined dewatering and excavation. A similar pattern was observed by Pickles, Lee and Norcliffe (2003) in their study of deep excavation construction in Hong Kong. This examined a diaphragm-walled excavation for a railway station on the coast. Here, the sea acted as a reservoir, recharging the water table on one side of the site and creating a complex hydrological regime. Dewatering through pumping had different effects on different sides of the site, with much larger settlements taking place on the landward than the seaward side.

The main potential chemical impact of large excavation will come from the construction of supporting walls for the sides of the excavation. Diaphragm walls and the like will usually be made of concrete or steel; these are major constructions bringing significant quantities of material into contact with the soil. Concrete walls may be prefabricated in sections or poured on site; in the latter case there is the potential for the diffusion of the wet concrete into any voids in the site. Temporary support for the ground while the concrete is being poured may be provided by bentonite slurry, or similar materials. In these cases this may also alter the chemical environment of the soil.

As was discussed in Section 4.4 any ground disturbance will usually lead to an increase of biological activity. How long this would last for is unknown, but it may be limited if any large excavation is sealed by the construction of walls and a floor acting as a barrier to oxygen ingress.

7.4 Tunnelling under

The final activity taking place in urban centres that can lead to large excavations is the construction of tunnels. The two main potential impacts from tunnelling are physical and hydrological.

The physical impacts of tunnels on the overlying ground have been studied by Yang and Wang (2002). They have observed that tunnelling causes settlement of the overlying soil and that this settling of the soil causes down-drag on piles or foundations in the soil which can impact on their load bearing potential and therefore weaken overlying structures. A laboratory study was undertaken by Lognathan, Poulos and Stewart (2000) using a centrifuge model test which was compared to a mathematical model. The results gave a general agreement and showed that there are small vertical and lateral movements in soil above tunnels.

The second potential impact would be through dewatering, if pumping is used to control the ground water level during the construction of the tunnel or if the tunnel itself is acting as a water channel.

7.5 Summary – large-scale excavations

Table 3: Summary – large-scale excavations

Impact type	Comments/keywords	Key refs
Physical	Ground disturbance. Truncation of archaeology. Stresses in surrounding deposits. Vertical settlements and lateral movements of soil near excavations or above tunnels. Damage to nearby building foundations (especially if old and weak). Soil movements relating to hydrological changes.	Hsieh and Ou 1998 Long 2001 Clough and O'Rouke 1990 Ng and Yan 1998, 1999 Il'ichev, Konovalov and Nikiforova 2002 Poh, Goh and Wong 2001 Ou, Liao and Cheng 2000 Poulos and Chen 1997 Wong and Chua 1999 Yang and Wang 2002
Hydrological	Dewatering (temporary or permanent). Diaphragm walls or large foundations create barriers to water flow, or change route of water flow. Changes in water table, altering areas of anaerobic conditions within and beyond the development area. Degradation of organic remains within and beyond development area.	French et al 1999 French and Taylor 1985 Ng, Leung and Lau 2004 Pickles, Lee and Norcliffe 2003
Chemical	Changes in soil chemistry due to backfill, foundation material or temporary supporting material.	
Biological	Likely increases in biological activity (uncertain duration).	

7.6 Current mitigation – large-scale excavations

Table 4: Current mitigation – large-scale excavations

Impact type	Comments/keywords	Key refs
Physical	Locate basements or deep foundations away from significant archaeological deposits (archaeological preservation *in situ*). Archaeological preservation by record. Bracing can reduce lateral soil movement. Use observational method to control movements[3].	Hsieh and Ou 1998
Hydrological		
Chemical		
Biological		

---

[3] **The observational method is used to refine predictions of stress and displacements based on *in situ* measurements; site operations can then be altered based on the observed results.**

Current mitigation for the excavation of basements is to locate them away from the most significant archaeology and preserve the archaeology *in situ*. This may be accompanied by preservation by record for any archaeology removed by the excavation. Beyond the area of excavation little archaeological work is usually undertaken; ground movements may be monitored, but as the impact of the ground movements on archaeological deposits or structures is not well understood this may be of limited value. Most minor ground movements are not likely to have major impacts, but this is still poorly understood.

8 PILES

Piles are a common type of foundation support for large buildings. There are numerous types of piles including hammer-driven piles, vibro-piles, Continuous Flight Auger (CFA), and screw piles. Piles are used because they are strong, quick to insert and cost-effective. However, the major disadvantage from an archaeological point of view is that they are inserted blind; archaeologists cannot observe the deposits they are driven through or the damage they are causing. Piles generally fall into two categories, displacement piles and non–displacement piles. In displacement piles the sediment through which the pile is inserted is pushed aside, resulting in the compression of material around the pile with increased lateral stresses extending beyond the pile. In non-displacement piles the pile is inserted to replace the soil which is removed; in theory this should not result in lateral stresses being imposed during insertion of the pile, although this will depend on the pile being inserted correctly. However, mobilisation of the pile capacity requires stress transfer to the surrounding soil. Piles are also classified as friction piles or end-bearing piles depending on how they support the load they carry. 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. However, piles can also use a combination of friction and end-bearing.

8.1 Archaeological observations of piling

Archaeologists have recently become more interested in identifying the impact of pile insertion on buried archaeology. However, much of the information currently available on archaeological impacts is anecdotal, with little accurately recorded data. Davies (2004) undertook a desktop study to identify records of piling effects observed on archaeological sites, but only five cases were identified with data that could be used. These are briefly described below.

Barclaycard Building site, Marefair, Northampton

In one of the trenches (Trench 10) that was excavated on this site a pile and pile cap were exposed and the impact of the pile on the sediments was recorded, although the type of pile used was not stated. The pile was 19" (48cm) in diameter and was topped by 1m thick pile cap. The report (Northamptonshire Archaeology nd) described that:

> 'Close to the building's north wall, the action of driving the foundation pile had produced a characteristic distortion of the stratigraphy. The layers through which it had been driven had been warped by the action of pile driving, each one drawn down in an inverted cone towards the central pile. Close to the pile itself, the layers were mixed together by the resultant vibration and liquefaction in a sleeve around the pile a few centimetres thick. As a result, the area of damage and distortion from each individual pile can be quantified as a circle, of a radius *c* 1.0m'.

Examination of a plan and a section in the report show that the vertical drag-down can be over 1.0m.

Market Mews, Wisbech, Cambridgeshire

On this site a modern borehole had been bored prior to excavation and the layers around the borehole were seen to be dragged down and distorted for an area of 0.5m radius around the borehole. The borehole was about 0.12m in diameter as estimated from the hole left, and the vertical drag-down was around 0.2m (Hinman 2002).

London, various sites

An examination was made of the photographic archives held by the Museum of London; however, it was difficult to identify the degree of damage caused by piling. There were three main reasons for this, one of which was the preference of archaeologists for focusing their work on areas with the best archaeological preservation, resulting in a selective avoidance of areas with extensive piling. The second related factor is that archaeologists are interested in recording the archaeology, not the damage to the archaeology. They consequently spend much less time and effort in recording the impacts of piling than recording the archaeology that has not been disturbed. Many of the photographs therefore showed archaeology in the foreground with piles in the background, but with no details of the impact of the piles on the archaeology. The final reason for the difficulty in identifying the degree of damage caused by piling related to the methodologies used to excavate the sites. Over the last 20 to 30 years the techniques used in excavating sites have changed. This has resulted in fewer sections on sites, but pile damage is often best seen in section, not in plan.

Despite these issues, a few observations can be made as to the impacts observed in the photographs. There was a great deal of variation in the apparent impact; in some cases there appeared to be no damage while in others the damage was quite extensive. In some images it can be seen that piles have passed close to wooden structural remains, and following excavation the wood was found to be undisturbed other than where the pile had touched it. A similar case of very limited damage was observed where the piles have passed through Roman mosaic floors without apparently disturbing the mosaic tiles beyond the footprint of the pile. An example of extensive damage was seen around a pile sleeve; in this case it passed through a thin, beaten-earth floor which had disintegrated or distorted for a radius of about 0.3m around the pile sleeve. The most likely factors that caused this variation are the type of pile employed along with the properties of the layers the pile passed through. A comparison of the two floors, mosaic and beaten earth, may help 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, while with the mosaic floor the mortar must have failed and the tiles stayed *in situ* just beyond the footprint of the pile.

Nixon (1998) provided some comments on the piling strategy and damage observed on Number 1 Poultry. The site contained a range of piles which were all exposed as the site was excavated. Excavation took place after the insertion of new piles to create a basement for the building as construction of the upper floors took place. Piles on the site included driven piles from the 1950s and 1960s, a modern secant pile wall and a number of modern augered piles in 2m diameter steel sleeves across the centre of the site. Of these, the 1950s and 1960s driven piles were observed to be the least destructive, causing little physical distortion. This contrasted with Thames Exchange where old piles had caused extensive damage to timber structures, 3 pile diameters beyond the pile. The sleeved augered piles at Number 1 Poultry showed almost no distortion, except in five out of the 74 piles where damage was observed up to 1m away at the level of the water table. The deposits in these cases appear to have 'liquefied'. This was seen at a sand/gravel to soil interface and in finely stratified clays within timber buildings. There were also a few piles where problems were caused by the casing dragging down timbers, creating voids which collapsed when water entered the voids.

The JunXion, Lincoln

ARCUS undertook a watching brief on two test piles which were driven on the site of the JunXion development for North Midland Building Ltd (Davies 2003). This was undertaken prior to finalising the piling methodology to be employed on the site. Two precast concrete, square sectioned, test piles of 0.25m width were driven, one after pre-augering. A trench was excavated with the piles in section and the observable impact of the piles recorded. The site had thin limestone and gritty sand hardcore layers overlying a compact clay silt deposit, which was up to 1.8m thick and contained numerous angular fragments of brick and stone rubble up to 0.3m in length. The observable impacts included, drag-down (which caused distortion of up to 1m vertically and extended for 0.1m around the pile), cracks in the soil, disturbance/mixing of deposits and the creation of voids, depending on the piling methodology. There were no significant differences in the impact of the two piles, with the disturbed area around the piles being similar; however, these results would not necessarily be replicated on another site where different conditions prevail.

Farrier Street, Worcester

During an excavation, drag-down was observed adjacent to a driven precast square pile, *c* 0.3m in width (Dalwood *et al* 1994). The area that was impacted was up to 0.3m from the pile while the vertical displacement was over 0.3m. Artefacts were found to have been displaced adjacent to the pile with later material dragged down and intermixed with earlier material. The report also noted that the piling did not appear to affect the soil micromorphology beyond the area of the pile, though no further details were provided on this.

Summary

A few general observations can be made as to the impact of piles on archaeology as observed by archaeologists:

- 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. It was observed at Northampton, Cambridge, Lincoln and Worcester. The maximum vertical displacement varied from 0.2m at Wisbech, and 0.3m in Worcester to about 1.0m in Lincoln and Northampton. The radial distance the displacement extended over varied from 0.1m in Lincoln to 1.0m in Northampton;
- the formation of cracks and voids was observed in Lincoln;
- mixing of layers adjacent to piles was observed in Northampton and Lincoln;
- disintegration or breaking up of thin hard layers adjacent to piles was observed in London;
- artefacts were observed to have been dragged down by piles at Worcester 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.

Table 5: Summary of archaeological observations

Place	Pile type	Pile diameter (m)	Soil type	Vertical displacement (m)	Horizontal radius of disturbance (m)
Northampton	circular driven	0.48	deep cultivated soils	1.0	1.0
Wisbech	borehole	0.12	silts and clays	0.2	0.5
Number 1 Poultry London *	variable				
Thames Exchange London *	variable				
Lincoln	square driven	0.25	compact clay silt	1.0	0.1
Worcester	square driven	0.30		0.3	0.3

* On some sites accurate measurements were unavailable and measurements have therefore not been provided.

8.2 Engineering studies on piling

Engineers have undertaken many studies on the interaction of piles with the surrounding sediments, both during insertion and afterwards. 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 the different types of piles impact in very different ways and they will therefore be discussed separately in this study.

One factor that is common to all types of piles are the potential pile movements after construction due to water or soil movements, the latter possibly caused by adjacent excavation. These movements are generally small and are likely to be of limited significance; however, these movements could increase the impact of the piles beyond that envisaged in their initial design. The impact of ground movements on piles due to adjacent excavation has been considered by Poulos and Chen (1997) and Wong and Chua (1999) as was noted above in Section 7.3.

Two studies have considered the impact of major water level changes on piles. Crilly and Driscoll (2000) examined ground heave problems that result from piling in areas where trees have recently been removed. Ground heave near trees was 160mm over 10 years and 60mm over 10 years 28.9m away from where the trees had been. In such conditions pad foundations are not recommended but short bored piles should be used. Also piles of greater size (length) than appears obvious may be needed to cope with the re-watering of the soil. A similar study undertaken through a combination of experiment and mathematical modelling by Georgiadis, Potts and Zdravkovic (2003) examined the impact of rising water table levels on piles in partially saturated soils. They concluded that if a pile tip is in partially saturated levels when the water table rises this can lead to excessive pile settlement. One of the main determining factors was the pile load; at low pile loads heave is predicted while at high pile loads excessive settlement occurs.

Piles can impact on the groundwater level. This can happen where secant pile walls are constructed as they can create impermeable barriers altering underground water flow. This is one of the of the factors that has resulted in rising groundwater in London, where impermeable basements have created underground dams stopping water flow over the impermeable London Clay (Nixon 1998).

One area that is receiving consideration at present is the reuse of old piles. Chow (2002) has suggested that this is cost-related as in London it can cost between two and five times as much to remove an old pile as to insert a new one. However, there are problems with the re-use of piles including a lack of detailed knowledge available as to the condition and load capacity of many old piles, and potential limitations on the design and structure of the new building. In heavily developed urban centres the cumulative history of development has resulted in a congested subsurface environment, where old foundations and services leave limited space for new development. This has prompted engineers to look at the potential for reusing foundations and, although not considering archaeology specifically, this work could have important implications in preserving archaeology *in situ*. The Re-use of Foundations for Urban Sites (RuFUS) is an EC 5th Framework project that is assessing the potential and problems of reusing foundations, developing methodologies for assessing pile strength, and developing a "Re-use of Foundations Decision Model" to enable the economic implications and potential risks of foundation re-use to be systematically assessed. Within the RuFUS project the requirements, both technical and documentary, for designing re-usable new foundations are also being considered. For foundation re-use to become a regular practice this would require new buildings to be constructed on foundations laid so that they could be easily adapted, with records kept through the life of the initial and subsequent building as to the design of the foundations, their load bearing capabilities, and any problems encountered with them during construction and throughout their life.

There are limited examples of pile re-use as a means of preserving archaeology, although at Lincoln the construction of a new City and County Museum is a particularly appropriate case for re-using old piles *in situ* (Williams and Chaddock 2003). Here the piles from a late 1960s multi-storey car park were reused in the new building, although additional piles were needed to cope with the design of the new building. However, the re-use of the old piles did significantly reduce the disturbance of *in situ* archaeological deposits.

An alternative strategy to re-using old piles is to drill them out and insert the new piles in the same holes (Hughes and Butler 2004 and Hughes *et al* 2004b). This issue will be discussed further in Section 13.1.

8.3 Driven piles

Driven piles have traditionally been one of the most commonly used pile types in the construction industry, with their use in Britain dating back to the late Iron Age. Modern driven piles are usually manufactured from concrete or steel. All archaeology on the line of a pile 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. Driven piles are displacement piles which cause compaction, and horizontal and vertical movement of the surrounding sediments. Dynamic stresses are also induced by the hammering action of the piling rig.

The potential impacts to archaeology 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 from the introduction of concrete.

Observations of some of these impacts have been made on archaeological sites such as Farrier Street, Worcester; Market Mews, Wisbech; the Barclaycard site, Marefair, Northampton; as well as various sites in London (see Section 8.1). However, the only recorded example of piles being inserted and immediately examined for adverse archaeological effects was on the JunXion Lincoln (Davies 2003).

A review by Stockwell (1984) examined different types of foundation techniques based on anecdotal rather than quantitative evidence and noted that with driven precast concrete piles disturbance may not extend far beyond the pile, but if the piles are closely spaced there may be little archaeology left *in situ*. Stockwell's observations were made in York and the results in the waterlogged, organic-rich deposits and fine-grained alluvial deposits may not be typical of the impact of these piles in other soils. This highlights one of the basic problems for archaeologists in understanding the impact of driven piles. Archaeologists base their knowledge on field observation and often do not understand the physical processes at work or how the interaction between pile and the deposit varies for different types of soil/sediment. Not surprisingly, engineers have studied the interaction of piles and soils in much greater detail, but their concern is 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 potential archaeology in the soil.

Pestana *et al* (2002) reviewed the research on soil deformation and soil water pore pressures around piles. Research started with the first studies in the 1940s and 1950s, which suggested that piles in soft clay caused significant distortion adjacent to the pile and minor affects up to two diameters from the pile. Early research also noted the affects on pore water pressure from pile driving; ground shear strength was found to be reduced following pile driving but recovered as pore water pressure dissipated, with maximum pore water pressure adjacent to the pile occurring as the pile tip passed by. Quoting from Cooke and Price (1973) they recorded that for a 168mm diameter pile, with measurements taken at a depth of 2m below ground level, there were minor displacements of soil until the pile was at a depth of 1.5m then large outward displacements of 10mm to 20mm occurred. Vertical displacements were found to be downwards as the pile tip approached, but upwards as the pile passes. Other work has emphasised the importance of radial displacements (Steenfelt *et al* 1981); in laboratory tests radial displacements on average accounted for about 80% of the deformation predicted by cavity expansion theory while vertical displacement, which comprised 10% of the remaining deformation, was mainly within 1 pile diameters distance from the pile.

Pestana *et al* (2002) also undertook experimental work with a test on lateral deformation using a 610mm diameter pile in clay with one thin sand layer in the middle of the clay. Measurements were taken at approximately 1m, 1.6m and 2.5m away from the pile centre immediately after piling. This recorded that at 1m away the maximum horizontal displacement was 69mm with an average displacement of 37mm between 10m and 18m below ground level. At 1.6m away from the pile the maximum horizontal displacement was 48mm and the average was 33mm, and finally at 2.5m away the maximum horizontal displacement was 28mm with an average of 21mm. As excess pore water dissipated there was some lateral consolidation, with average return deflections of 7mm, 6.5mm and 5.5mm respectively after 47 days. After 678 days return deflections were 12-15 mm, 9mm and 8mm respectively. Measurements of excess pore water pressure dissipation showed that varying timescales were required before measurements returned to normal and that this depended on the sediment type. In clay near a sandy layer 80% of dissipation had occurred after 50 days while in the centre of thick clay layers 80% dissipation occurred at 80 days.

A study by Sagaseta and Whittle (2001) related predictions from a mathematical model to field observations and three main conclusions were drawn. Firstly, driven piles cause horizontal displacement and ground heave; the heave is associated with radial and circumferential cracking in some soils such as stiff clays. Secondly, pile penetration generates pore water pressure. And finally, dissipation of pore water pressure causes consolidation and settlement of soil; in some cases the settlement can be greater than the initial heave resulting in a net reduction in ground level.

Hwang *et al* (2001) considered the impact on the pile of different soils. This was studied experimentally and they showed that the properties of the soil may be altered by pile driving. Among the observations recorded it was found that at a distance of 3 pile diameters from the pile centre:

- during pile penetration pore water pressure began to rise when the pile tip reached 4 to 7 diameters above the measuring point, and reached a maximum value when the pile tip passed 4 diameters below the measuring point;
- excess pore water pressure in a sandy layer at 6m below ground reached a value equal to 1.5 times the effective overburden pressure. The excess pore water pressure in a clayey layer at 9m below ground reached 3.5 times the effective overburden pressure; [4]
- maximum excess pore water pressure build-up decreased rapidly with an increase in distance from the pile;
- excess pore water pressure in a sandy layer reached a static condition in 3.5 minutes, whereas in a clayey layer it required 18 hours. Dissipation of excess pore water pressure was always much faster in a sandy layer than a clay layer;
- lateral displacement of the ground caused by pile driving decreased with an increase in distance from the pile;
- at a distance of 1.5 diameters from the pile centre, the measured maximum heaving at ground surface was 36mm;
- the penetration force measured at the pile tip and the number of blows required for each metre's penetration during the driving process showed good correlation with changes in stratigraphy;
- pile driving produced high-frequency vibrations. These sent shock waves through the ground which spread out from the pile.

Work by Teh and Wong (1995) on the impact of excess water pressure created by piling has considered how dissipation results in soil compaction and settling. This can result in down-drag forces on precast concrete piles. However, other causes of down-drag do occur and are probably more important. One result of all the movement between pile and soil is that in driven piles the zone of soil adjacent to the pile is completely remoulded by the installation process.

---

[4] **If excess pore water pressure exceeds effective overburden pressure, ground heave would be expected.**

A mathematical model of the behaviour of sand under stress (Simonini 1996) suggests that particles are only crushed or broken beneath the pile, not adjacent to it.

The nature of the stresses that occur between piles and the sediment around them for completed piles depends on how the pile bears its load. Lee, Bolton and Al-Tabbaa's (2002) study examined drag loads on piles and resulting down-drag. They found that end-bearing piles had high drag load and low down-drag, while friction piles had low drag load and high down-drag[5].

The visible disturbance of the soil from piling can be seen as distortions in the layers it passed through and smearing of sediment along the side of the pile. This property has been studied on vertical drains used to speed up consolidation by Hird and Moseley (2000). The data from this are of relevance as the drains were inserted with a full displacement mandrel. The tests were conducted on alternating layers of fine sands and clays, the thickness of layers varying with sand usually 2mm thick and clay around 20mm. This study identified that:

- layers were bent down adjacent to the drain;
- displacement of sand layers was visible up to 30mm from the 25mm drain but pore pressure data showed the effect of smear was within a radius of 20mm;
- vertical displacement was up to 13mm, and continuity of sand layers was lost with a clay smear separating the sand layer from the drain;
- severity of smearing (in terms of water flow) increased with decreasing clay layer thickness and sand layer thickness;
- deformation of sand layers was not axially symmetrical.

Further scale model research by Hird and Sangtian (2002) found the smear effect could be reduced by changing from a circular sectioned mandrel to a slim rectangular one.

One major study has been undertaken on the impact of piling on adjacent buried artefacts through stresses on the sediment (Sidell *et al* 2004; Allison and Higuchi pers comm). This study used test cells to study the effect of static and dynamic stresses on buried finds. The materials used were glass, bone and wood, these have decreasing brittleness. The mediums the test were undertaken in were sand and gravel. This study varied static and dynamic stresses in the test cells to mimic the effects of hammered, vibro- and continuous flight auger (CFA) piles. Vibro-piles are often used today as they are quieter. The results suggest that vibro-piles produce much greater stresses in sediment and objects while CFA produce negligible vibrations. The study has suggested which stress conditions cause failure in different materials. It is intended that hazard charts will be drawn up that will show the conditions which will cause failure in different materials. The aim is to produce usable information for archaeologists based on determining what stresses would be produced by a particular piling technique in a known sediment. Reference to a hazard chart should determine the threat to buried artefacts from piling. There will be

---

[5] The drag load is the compressive force on a pile caused by the sediment around it settling, and the down-drag is the settlement on the pile due to the drag load.

complicating factors in the field as it is known that structures in the ground affect how stresses are transferred, as does soil moisture content.

The impact of piling on soil chemistry has been subject to a study by the Environment Agency (2001; see also Westcott, Smith and Lean 2003). Their concern was how piling may impact on ground contamination but many of the processes operating will also be relevant to archaeological discussions of potential changes in soil chemistry. The study defines six scenarios by which pollution (contamination) can result in environmental impacts and thus what chemical and hydrological impacts can occur on buried archaeology. The study considered displacement piles, non-displacement piles and penetrative ground improvement. The six scenarios are:

1: The creation of preferential flow paths, allowing contaminated groundwater and leachate to move downwards through low permeability layers into underlying aquifers or between permeable horizons in a multilayered aquifer. (Applies to all piles, Vibro-replacement Concrete Column [VCC] or stone column.)

2: The breaching of impermeable covers (caps) by piling or penetrative ground improvement, allowing surface water infiltration into contaminated ground (thus creating leachate), or allowing the escape of landfill or ground gases. (Applies to all piles, VCC or stone column.)

3: Contaminated arisings being brought to the surface by piling work, with the risks of subsequent exposure for site workers and residents, run-off into surface waters, and the need for appropriate handling. (Applies to non-displacement piles.)

4: The effects of aggressive ground conditions on materials used in piles, where the secondary effect is to increase the potential for contaminant migration. (Applies to all piles, VCC, or stone column.)

5: Driving contaminated material downwards into an aquifer during installation. (Applies to driven piles.)

6: Concrete or grout contamination of groundwater and nearby surface waters. (Applies to *in situ* formed piles or VCC.)

This study has demonstrated the range of different ways that hydrological changes can be created in a site and how potentially damaging chemical contaminants could be brought into contact with archaeological deposits.

Two previously mentioned studies by Wong and Law (1999) and Ohsaki (1982) have suggested that chemical interaction between steel piles and the soil are generally slow and limited in nature and are therefore unlikely to have major or rapid impacts on the soil chemistry. However, no data on the changes from the introduction of concrete piles, with much larger masses, was identified. The study from York (Carrott *et al* 1996 and Davis *et* *al* 2001) has shown that chemical reactions can take place between concrete bodies and the soil.

Summary – driven piles

Table 6: Summary - driven piles

Impact type	Comments/keywords	Key refs
Physical	Piles cause static and dynamic stresses. Long-term loading of soil. Compression of deposits. Drag-down of sediments around pile. Imposed stresses fracture artefacts.	Davies 2003, 2004 Hinman 2002 Nixon 1998 Dalwood et al 1994 Pestana et al 2002 Sagaseta and Whittle 2001 Hwang et al 2001 Simonini 1996 Lee, Bolton and Al-Tabbaa 2002 Hird and Moseley 2000 Sidell et al 2004
Hydrological	Piles can puncture impermeable layers. Pore water pressure raised, leading to water movements. Water pathways created along smear zones adjacent to pile.	Crilly and Driscoll 2000 Wescott, Smith and Lean 2003 Geordiadis, Potts and Zdravkovic 2003 Nixon 1998 Pestana et al 2002 Hwang et al 2001 Teh and Wong 1995
Chemical	Concrete or steel introduced into soil may change chemical environment. Migration of contaminants/chemicals between deposits.	Environment Agency 2001 Wescott, Smith and Lean 2003 Wong and Law 1999 Ohsaki 1982 Davis et al 2001 Carrott et al 1996
Biological	Uncertain if piling increases biological activity.	

Current mitigation – driven piles

Table 7: Current mitigation – driven piles

Impact type	Comments/keywords	Key refs
Physical	Limit extent to 5% or less of archaeologically sensitive areas. Devise piling layout to avoid archaeology if possible. Monitoring of ground movements is occasionally undertaken. Re-use of old piles or pile locations. Change shape of the pile cross-section.	Chow 2002 Hughes and Butler 2004 Hughes et al 2004b Hird and Sangtian 2002 Williams and Chaddock 2003
Hydrological	Monitoring of ground water is occasionally undertaken.	
Chemical		
Biological		

8.4 Vibro-piles

Although becoming more common in their use, vibro-piles have been much less studied by engineers and archaeologists. They are similar to hammer-driven piles in that they are displacement piles but the stresses induced by their insertion are quite different. The main difference (Sidell *et al* 2004; Allison and Higuchi pers comm) is that the stresses from vibro-piles are much greater than those from hammer-driven piles and that they are therefore much more likely to be destructive to buried artefacts in the ground.

Other physical effects, as well as chemical and hydrological effects, are likely to be similar to driven piles as was outlined in the Environment Agency (2001) study on contamination (Section 8.1).

Summary – vibro-piles

Table 8: Summary – vibro-piles

Impact type	Comments/keywords	Key refs
Physical	Piles cause static and dynamic stresses. Long-term loading of soil. Compression of deposits. Drag-down of sediments around pile. Crushing and fracturing of sediment particles. Imposed stresses fracture artefacts.	Sidell *et al* 2004
Hydrological	Piles can puncture impermeable layers. Pore water pressure raised, leading to water movements. Water pathways created along smear zones adjacent to pile.	
Chemical	Concrete or steel introduced into soil may change chemical environment. Migration of contaminants/chemicals between deposits.	
Biological	Uncertain if piling increases biological activity.	

Current mitigation – vibro-piles

Table 9: Current mitigation – vibro-piles

Impact type	Comments/keywords	Key refs
Physical	Limit extent to 5% or less of archaeologically sensitive areas. Devise piling layout to avoid archaeology if possible. Monitoring of ground movements is occasionally undertaken.	
Hydrological	Monitoring of ground water is occasionally undertaken.	
Chemical		
Biological		

8.5 Continuous flight auger

Continuous flight auger (CFA) piles have been extensively used on archaeological sites. These are often thought to be less destructive than driven piles as they are non-displacement piles and should not, in theory, impact beyond the footprint of the pile. However, there are many potential problems with the technique if not operated properly. With this technique, a hole is bored by an auger and as it is withdrawn concrete is pumped in to form the pile. If the rate of concrete pumping does not correspond with the withdrawal of the auger, voids can be left behind. If too much concrete is pumped in, it can dissipate into the surrounding soil. There is also the suggestion that the auger head could get stuck into large buried timbers, spinning them around and churning up a much larger area than the pile itself.

Relatives of the CFA are small- and large-diameter bored piles, where the concrete is pumped in after removal of the auger, and Stockwell (1984) has considered the impact of these types of piling techniques. He has noted in both cases that a twisting effect can be imparted in the surrounding soil causing disturbance up to 0.25m away from the hole. This effect can be reduced by using bentonite slurry to shore the hole as this reduces the friction between the auger and the soil. The use of a liner should remove this problem entirely.

The vibrations and ground stresses created by CFA piles are much less than those induced by hammer-driven or vibro-piles (Allison and Higuchi pers comm).

The potential hydrological impacts have already been referred to in the discussion of the 2001 Environment Agency study (Section 8.3). In the case of CFA piles drag-down problems should be reduced to almost nothing, but a core of material is completely lost.

Summary – continuous flight auger

Table 10: Summary – continuous flight auger

Impact type	Comments/keywords	Key refs
Physical	Static and dynamic stresses significantly reduced in comparison to non-displacement piles. Churning of deposits possible, if debris trapped in auger head. Potential voids created during installation may lead to soil movements.	Stockwell 1984
Hydrological	Piles can puncture impermeable layers. Water pathways may be created along smear zones adjacent to pile liners (if used).	Environment Agency 2001
Chemical	Concrete or steel introduced into soil may change chemical environment. Liquid concrete or grout may migrate into voids or be forced between layers if over-pumped. Migration of contaminants/chemicals between deposits.	Environment Agency 2001
Biological	Uncertain if piling increases biological activity.	

Current mitigation – continuous flight auger

Table 11: Current mitigation – continuous flight auger

Impact type	Comments/keywords	Key refs
Physical	Limit extent to 5% or less of archaeologically sensitive areas. Devise piling layout to avoid archaeology if possible. Use of cutting heads may reduce impact on deposits adjacent to pile. Monitoring of ground movements is occasionally undertaken.	
Hydrological		
Chemical	Liners reduce potential for liquid concrete or grout to migrate or interact with archaeological deposits.	
Biological		

8.6 Screw piles

Screw piles have been used since the nineteenth century, but mainly in marine contexts in Britain. Recently they have been used on land as an alternative, potentially less destructive, pile in archaeologically sensitive areas. Sheward (2003) describes their use on a sensitive site in the cathedral close in Salisbury where 5m deep steel screw piles were inserted. These piles were chosen as they produce no spoil, are easy to remove and should have minimal impact beyond the pile, resulting in negligible disturbance. With screw piles different designs are used in different soil conditions.

Summary – screw piles

Table 12: Summary - screw piles

Impact type	Comments/keywords	Key refs
Physical	Some mixing of layers may occur.	Sheward 2003
Hydrological	Piles can puncture impermeable layers.	
Chemical	Steel introduced into soil may change chemical environment.	
Biological	Uncertain if piling increases biological activity.	

Current mitigation – screw piles

Impact type	Comments/keywords	Key refs
Physical	Limit extent to 5% or less of archaeologically sensitive areas. Devise piling layout to avoid archaeology if possible.	
Hydrological		
Chemical		
Biological		

8.7 Open-ended piles and boreholes

Open-ended or tubular steel piles are driven into the ground like solid concrete piles but as they are open-ended they should be non-displacement. However, plugging is very common on open-ended piles, effectively converting them into driven piles. Laboratory studies by Nicola and Randolph (1997) examined soil plugging and concluded that the length of soil plug in open-ended piles was related to soil density.

Boreholes used for site investigation can be considered as open-ended or tubular piles in terms of their potential impact. At Market Mews, Wisbech, Cambridgeshire (discussed earlier Section 8) the impact of a borehole was recorded, in this case drag-down and distortion of deposits around the borehole (Hinman 2002).

Many of the potential alterations to ground hydrology and movement of contaminants observed in the Environment Agency (2001) study apply here.

Summary – open-ended piles

Table 13: Summary – open-ended piles

Impact type	Comments/keywords	Key refs
Physical	Piles cause static and dynamic stresses. Long-term loading of soil. Compression of deposits, where plugging occurs. Drag-down of sediments around pile. Imposed stresses fracture artefacts.	Nicola and Randolph 1997 Hinman 2002
Hydrological	Piles can puncture impermeable layers. Water pathways created along smear zones adjacent to pile. If boreholes are not refilled properly, they can act as water routes, bypassing impermeable layers.	Environment Agency 2001
Chemical	Steel introduced into soil may change chemical environment. Migration of contaminants/chemicals between deposits.	Environment Agency 2001
Biological	Uncertain if piling increases biological activity.	

Current mitigation – open-ended piles

Table 14: Current mitigation – open-ended piles

Impact type	Comments/keywords	Key refs
Physical	Limit extent to 5% or less of archaeologically sensitive areas. Boreholes usually undertaken as part of geotechnical site evaluation, thus limited to less than 1% of site area. Devise piling layout to avoid archaeology if possible. Monitoring of ground movements is occasionally undertaken.	
Hydrological	Monitoring of ground water is occasionally undertaken.	
Chemical		
Biological		

9 SHALLOW FOUNDATIONS

As an alternative to piling, shallow foundations can be used. These do not have the same load-bearing potential as piles and are therefore not used for large buildings or on unstable ground. There are two types of shallow foundations: pads and rafts. Pads are smaller and are only located under the load bearing walls or columns, whereas rafts cover the whole footprint of the building.

Physical damage from shallow foundation construction starts with the excavation of the foundation trench or trenches. Within the foundation trench all archaeology will be destroyed and lost, unless preserved by record. As shallow foundations do not extend to a great depth these may be located above the archaeology. The weight of the foundations and building will apply a static load to the ground and this could impact on buried archaeology. The compressive stress from localised foundations could be more than ten times the *in situ* overburden pressure (Hyde pers comm). Compression of deposits is possible, but the building will have been designed so as to avoid substantial settlement, as this would not be desirable.

The introduction of a mass of concrete can lead to chemical reactions with the soil as was observed in York (Carrott *et al* 1996 and Davis *et al* 2001), but how serious this is will depend on the existing soil structure and chemistry.

One interesting example of the interaction of concrete foundations and archaeology was observed at Regis House, London. Concrete foundation piers were constructed when the house was built in the 1930s. These were constructed in contact with exposed large Roman timbers, parts of which had been sawn out to make room for the foundations. During work in 1995-6 the timbers were re-exposed and found to have suffered surface decay and shrinkage. The decay had only occurred where the wood had been exposed in the original 1930 excavations and the shrinkage was on the end grain adjacent to the concrete and appears to have occurred as the concrete cured. Once the concrete had cured stable anoxic conditions appear to have been re-established and decay stopped (Nixon 1998).

Summary – shallow foundations

Table 15: Summary – shallow foundations

Impact type	Comments/keywords	Key refs
Physical	Removal or truncation of shallow archaeology. Slight compaction may occur from static stress.	
Hydrological	Concrete rafts may act as water barriers (both rainfall and evaporation), thus changing soil water conditions. Potential soil shrinkage if soil dries out.	
Chemical	Introduction of large areas of concrete may lead to chemical reaction with the soil.	Carrott *et al* 1996 Davis *et al* 2001
Biological	Biological activity increases during excavation, but may cease once concrete has cured.	Nixon 1998

Current Mitigation – shallow foundations

Table 16: Current mitigation – shallow foundations

Impact type	Comments/keywords	Key refs
Physical	Archaeological preservation *in situ* by redesign. Archaeological preservation by record.	
Hydrological	Use lining to stop grout migration in foundation trenches.	
Chemical	Use lining to stop grout migration in foundation trenches.	
Biological		

10 GROUND IMPROVEMENTS

Charles and Skinner (2001) examined the compressibility of foundation fills in relation to construction on brownfield sites. They examined two concepts: creep or consolidation settlement, and collapse compression. The former is an ongoing process in all fills and takes place due to the weight of the sediment. When loads are applied, ie a new building is constructed, additional settlement will take place, although any movement is usually quite small. Collapse compression occurs when sediments are inundated with water, either from a rising water table or surface water penetration, and compressions of up to 6% have been recorded. This would be a great hazard for any building so any ground susceptible to this would normally be improved prior to construction.

As collapse compression is a risk on some brownfield sites, and as more are being developed, ground improvement is likely to become an increasing problem for archaeologists.

Ground improvement includes a range of techniques that can impact on buried archaeology. Charles (2002) summarises the aims and main techniques used in ground improvement and gives a basic classification of ground improvement techniques currently used. He subdivides the techniques into two groups based on what he sees as the two basic approaches, densification and stiffening columns.

Within densification he further subdivides the techniques based on whether this is achieved through compaction or consolidation. Compaction is quick and usually involves squeezing air out of the deposit while consolidation is slower and usually involves squeezing water out of the deposit.

Descriptions of how each technique works are provided in Charles (2002). The following list names the main techniques and notes the principal possible physical impacts on the archaeology.

Densification can be undertaken by compaction through:

a. deep vibratory compaction - depth vibrators are used to set up horizontal vibrations. This technique is being applied to an increasing range of sediments, impacts include dynamic forces and compaction of sediment;

b. impact compaction - both dynamic compaction and rapid impact compaction are forms of impact compaction. Dynamic compaction involves dropping a heavy weight on the ground surface while in rapid impact compaction a modified piling hammer applies impacts through a steel compacting foot that is in constant contact with the ground surface. Impacts on archaeology arise from dynamic forces and compaction of sediments;

c. explosive compaction – although explosive contraction does work it is technically difficult and considerable experience is required to apply it successfully. Impacts include dynamic forces and compaction of sediments;

d. compaction grouting - compaction grouting involves the injection of a grout under pressure into the soil mass, consolidating, and thereby densifying surrounding soils *in situ*. Although classified as a densification technique, compaction grouting is also related to consolidation techniques and stiffening columns. Impacts include the introduction of material that may change soil chemistry and compaction of sediments.

Densification can also be undertaken by consolidation where temporary preloading prior to construction is used to make the ground stiffer under subsequent applied loads:

a. applying a surcharge of fill without installing drains - this is the simplest method whereby the ground is loaded with additional fill, and can work well on highly permeable soils where soil water is expelled leading to consolidation. Impacts include static forces, consolidation of sediments and dewatering;

b. applying a surcharge of fill with the installation of drains. In low permeable soils, such as clays, drains will speed up the dissipation of excess pore water pressures. Impacts include static forces, consolidation of sediments and dewatering;

c. lowering the groundwater level - in high permeability soils lowering the groundwater may increase applied stresses, resulting in consolidation. Impacts include consolidation of sediments and dewatering;

d. vacuum preloading - vacuum pumps apply suction under a sealed membrane. This results in the water in the soil moving to the surface due to the hydraulic gradient created. Impacts include consolidation of sediments and dewatering.

Stiffening columns can be added to sediments to form a new composite soil structure. This is usually used where soils are not easy to densify, although some densification may occur through the addition of stiffening columns. There are four commonly used techniques:

a. vibrated stone columns - destroys archaeology where the column is inserted and vibrations disturb an area around the column. The introduction of material may change soil chemistry;

b. soil-stabilised columns - destroys archaeology where the column is inserted and vibrations disturb an area around the column. The introduction of material may change soil chemistry;
c. jet-grouted columns - destroys archaeology where the column is inserted and may disturb an area around the column. The introduction of material may change soil chemistry;
d. vibrated concrete columns (vibro-columns) - destroys archaeology where the column is inserted and vibrations disturb an area around the column. The introduction of material may change soil chemistry.

Archaeological assessments of the impacts of ground improvements have been limited; however, Stockwell (1984) looked at different types of ground stabilisation in his review of development impacts on archaeology. Although this study was based on anecdotal rather than quantitative evidence, it argued that ground stabilization is more destructive than piling. The problems associated with the three main techniques were identified and discussed.

With dynamic compaction, where large weights are used, Stockwell noted that large forces compress deposits and displace them outwards, and that artefacts will also be crushed and stratigraphic relationships displaced.

In the case of vibrated stone columns, a poker vibrator is inserted in the ground and vibrations transmitted horizontally. The hole created by the poker is filled with aggregate and a stone column is created as the poker is withdrawn. The damage caused will depend on the spacing between the columns. As compaction extends for about 2m horizontally, everything within that area is heavily compacted and subject to crushing forces. Within the column there will be total destruction of the deposits.

Dynamic piling compaction involves driving a plugged steel tube into the ground. The plug is then expelled and stone aggregate introduced which expands from the base of the tube. The tube is then withdrawn with further compacted aggregate introduced. Stockwell noted that this was unusual for a foundation or ground improvement technique in that it causes more damage at depth than near the surface, and that on weak deposits the expansion of the aggregates at the base of the tube can be extensive.

Enhancements to ground improvement techniques are being developed all the time. Slocombe, Bell and Baez (2000) have noted that the machines originally used for this technique could only densify ground with up to 15% of fine sediment in the deposit. However, new machinery will work with sands without the addition of stone aggregate. This means that the technique has the potential to be applied to many more sites than used to be the case, thus potentially damaging more archaeology.

The Environment Agency study (2001) noted how some of these stiffening column techniques used in ground improvement could impact on groundwater hydrology or lead to the movement of material that may change soil chemistry (Section 8.3).

Experimental lab tests were used by Hird and Moseley (2000) to examine the impact of the insertion of vertical drains used to speed up consolidation. These looked at the deformation and smearing of alternating layers of sand and clay and identified that:

- layers were bent down adjacent to the drain;
- displacement of sand layers was visible up to 30mm from the 25mm diameter drain but pore pressure data showed the effect of smear was within a radius of 20mm;
- vertical displacement was up to 13mm. Continuity of sand layers was lost with a clay smear right across the drain surface;
- severity of smearing, in terms of water flow, increased with decreasing clay layer thickness and sand layer thickness;
- deformation of sand layers was not axially symmetrical;
- sheathed mandrels gave less displacement than unsheathed mandrels. This resulted from friction as the sheathed mandrels were smoother.

Further research by Hird and Sangtian (2002) found that these effects could be reduced by changing from a circular-sectioned mandrel to a slim rectangular one.

Summary – ground improvement

Table 17: Summary – ground improvement

Impact type	Comments/keywords	Key refs
Physical	Static and dynamic forces. Compaction of deposits. Crushing of artefacts under stress.	Charles and Skinner 2001 Charles 2002 Stockwell 1984 Slocombe, Bell and Baez 2000 Hird and Moseley 2000
Hydrological	Soil compaction and consolidation may restrict water movement and lead to dewatering. Creation of water pathways by introduction of stone stiffening columns.	Environment Agency 2001
Chemical	Introduction of concrete or aggregates may alter soil chemistry.	Environment Agency 2001
Biological	Uncertain if biological activity increases with ground improvement.	

Current mitigation – ground improvement

Table 18: Current mitigation – ground improvement

Impact type	Comments/keywords	Key refs
Physical	Archaeological preservation by record. Archaeological preservation *in situ* by redesign (to select most appropriate method of ground improvement). Change shape of mandrel head to reduce displacement and smearing.	Hird and Sangtian 2002
Hydrological		
Chemical		
Biological		

11 SITE BURIAL

Site burial can be undertaken during site enabling works or as a mitigation procedure for the protection of the archaeological layers. However, this may result in compaction through physical loading (static stress), which may cause fracturing and cracking of artefacts. Each metre of fill will increase vertical compression by 10 to 20 kPa (kiloPascals). Potential chemical impacts will depend on the nature of the material used to bury the site, careful choice of the material used should minimise chemical impacts.

Garfinkel and Lister (1983) undertook a study to assess damage inflicted on artefacts by artificial site burial. They created a fake 'site' and then buried it under a 75ft (22.85m) embankment; tunnels were located in the embankment so that the site could be excavated later. After excavation most artefacts were found in good condition including stone tools and charcoal sticks, however, faunal remains showed signs of damage including cracking. The faunal remains were also damp with signs of decomposition present. They concluded that there was little vertical or horizontal movement; however, the access tunnel and 'site' were not found in the relationship expected but had 'moved' relative to each other. This could be due to movements during construction of the culvert or to movements due to burial. This suggests that the process of site burial might cause upstanding structural remains to be displaced.

Several other studies have been undertaken in the United States of America on the use of burial as a means of site stabilization and *in situ* preservation. Much of this work has been undertaken by Thorne (1988), who described the decision-making process for undertaking site stabilization but did not describe the techniques used. He listed the most common techniques: bulkheads, synthetic technology, stone covering, continuous hard covering, mattresses, earth burial, vegetation and innovative technology. A further review by Thorne (1991a) provided a general review of the problems and advantages of site burial, noting the need to evaluate the site components, the preservation conditions needed, and how this should be combined with long term monitoring to determine if the desired results have been achieved. He has also produced a publication on American sources of information on site stabilization (Thorne 1991b).

The effects of deliberate site burial have not been studied as comprehensively in the UK, although a few examples have been published. Hughes and Seaman (2004) describe how London Clay was used to cover archaeological deposits preserved *in situ* on the site of the Millennium Bridge. Clay was chosen to create a low permeability barrier which would maintain the buried organic-rich deposits in a saturated, low oxygen regime.

Ashurst *et al* (1989) published the mitigation strategy on the Rose Theatre including details of the re-burial procedure. However, this was designed to protect the site from the construction of the building but not in itself provide long term protection.

Temporary burial was used to protect Bronze Age timbers at Bramcote Grove in Southwark (see Section 4.4). On reopening, fungal growth was found to have taken place

(Nixon 1998). This study demonstrates that the very act of evaluation may set off processes that will lead to biological damage to the site that the burial is designed to preserve, therefore negating the process of reburial.

The choice of material with which to rebury the site is very important and Canti and Davis (1999) have undertaken a study as to which are the best sands to use for reburial. High grade silica sands are best, but these are rare and expensive. They therefore identified the most suitable characteristics to chose: low iron (these are generally pale coloured), non-calcareous, low in clay, low loss-on-ignition (less than 2%) and generally fine-grained sand.

A specific form of burial for archaeological mitigation is covering the site with an impermeable layer (concrete, tarmac). Common examples are surface car parks positioned over archaeological remains that merit preservation *in situ*. This does not add great physical stress but may change the hydrological regime as the surface prevents rainwater entering, and also inhibits evaporation. How important these alterations are will depend on the nature of deposits and the archaeology buried beneath them.

Summary – site burial

Table 19: Summary – site burial

Impact type	Comments/keywords	Key refs
Physical	Static forces. Compaction of deposits. Crushing of artefacts under stress (effect is likely to be limited since 1m of fill = 10-20 kPa).	Garfinkel and Lister 1983 Thorne 1988, 1991a, 1991b
Hydrological	Soil compaction may restrict water movement. Compaction may raise pore water pressure. Limitations on surface water ingress may cause deposits to dry out.	
Chemical	Inappropriate burial material may change soil chemistry.	
Biological	Site evaluation prior to burial may increase biological activity.	Hughes and Seaman 2004 Nixon 1998

Current mitigation – site burial

Table 20: Current mitigation – site burial

Impact type	Comments/keywords	Key refs
Physical	Burial is often used as a form of archaeological mitigation (preservation *in situ*) in its own right.	
Hydrological		
Chemical	High grade silica sands are least reactive and good for reburial, but are rare and expensive.	Canti and Davis 1999
Biological		

12 FOUNDATION REINFORCEMENT/UNDERPINNING

In developments where old buildings are being refurbished it is sometimes necessary to add additional support to the existing foundations. This can also be required to extend the lifetime of old buildings, or to make them safe. The first stage is to identify the strength of existing foundations and what additional support is needed; however, identifying the strength of buried foundations and monitoring them can be difficult (Skal'nyi *et al* 2002).

Three techniques that have been used for strengthening foundations on archaeologically sensitive sites are compensation grouting, inserting steel underpinning rods and soil extraction.

12.1 Compensation grouting

Compensation grouting involves injecting a grout of cement, sand and water under the building through tubes. The grout is injected into the ground under pressure and spreads out to add stability to the soil.

Compensation grouting was used to add support to the tower of Big Ben prior to the construction of the Jubilee Line extension (Mair and Harris 2001). This was undertaken because of fears that the stability of the tower might be compromised by the construction works. This site was unusual in that monitoring of the impact of the grouting was possible for part of the area (Nixon 1998). The monitoring work suggested that deep compensation grouting, undertaken from large shafts to enable deep deposits to be accessed, had no impact on overlying archaeological remains. However, grouting at higher levels did produce problems as the plastic pipes used to inject the grout often split. As these pipes passed through the archaeological layers and the escaping grout took the path of least resistance, any voids were filled and sheets of grout spread out through the archaeological horizons.

Summary – compensation grouting

Table 21: Summary – compensation grouting

Impact type	Comments/keywords	Key refs
Physical	Limited static and dynamic forces. Compaction of deposits. Grout can cement archaeological remains together.	Skal'nyi *et al* 2002 Nixon 1998 Mair and Harris 2001
Hydrological	Grout may contaminate the groundwater. Grout may act as a barrier to water movements.	
Chemical	Grout may alter soil chemistry.	
Biological		

Current mitigation – compensation grouting

As compensation grouting is used to support existing buildings, the work is undertaken below the structure in an area that cannot usually be accessed for either pre-construction evaluation or post-construction monitoring. Thus the initial and long-term impacts on the archaeology can rarely be assessed.

12.2 Steel underpinning rods

Reinforcing works were undertaken on the foundations of the Cathedral of Saint Pierre, Geneva (Bonnet 1987). The underpinning involved the insertion of 10m long steel rods through the foundations of the building and into the underlying ground. While underpinning the building the opportunity was taken to display the remains of an earlier cathedral beneath the present building.

Summary – steel underpinning rods

Table 22: Summary – steel underpinning rods

Impact type	Comments/keywords	Key refs
Physical	Limited static and dynamic forces during insertion of rods.	
Hydrological	Impacts likely to be slight, unless impermeable layers are punctured.	
Chemical	Chemical reactions could occur between rod and soil. Corrosion of rod could cause expansion, and damage archaeological deposits.	
Biological		

Current mitigation – steel underpinning rods

As the rods are relatively thin, the area of the site impacted should be small. However, as they are supporting a standing building there is little that can be done to assess their impact; at Saint Pierre the excavation could not examine the rods as this would potentially have undermined the support they were providing.

12.3 Soil extraction

This technique was used to stabilise the leaning tower of Pisa (Burland 2001). A hollow stem auger attached to a drilling rig was used to remove soil from beneath the tower to correct its lean This work was very slow and had to be undertaken very carefully, allowing the tower to be monitored as work proceeded. No evaluation of the archaeology under the tower was possible, nor mitigation for loss of archaeology due to soil extraction.

Summary – soil extraction

Table 23: Summary – soil extraction

Impact type	Comments/keywords	Key refs
Physical	Removal of archaeology within excavated sediments. Alteration of static forces. Ground movements resulting from soil settlement.	
Hydrological	Possible alterations to hydrological regime.	
Chemical	Possible chemical changes relating to soil hydrology.	
Biological		

Current mitigation – soil extraction

It is almost impossible to undertake any effective mitigation measures.

13 CURRENT MITIGATION PRACTICE

As has been previously described (Section 1.2), archaeology is now a material consideration within the planning process. The final stage of archaeological works is the implementation of mitigation measures. Before a scheme of archaeological mitigation can be agreed for a development the archaeology must be evaluated, and the quality of any mitigation scheme will be dependent on the quality of the evaluation. How the evaluation is carried out will depend on the nature of the site, its likely archaeology and its accessibility. Generally, field evaluation trenches are relatively small as this limits the area of potential archaeological impact. However, Badcock *et al* (2004) have argued that on large brownfield sites open evaluation areas are needed to allow the archaeology to be more fully understood.

As Miller identified in his 1994 paper, the decision on whether to dig or preserve a site *in situ* is hugely dependant on the available information on the site and is based on existing knowledge and the results of field evaluation. In the case of York a pioneering GIS system has allowed better informed judgements to be made as to the archaeological potential of a site and its significance.

As long ago as 1989 Wainwright had identified that preservation *in situ* could be achieved by:

- sympathetic design;
- specialised minimally damaging foundations;
- raising the ground level;
- careful siting of open areas.

All of these require information and careful forward planning.

In developing mitigation strategies archaeologists and engineers should work together from the earliest stages of the proposed development, as redesigning foundations or structures is expensive and time consuming. The range of sources of information available for archaeologists and engineers to draw upon is wide; this includes the results of field evaluations, archives of previous work, Sites and Monuments Records or Historic Environment Records, and geotechnical records such as the British Geological Survey database, which contains over 1,000,000 borehole and well records. However, in the early stages of developments, during the desk-based research, archaeologists tend to consult archaeological records and engineers consult geotechnical records, although they will consult data provided by each other, eg archaeologists will examine borehole data. However, there are large geotechnical databases available in some cities, some of the best examples being the Helsinki Geotechnical Database (Vähäaho 1999) or the London Docklands Geotechnical Database (Howlands 2001), which will contain data covering wider areas and if consulted by archaeologists might aid their understanding of the archaeological potential of the site.

The Ove Arup (1991) study of the city of York suggested that old foundations should be reused to avoid new disturbance (Shilston and Fletcher 1998). In York, this has led to new foundations being designed for subsequent reuse on important archaeological sites. This is being undertaken to avoid the gradual destruction of the site, whereby 5% of the archaeology is lost at each redevelopment. Shilston and Fletcher (1998) outline the information required if old foundations are to be reused or if new foundations are to be designed for reuse.

One aspect of mitigation schemes that has long been underdeveloped is monitoring the results of the mitigation scheme, ie if it worked. Another area that has been underdeveloped is the dissemination of information on successful mitigation schemes.

13.1 Examples of mitigation schemes

This section includes examples of published mitigation schemes and problems that were encountered.

Ashurst *et al* (1989) published the mitigation strategy on the Rose Theatre including details of the procedure followed in re-burying the site. The strategy employed here was unusual in that the building design left space to access the archaeological remains underneath the building once it was complete and further excavations are now under consideration. However, the cost to the developer including excavation costs, delays and design alterations was estimated at £11 million (Davis 2004).

Cowie and Blackmore (1999) detailed the mitigation strategy developed for the redevelopment of Bruce House in London. This involved re-use of piles and movement of new piles to less sensitive areas, partial excavation and limits on the area of basement in the new development. This limited disturbance of the site to 3.5% but archaeological problems were still encountered. In some areas features were half excavated making their interpretation difficult, while in other areas features were exposed and recorded but not excavated, leaving them undated and poorly understood. This has made interpretation of the site difficult and open to question. Also Cowie and Blackmore (1999) note that some of the issues left unanswered can only be determined by further excavation which will presumably only take place when the site is next redeveloped.

Piles were also reused during the construction of a new City and County Museum in Lincoln. New piles were needed in part for the new building, but piles from the previous building on the site, a late 1960s multi-storey car park, were also reused. The re-use of the old piles did significantly reduce the disturbance of *in situ* archaeological deposits (Williams and Chaddock 2003).

Hughes *et al* (2004a) describe how pile locations were reused on the Governor's House site in London. This was undertaken to minimise disturbance of *in situ* archaeology, and was done by drilling out the old piles and inserting new piles in the same locations, where possible. However, as there were 25 new piles (as opposed to 16 old piles), and the new piles were between 1050mm and 1800mm in diameter while the old piles were only 600mm to 750mm in diameter, there was around a four-fold increase in the area of the site impacted by the piles.

Tilly (1998) describes six mitigation strategies related to PPG16 work.

Table 24: Examples of mitigation strategies (after Tilly 1998, 3)

Scheme	Archaeological receptor	Engineering solution
Accommodation buildings	Site of Saxon town.	Designed to minimise disturbance. Where this was not possible remains were excavated.
Factory extension	Scheduled Ancient Monument. Other archaeological remains discovered. Soil cover too thin.	The area to be disturbed was excavated and recorded.
Domestic housing	Ancient burial ground. Possible formation of 'swallow holes'. Possible damage by gardeners.	The burial site was preserved by a post-tensioned concrete slab.
Commercial development	Significant archaeological remains beneath surface.	Positions of piles located to minimise damage. (Scheme became too costly and was abandoned.)
Redevelopment of office building	Significant archaeological remains about 1m below ground. Damage caused by earlier construction.	Position of piles located to minimise damage.
Woolbeding Bridge	16th-century masonry arches strengthened to meet requirements of modern traffic.	Excavated and recorded previous levels of road surfacing and fill.

Woodiwiss (1998) describes the mitigation strategy at Longtown where medieval deposits were only 200mm below the current ground surface. Here the foundations consisted of a raft requiring a maximum excavation of 150mm, while 450mm of topsoil were imported to protect the garden areas.

Following the discovery of substantial timber remains in the moat of the Tower of London (Keevill *et al*, 2004), it was decided to preserve these *in situ* rather than to excavate them. This was undertaken by reburying the remains using the deposits that had been removed from around them and setting up a monitoring programme to establish whether the pre-excavation water levels and redox conditions were re-established. Groundwater and soil moisture soon returned to normal and redox potential had also returned to normal within three months.

Hughes and Seaman (2004) describe how London Clay was used to cover archaeological deposits preserved *in situ* on the site of the Millennium Bridge. Clay was chosen to create a low permeability barrier which would maintain the buried organic-rich deposits in a water saturated low oxygen regime.

In London, redesign has been used to preserve blocks of representative deposits on some sites while allowing development of the rest of the site (Nixon 1998).

During the redevelopment of Alder, Castle and Falcon Houses in London preservation *in situ* was required as the site contained Roman and medieval Scheduled Ancient Monuments (Hughes and Butler 2004). The decision was therefore taken to insert new piles through old pad foundations. This was done by drilling through the pads (which were up to 5.5m deep and comprised concrete with iron railway tracks used as reinforcing). The piling rig was recorded as cutting precise cores for the full pile diameter, although no further details were provided. A similar strategy was employed during the redevelopment of Plantation Place (Hughes *et al* 2004b). In this case mitigation involved 50% preservation *in situ* and 50% preservation by record. In the areas of *in situ* preservation piles were again inserted through old concrete pad footings to minimise disturbance to the archaeology. During site works vertical and horizontal ground movements were also monitored.

During the proposed development at Blackfriars, Gloucester, a mitigation scheme was developed that proposed using relatively few but large piles within the footprint of the building, and upstand ground beams around the perimeter (Pugh-Smith *et al* 2004). This had three advantages: the piles only represented 3% of the site area; the piles would be reusable by subsequent developments; and the piles were large enough, at 2m diameter, for the archaeological layers to be excavated prior to development. Archaeological excavation of the piles could be undertaken within concrete pre-cast shaft lining units. However, this scheme was never put into practice as the development did not take place.

Probably one of the most complicated *in situ* preservation projects ever undertaken in Britain was on the Roman amphitheatre discovered under the Guildhall, London (Ganiaris and Bateman 2004). The remains consisted of masonry walls and wooden structural remains. The mitigation strategy in this case involved excavating basements under the amphitheatre remains so that they were totally surrounded by a modern building. This involved a number of stages to reach the desired goal. During the archaeological excavation all the wood was removed for conservation while the masonry was left *in situ*, it was then encased in plywood boxing to protect it during the construction works. The natural gravels under the walls were strengthened with an epoxy grout and supported externally while the remains were carefully undermined. This was undertaken in sections and a supporting floor was constructed as the undermining proceeded. Once the structural work was completed the masonry, which had been waterlogged, was allowed to dry slowly so as not to crack. The remains were subsequently put on public display with the intention of returning the wooden remains following conservation. This complex and expensive mitigation strategy was only possible due to the archaeological importance of the site and the financial commitment the developer was able to make to the archaeology; on most sites such a strategy would not be possible.

13.2 Monitoring programmes

Monitoring programmes are being developed to assess the results of mitigation schemes. These have frequently been undertaken on waterlogged sites to determine if anaerobic waterlogging is being maintained.

One of the best known examples of mitigation with archaeological deposit monitoring is the Marks and Spencer site in York (Davis *et al* 2001). Here dipwells (water level), neutron probe tubes (soil moisture content), moisture cells (estimate moisture content and temperature) and suction samplers were installed, while additional parameters were measured using portable dip probes (temperature, electrical conductivity, pH, dissolved oxygen and redox potential). The monitoring suggests that the burial environment on the site is stable but with seasonal variation in the upper layers. However, this cannot be confirmed due to the lack of comparable data from before the development took place. To truly interpret the data produced, Davis *et al* (2001) argue that laboratory-based analogue studies are needed to understand the effects of changes in the burial environment on the artefacts and ecofacts within it.

Peacock and Turner-Walker (2004) have described monitoring undertaken in Trondheim. This has demonstrated the difficulty of inserting monitoring probes to the correct locations without trenching, but trenching would have been destructive and therefore preservation *in situ* would not have been achieved. However, hitting the full range of deposits and most sensitive deposits cannot be guaranteed when inserting probes blind, and it is not known if the most appropriate monitors were inserted in each case. The work has demonstrated that soil water monitoring can be undertaken even in the subarctic, although there will be parts of the years when sampling is impossible as the ground water is frozen.

In Norway archaeological deposits in the centre of historic towns are now subject to tight planning control with the aim being to preserve archaeological deposits as ancient monuments (Reed 2004). While this has restricted some forms of development, it is leading to the development of innovative construction designs, avoiding piles and basements, allied to site monitoring of water, temperature, pH and redox. Site monitoring can last from five to fifteen years and is developer funded.

Monitoring of an Anglo-Saxon cemetery has been instigated under a new development in Croydon (Hughes *et al* 2004c). The monitoring has covered soil temperature, moisture and ground movements through fixed monitors as well as annual chemical testing of soil samples. After one year there had been little observable change, with the exception of soil phosphate levels which had doubled; the cause of this change is not known at the time of writing.

The physical and chemical monitoring of archaeological sites is an area that has developed in recent years. This has taken place on sites other than those threatened by construction development, with sites such as Sutton Common and Fiskerton monitored for changes in the water table, as these are threatened by dewatering through agricultural activity and changing land use.

14 MITIGATION GUIDELINES

14.1 Summary of current state of knowledge

Current knowledge is patchy, with some of the potential impacts of development on archaeology much better understood than others. This is to some degree a result of the relatively short history of research in this area and also the result of the difficulty in gaining field data while aiming to preserve archaeology *in situ*, which minimises the potential for excavation.

Research projects to examine the impact of development are being undertaken. These have been, or are, primarily focused on physical and hydrological impacts. One study recently completed at Durham was *The Response of Archaeological Sediments and Artefacts to Imposed Stress Regimes as a Consequence of Past and Present Anthropogenic Activity*. This has yet to be fully published but the results show that it is possible to predict the impact of piling on buried artefacts (Allison and Higuchi forthcoming). Further research is currently underway in the Department of Civil and Structural Engineering at the University of Sheffield. One project led by Dr C. Hird is examining the *Movement of Soil and Groundwater Around Driven and CFA Piles in Layered Ground*, while a second, led by Dr A F L. Hyde, is developing *A Stochastic Model for Damage to Archaeological Artefacts Due to New Construction Work*.

The main gaps in our knowledge and areas for potential research are identified for each of the four types of potential impact.

Physical impacts

Physical impacts come about due to the dynamic and static forces exerted on buried deposits and artefacts due to engineering works. This can lead to compression, distortion and mixing of deposits, and to surface damage, breakage or complete crushing of artefacts. In the case of excavations and piles, engineers have long studied the forces and their impact on sediments, and they understand the range of potential impacts well. The details of how these impacts vary with different soil conditions on different archaeological sites is only just starting to be investigated (Sidell *et al* 2004). Current research will improve our understanding of these impacts. The potential impacts of ground improvement techniques have been less well studied although some extrapolation can be made from the engineering studies of piling, and the dynamic and static forces involved, that will fill some of the gaps in our knowledge. Some of the ground improvement techniques are so destructive that one should assume they lead to total destruction of any buried archaeology.

In the case of physical impacts, topics in need of further research include:

- impact of piles on different soil types and layered soils;
- impact of piles on hard 'floor' levels buried beneath the ground;
- impact of compressive forces and deformation in stratified deposits;
- possibilities for the re-use of old piles (or re-drilling old pile locations);
- impact of deformities associated with excavations on buried artefacts and structures.

Hydrological impacts

Hydrological changes brought about by development processes have also been studied, particularly in relation to piling and pumping associated with large scale excavation. However, in the case of piling, the engineering studies have largely been concerned with identifying short-term changes in pore water pressure, not potential long-term alterations to water level or ground water movements. Long-term changes have been considered in the context of ground contamination, where potential water flow changes have been identified, but as yet it is not possible to be certain when and under what conditions changes to water flow will take place. Current research should answer some of these questions.

Temporary dewatering is known to lead to the degradation of organic remains, and possibly other materials, but it is not known how long the dewatering needs to last for significant damage to ensue, or if re-watering stops further degradation. Further research is certainly needed as this is a potential impact not only on the site under development but also for all the adjoining land, meaning the impact could extend over the widest area.

In the case of hydrological impacts, topics in need of further research include:

- the impact of piling on impervious clay layers and water flow;
- permanent dewatering, deposit shrinkage, artefact damage, degradation of organic material;
- impact of temporary dewatering on preservation of organic archaeological remains;
- impact of dewatering on effective stresses and compression of artefacts.

Chemical impacts

In theory, the chemical conditions that will lead to the preservation of different materials are well known. It is also known that changes in the chemical environment can have drastic effects on artefact preservation. What is not known is how the introduction of large quantities of concrete, steel or aggregate may alter soil chemistry and how this varies with different soil chemistries; this is an area in need of research. The inter-relationships of soil chemistry and hydrology are complex and will relate to the nature of the deposits in which they occur. The changes that may occur in soil chemistry due to hydrological changes are poorly understood and in need of further research. During construction works many changes in ground conditions may be temporary, eg lowering of the water table and introduction of liquid grout or concrete. The impacts of temporary changes to soil chemistry are not understood, nor is the likelihood of chemical equilibrium being re-established and how long that would take.

In the case of chemical impacts topics in need of further research include:

- the impact of large concrete, steel or aggregate bodies on soil chemistry, with reference to groundwater flows and artefact and organic preservation;
- temporary and permanent dewatering of sites and its impact on the soil chemistry (pH, redox, etc);
- temporary and permanent changes to soil chemistry and its impact on artefact degradation.

Biological impacts

The range of biological organisms that live in the ground are known, as are their foods and lifecycles. The requirement for oxygen for life to exist and the preservation potential of anaerobic deposits are known. We also know that ground disturbance, such as excavation, often leads to an increase in biological activity. Unfortunately, we are less clear on how long the increase in activity will last following reburial or the construction of structures in excavated holes. Also, we do not know if this increase in biological activity will also occur in association with piling and similar processes. It is in these areas that further research is needed.

In the case of biological impacts, topics in need of further research include:

- temporary and long term impacts on soil biological activity of excavation and backfilling (including structural backfilling);
- if there are any impacts on soil biological activity from piling operations;
- soil biological activity on brownfield sites and the impacts of ground remediation.

14.2 Potential to draw up mitigation guidelines

The Cork Corporation Feasibility Study of Archaeology/Engineering Interfaces by Fearon, O'Neill, Rooney Consulting Engineers (1996) has attempted to identify the archaeological concerns and appropriate engineering responses associated with pre-construction activities, construction activities and permanent works. These are effectively simple mitigation guidelines for construction activities. However, as they are only seven pages long, and do not take account of different soil conditions or distinguish between different types of piles, they should be seen as a starting point for the development of comprehensive guidelines.

Given the current state of knowledge we can make reasonable mitigation recommendations in some areas, but in others further research is required before detailed recommendations can be made.

Physical impact mitigation

We can identify the range of physical impacts that can result from piling, excavation and from ground improvements. However, we are less clear on the scale and extent of these impacts and how they vary with different soil conditions. Current research should fill in some of these gaps.

In general, we can make reasonable recommendations as to the potential physical impacts of developments but further study is required to make site-specific mitigation recommendations.

Hydrological impact mitigation

With the impact of development on hydrology and specifically groundwater levels and the presence or absence of anaerobic conditions, we can identify the range of actions that can change these conditions but we lack knowledge of how this will vary with differing soil conditions, ie how thick an impermeable layer needs to be to still function despite a pile passing through it. Current research will clarify some of these points. We also lack knowledge on how well re-watering restores previous groundwater conditions and how long this takes to stabilise. The impact of variations in the hydrological regime on soil chemical and biological activity can be predicted at a broad level but not in detail.

In general, we can make reasonable recommendations as to the potential hydrological impacts of developments but further study is required to make site-specific mitigation recommendations.

Chemical impact mitigation

We have only limited knowledge of the impact of development on soil chemistry and the impact this has on archaeological preservation. We do not know the potential impacts of the introduction of large bodies of concrete or steel in contact with archaeological remains and how that may vary with soil conditions. We also lack knowledge of how variations in groundwater conditions may impact on soil chemistry, although most alterations will be detrimental to the preservation of artefacts that have reached a stable equilibrium with their environment.

In general, we can make only broad recommendations as to the potential chemical impacts of developments and further study is required to make these more detailed and site-specific.

Biological impact mitigation

We have only limited knowledge of the impact of development on soil biology and the effect this has on archaeological preservation. We know that ground disturbance can lead to increased biological activity, but when this occurs, how long it will last, or how it ceases or slows down are at present simply conjecture.

In general, we can make only broad recommendations as to the potential chemical impacts of developments and further study is required to make these more detailed and site-specific.

Although this final section may appear depressing we must remember that 20 years ago the same review would probably have concluded that we have no idea of the impact of development in any of the above areas. Therefore, substantial progress has been made and in certain areas, mainly physical and hydrological, we have made substantial progress towards understanding how development affects archaeology and can produce general mitigation guidelines. In these areas we should soon be able to take account of site-specific soil conditions in drawing up mitigation strategies.

BIBLIOGRAPHY

Affelt, W 2002 'Cultural heritage preservation – the engineers contribution.' Paper presented at *The 5th European Commission Conference on Research for Protection, Conservation and Enhancement of Cultural Heritage*. Cracow, Poland

Allison, R J and Higichi, T forthcoming *Response of Archaeological Sediments and Artefacts to Imposed Stress Regimes as a Consequence of Past Present and Future Anthropogenic Activity.*

Arnott, S, Dix, J K, Best, A I and Gregory, D 2004 'The acoustic characteristics of archaeological wood.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 18-25. London: Museum of London Archaeology Service

Arup 1991 *The York Development and Archaeology Study*. Ove Arup and Partners and York University in association with Bernard Thorpe

Ashurst, J, Balaam, N and Foley, K 1989 'The Rose Theatre: overcoming the technical preservation problems.' *Conservation Bulletin* 9, 9-10

Astrakhanov, B N 2002 'Trends in the development of procedures for the installation of foundation-pit enclosures in dense urban setting.' *Soil Mechanics and Foundation Engineering* 39, 117-122

Badcock, A, Lines, A, and Symonds, J 2004 'A damn'd bad place, Sheffield: challenges and opportunities of the "urban renaissance".' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 249-254. London: Museum of London Archaeology Service

Banwart, S A 1998 'Groundwater geochemistry in the burial environment.' In Corfield, M, Hinton, P, Nixon, T and Pollard, M (eds) *Preserving Archaeological Remains in situ: Proceedings of the Conference of 1st-3rd April 1996,* 66-72. London: Museum of London Archaeological Service

Biddle, M 1994 *What Future for British Archaeology. The opening address at the Eighth Annual Conference of the Institute of Field Archaeologists, Bradford 13-15 April 1994*. Archaeology in Britain Conference 1994. Oxford: Oxbow Books

Bonnet, C 1987 'The Archaeological Site of the Cathedral of Saint Peter (Saint-Pierre), Geneva.' *World Archaeology* 18, 330-340

Burland, J R 2001 'The Stabilisation of the Leaning Tower of Pisa.' *Ingenia* 10, 10-18

Canti, M G and Davis, M 1999 'Tests and guidelines for the suitability of sands to be used in archaeological site reburial.' *Journal of Archaeological Science* 26, 775-781

Caple, C 1998 'Parameters for monitoring anoxic environments.' In Corfield, M, Hinton, P, Nixon, T, and Pollard, M (eds) *Preserving Archaeological Remains in situ: Proceedings of the Conference of 1st-3rd April 1996,* 113-123. London: Museum of London Archaeological Service

Caple, C and Dungworth, D 1998 *Waterlogged Anoxic Archaeological Burial Environments*. Unpublished Ancient Monuments Laboratory Report 22/98

Carrott, J, Hall, A, Issitt, M, Kenward, H, Large, F, Milles, A and Usai, R 1996 *Suspected Accelerated in situ Decay of Delicate Bioarchaeological Remains: a Case Study from Medieval York*. York: Reports from the Environmental Archaeology Unit 96/15

Chapman, H P and Cheetham, J L 2002 'Monitoring and modelling saturation as a proxy indicator for *in situ* preservation in wetlands – a GIS-based approach.' *Journal of Archaeological Science* 29, 277-289

Charles, J A 2002 'Ground improvement: the interaction of engineering science and experience- based technology.' *Géotechnique* 52, 527-532

Charles, J A and Skinner, H D 2001 'Compressibility of foundation fills.' *Proceedings of the Institution of Civil Engineers, Geotechnical Engineering* 149, 145-157

Charles, W W and Yan, R W M 1998 'Stress transfer and deformation mechanisms around a diaphragm wall panel.' *Journal of Geotechnical and Geoenvironmental Engineering* 124, 638-648

Chow, F 2002 'Underground space: the final frontier?' *Ingenia* 14, 15-20

Clark, K 2004 'Between a rock and a hard decision: the role of archaeology in the conservation planning process.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 202-208. London: Museum of London Archaeology Service

Clough, G W and O'Rourke, T D 1990 'Construction induced movements of *in situ* walls.' In *Design and Performance of Earth Retaining Structures*, 439-470. New York: ASCE Geotechnical Special Publications 25

Cooke, R W and Price, G 1973 'Strains and displacements around friction piles.' *Proceedings of the 8th International Conference on Soil Mechanics Foundation Engineering* 2, 53-60. Moscow

Corfield, M, Hinton, P, Nixon, T and Pollard, M (eds) 1998 *Preserving Archaeological Remains in situ: Proceedings of the Conference of 1st-3rd April 1996.* London: Museum of London Archaeological Service

Council for British Archaeology 2001 *Comments to Royal Commission on Environmental Pollution Study into the Long Term Effects of Chemicals in the Environment.* Comments to RCEP

Council for British Archaeology 2001 *Consultation on a Draft Soil Strategy for England.* Comments to the Ministry of Agriculture, Fisheries and Food

Council for British Archaeology 2002 *Research and Guidance on the Risk Posed by Land Contamination and its Remediation on Archaeological Resource Management.* Comments to University of Nottingham Research Team

Council for British Archaeology 2002 *Development on Land Affected by Contamination: Consultation Paper on Draft Planning Technical Advice.* Comments to the Department for Transport, Local Government and the Regions

Council of Europe 1992 *European Convention on the Protection of the Archaeological Heritage (Revised).* (Valletta Convention) European Treaty Series 143

Council of Europe 2000 *European Code of Good Practice, Archaeology and the Urban Project*

Cowie, R and Blackmore, L 1999 'Excavation and mitigation in Lundenwic: a case study.' *London Archaeologist* 8, 311-319

Cox, M, Earwood, C, Jones, E B G, Jones, J, Straker, V, Robinson, M, Tibbett, M and West, S 2001 'An assessment of the impact of trees upon archaeology within a relict wetland.' *Journal of Archaeological Science* 28, 1069-1084

Crilly, M S and Driscoll, R M C 2000 'The behaviour of lightly loaded piles in swelling ground and implications for their design.' *Proceedings of the Institution of Civil Engineers, Geotechnical Engineering* 143, 3-16

Dalwood, C H, Buteux, V A and Darlington, J 1994 'Excavations at Farrier Street and other sites north of the city wall, Worcester 1988-92.' *Transactions of the Worcestershire Archaeology Society 3rd Series* 14, 75-114

Davies, G 2003 *Archaeological Field Evaluation of the Impacts of Piling at The JunXion, St Marks Street, Lincoln.* ARCUS unpublished report 750.1

Davies, G 2004 *Interim Report on the Impacts of Piling on Archaeological Deposits.* ARCUS unpublished report 711.1

Davis, M 1998 '*In-situ* monitoring of wet archaeological environments: a review of available monitoring technologies.' In Corfield, M, Hinton, P, Nixon, T, and Pollard, M (eds) *Preserving Archaeological Remains in situ: Proceedings of the Conference of 1st-3rd April 1996,* 21-25. London: Museum of London Archaeological Service

Davis, M 2004 'A study into the mitigation of construction impact on archaeological remains.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 224-229. London: Museum of London Archaeology Service

Davis, M, Hall, A, Kenward, H and Oxley, J 2001 'Preservation of urban archaeological deposits: monitoring and characterisation of archaeological deposits at Marks and Spencer, 44-45 Parliament Street, York.' *Internet Archaeology* 11, at http://intarch.ac.uk/journal/issue11/oxley_index.html

Davis, M J, Gdaniec, K L A, Brice, M and White, L 2004 *Mitigation of Construction Impact on Archaeological Remains*. English Heritage

DEFRA 2001 *Draft Soil Strategy for England – A Consultation Paper*

DEFRA 2004 *The First Soil Action Plan for England: 2004-2006.* (Draft)

DETR 1997 *Planning Policy Guidance Note 01 – General Policy and Principles*. London: HMSO

DETR 2000 *Planning Policy Guidance Note 03 – Housing*. London: HMSO

DOE 1990 *Planning Policy Guidance 16: Archaeology and Planning*. London: HMSO

Durham, B 2004 '"Cleaning up": protecting deposits on brownfield sites under environmental impact assessment.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 239-248. London: Museum of London Archaeology Service

Edwards, R 1998 'The effect of changes in groundwater geochemistry on the survival of buried metal artefacts.' In Corfield, M, Hinton, P, Nixon, T and Pollard, M (eds) *Preserving Archaeological Remains in situ? Proceedings of the Conference of 1st-3rd April 1996,* 86-92. London: Museum of London Archaeological Service

English Heritage 2000 *The Power of Place. The Future of the Historic Environment*. London: English Heritage

Environment Agency 2001 *Piling and Penetrative Ground Improvement Methods on Land Affected by Contamination: Guidance on Pollution Prevention*. Bristol: Environment Agency

Environment Agency 2002 *Piling into Contaminated Ground*. National Groundwater and Contaminated Land Centre

Fadeev, A B, Inozemtsev, V K and Lukin, V A 2001 'Settlements of buildings founded on weak soils of Saint Petersburg.' *Soil Mechanics and Foundation Engineering* 38, 154-158

Fearon, O'Neill, Rooney Consulting Engineers 1996 *Feasibility Study of Archaeological/Engineering Interfaces in a City Environment*. Cork Corporation

Fox, G L 1994 'Cupreous metal corrosion at a Bronze Age Coastal marine archaeological site: a study of site processes at Tel Nami, Israel.' *The International Journal of Nautical Archaeology* 23, 41-47

French, C and Taylor, M 1985 'Desiccation and destruction: the immediate effects of dewatering at Etton, Cambridgeshire." *Oxford Journal of Archaeology* 4, 139-155

French, C, Davis, M and Heathcote, J 1999 'Hydrological monitoring of an alluviated landscape in the Lower Great Ouse Valley, Cambridgeshire: interim results of the first three years." *Environmental Archaeology* 4, 41-56

Ganiaris, H and Bateman, N 2004 'From area to art gallery: the preservation of London's Roman amphitheatre *in situ*.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 60-64. London: Museum of London Archaeology Service

Garfinkel, A P and Lister, B L 1983 *Effects of High Embankment Construction on Archaeological Materials*. Sacramento: Transportation Laboratory, California Department of Transportation (CALTRANS)

Georgiadis, K, Potts, D M and Zdravkovic, L 2003 'The influence of partial soil saturation on pile behaviour.' *Géotechnique* 53, 11-25

Gui, M W 1998 'Analysis of Behaviour of Sand Surrounding Pile Tips.' *Journal of Geotechnical and Geoenvironmental Engineering* 124, 652-653

Heaton, M and Cleal, R M J 2000 'Beaker Pits at Crescent Copse, near Shrewton, Wiltshire, and the effects of arboreal fungi on archaeological remains.' *Wiltshire Archaeological and Natural History Magazine* 93, 71-81

Heritage Council, ICMOS Irish Committee 2000 *Archaeology and Development: Guidelines for Good Practice for Developers*. Dublin: The Heritage Council

Hinman, M 2002 *Deeply Stratified Medieval and Post-Medieval Remains at Market Mews Wisbbech*. Cambridgeshire County Council Archaeological Field Unit Report 156

Hird, C C and Moseley, V J 2000 'Model study of seepage in smear zones around vertical drains in layered soil.' *Géotechnique* **50**, 89-97

Hird, C C and Sangtian, N 2002 'Model study of seepage in smear zones around vertical drains in layered soil: further results.' *Géotechnique* **52**, 375-378

Hopkins, D W 1998 'The biology of the burial environment.' In Corfield, M, Hinton, P, Nixon, T and Pollard, M (eds) *Preserving Archaeological Remains in situ: Proceedings of the Conference of 1st-3rd April 1996*, 73-85. London: Museum of London Archaeological Service

Hopkins, D 2004 'Even the ancient was once young: lessons about biodegradation from the Wareham (Dorset) experimental earthwork.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 60-64. London: Museum of London Archaeology Service

Howlands, A F 2001 'The history and the development of procedures for the rapid assessment of environmental conditions to aid the urban regeneration process at London Docklands.' *Engineering Geology* **60**, 117-125

Hsieh, P G and Ou, C Y 1998 'Shape of ground surface settlement profiles caused by excavation.' *Canadian Geotechnical Journal* **35**, 1004-1017

Hughes, R 1998 A review of works at the World Heritage Monument at Moenjodaro, Pakistan.' In Corfield, M, Hinton, P, Nixon, T and Pollard, M (eds) *Preserving Archaeological Remains in situ: Proceedings of the Conference of 1st-3rd April 1996*, 26-30. London: Museum of London Archaeological Service

Hughes, R and Butler, J 2004 'Archaeology and preservation at Alder House, Castle House and Falcon House.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 112-115. London: Museum of London Archaeology Service

Hughes, R and Seaman, J 2004 '*In situ* preservation of medieval waterfront archaeological resources at the north abutment of the London Millennium Footbridge.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 105-111. London: Museum of London Archaeology Service

Hughes, R, Coles, B and Henley, R 2004a 'The reuse of pile locations at Governor's House development site, City of London.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 98-104. London: Museum of London Archaeology Service

Hughes, R, Lawrence, A, and Patel, D 2004b 'The redevelopment of Plantation Place, City of London.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of* *the 2nd Conference 12-14 September 2001*, 116-127. London: Museum of London Archaeology Service

Hughes, R, Dillon, J, McKinley, J, Patel, D and Shields, H 2004c 'The geotechnical instrumentation of Park Lane, Croydon, an Early Anglo-Saxon cemetery.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 128-136. London: Museum of London Archaeology Service

Hunting Technical Services 1998 *York City Council. Archaeological Deposit Monitoring at 44/45 Parliament Street, York*. Hunting Technical Services report R1182 to York City Council

Hwang, J H, Liang, N and Chen, C H 2001 'Ground Response during Pile Driving.' *Journal of Geotechnical and Geoenvironmental Engineering* 127, 939-949

Hyde, A 2004 'Damage to inclusions in sand subjected to one-dimensional compression.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 32-39. London: Museum of London Archaeology Service

IAEA (International Atomic Energy Agency) 2002 *Scientific and Technical Basis for the Near Surface Disposal of Low and Intermediate Level Waste*. Technical Reports Series 412

ICOMOS 1990 *ICOMOS Charter for the Protection and Management of the Archaeological Heritage*. International Council on Monuments and Sites

Il'ichev, V A, Konovalov, P A and Nikiforova, N S 2001 'Effect of construction of deep-seated structures on existing historic buildings in Moscow.' *Soil Mechanics and Foundation Engineering* 38, 130-136

Il'ichev, V A, Konovalov, P A and Nikiforova, N S 2002 'Influence of deep-seated structures under construction on deformation of existing nearby buildings.' *Soil Mechanics and Foundation Engineering* 39, 123-127

Kaplan, M F 1980 'Characterization of weathered glass by analysing ancient artefacts.' In Northrup, C J M (ed) *Scientific Basis for Nuclear Waste Management* 2, 85-92. New York: Plenum.

Kars, H, Collins, M J, Jans, M, Nord, A, Arthur, P and Kars E 2004 'Bone as an indicator in the *in situ* degradation of archaeological heritage. Two examples: Apigliano, Italy, and Aartswoud, the Netherlands.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 11-17. London: Museum of London Archaeology Service

Keevill, G, Hogan, D, Davis, M and Howell, D 2004 'Waterlogged archaeological remains, environmental conditions and preservation in situ: a case study from the Tower of London.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 137-142. London: Museum of London Archaeology Service

Kenward, H and Hall, A 2000 'Decay of delicate organic remains in shallow urban deposits: are we at a watershed?' *Antiquity* 74, 519-525

Kenward, H and Hall, A 2004 'Actively decaying or just poorly preserved? Can we tell when plant and invertebrate remains in urban archaeological deposits decayed?' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 4-10. London: Museum of London Archaeology Service

Kenward, H and Large, F 1998 'Recording the Preservation Condition of Archaeological Insect Fossils.' *Environmental Archaeology* 2, 49-60

King, F 1995 'A natural analogue for the long term corrosion of copper nuclear waste containers – reanalysis of a study of a bronze cannon.' *Applied Geochemistry* 10, 477-487

Kjekstad, O 2002 'Soil structure interaction in urban civil engineering, an overview of COST Action C7.' *Proceedings of the Second International Conference On Soil Structure Interaction in Urban Civil Engineering*. Zurich

Lee, C J, Bolton, M D and Al-Tabbaa, A 2002 'Numerical modelling of group effects on the distribution of dragloads in pile foundations.' *Géotechnique* 52, 325-335

Loganathan, N, Poulos, H G and Stewart, D P 2000 'Centrifuge model testing of tunnelling-induced ground and pile deformations.' *Géotechnique* 50, 283-294

Long, M 2001 'Database for retaining wall and ground movements due to deep excavations.' *Journal of Geotechnical and Geoenvironmental Engineering* 127, 203-224

MacLeod, I D 1995 '*In situ* corrosion studies on the Duart Point wreck, 1994.' *The International Journal of Nautical Archaeology* 24, 53-59

Madsen, H B, Andersen, J H and Andersen, L B 2004 'Deterioration of prehistoric bronzes as an indicator of the state of preservation of metal antiquities in the Danish agrarian landscape: preliminary results.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 50-57. London: Museum of London Archaeology Service

Mair, R and Harris, D 2001 'Innovative engineering to control Big Ben's tilt.' *Ingenia* 9, 23-27

Matthiesen, H, Gregory, D, Sørensen, B, Alstøm, T and Jensen, P 2004 'Monitoring methods in mires and meadows: five years of studies at Nydam Mose, Denmark.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 91-97. London: Museum of London Archaeology Service

Mavlyanova, N G and Ismailov, V A 2004 'Influences of human activity on deformations of the ancient structures of Ichan-Kala in Kiva City.' *Geotechnical and Geological Engineering* 22, 135-149

McCobb, L M E, Briggs, D E G, Hall, A R and Kenward, H K 2004 'The preservation of invertebrates in 16th-Century Cesspits at St Saviourgate, York.' *Archaeometry* 46, 157-169

McGill, C 1995 *Building on the Past. A Guide to the Archaeology and Development Process*. London: E and F N Spon

McGill, C 1996 'Designs on the past.' *Architects Journal* 204, 18 August 1996

Millard, A 1998 'Bone in the burial environment.' In Corfield, M, Hinton, P, Nixon, T and Pollard, M (eds) *Preserving Archaeological Remains in situ: Proceedings of the Conference of 1st-3rd April 1996,* 93-102. London: Museum of London Archaeological Service

Miller, B 1998 'Archaeological material as natural analogues for the geological disposal of radioactive wastes.' In Corfield, M, Hinton, P, Nixon, T and Pollard, M (eds) *Preserving Archaeological Remains in situ: Proceedings of the Conference of 1st-3rd April 1996,* 103-112. London: Museum of London Archaeological Service

Miller, P 1994 'Dig or pile?' *Planning Week*, 27 October 1994, 8-9

Miller, W, Alexander, R, Chapman, N, McKinley, I and Smellie, J 2000 *Geological Disposal of Radioactive Wastes and Natural Analogues: Lessons from Nature and Archaeology*. Waste Management Series 2. Pergamon

Moseley, H 1998 'Archaeology and development.' In Corfield, M, Hinton, P, Nixon, T and Pollard, M (eds) *Preserving Archaeological Remains in situ: Proceedings of the Conference of 1st-3rd April 1996,* 47-50. London: Museum of London Archaeological Service

Nardi, R and Schneider, K 2004 'Zeugma Archaeological Project 2000: the conservation programme.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 157-167. London: Museum of London Archaeology Service

Negueruela, I 2000 'Managing the maritime heritage: the National Maritime Archaeological Museum and National Centre for Underwater Research, Cartagena, Spain.' *The International Journal of Nautical Archaeology* 29, 179-198

Newton, R and Davison, S 1989 *Conservation of Glass*. London: Butterworth Heinemann

Ng, C W W and Yan, R W M 1998 'Stress transfer and deformation mechanisms around a diaphragm wall panel.' *Journal of Geotechnical and Geoenvironmental Engineering* 124, 638-648

Ng, C W W and Yan, R W M 1999 'Three-dimensional modelling of a diaphragm wall construction sequence.' *Géotechnique* 49, 825-834

Ng, C W W, Leung, E H Y and Lau, C K 2004 'Inherent anisotropic stiffness of weathered geomaterial and its influence on ground deformations around deep excavations.' *Canadian Geotechnical Journal* 41, 12-24

Nicola, A De and Randolph, M F 1997 'The plugging behaviour of driven and jacked piles in sand.' *Géotechnique* 47, 841-856

Nielson-Marsh, C M and Hedges, R E M 2000 'Patterns of diagenesis in bone I : the effects of site environments.' *Journal of Archaeological Science* 27, 1139-1150

Nixon, T 1998 'Practically preserved: observations on the impact of construction on urban archaeological deposits.' In Corfield, M, Hinton, P, Nixon, T and Pollard, M (eds) *Preserving Archaeological Remains in situ: Proceedings of the Conference of 1st-3rd April 1996,* 39-46. London: Museum of London Archaeological Service

Nixon, T (ed) 2004 *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*. London: Museum of London Archaeology Service

Northamptonshire Archaeology n.d. *Archaeological Evaluation at Barclaycard, Marefair, Northampton, Stage 2: Trial Excavation*. Unpublished Northamptonshire Archaeology report

Ohsaki, Y 1982 'Corrosion of steel piles driven in soil deposits.' *Soils and Foundations* 22, 57-76

Ou, C-Y, Liao, J-T and Cheng, W-L 2000 'Building response and ground movements induced by a deep excavation.' *Géotechnique* 50, 209-220

Oxley, J 1998 'Planning and the conservation of archaeological deposits.' In Corfield, M, Hinton, P, Nixon, T and Pollard, M (eds) *Preserving Archaeological Remains in situ: Proceedings of the Conference of 1st-3rd April 1996,* 51-54. London: Museum of London Archaeological Service

Paul, T and Chow, F 1999 'Availability and use of geotechnical information for urban planning.' *Proceedings from COST C7 Workshop in Thessaloniki*, 1-2 October 1999

Peacock, E and Turner-Walker, G 2004 'Building for the new millennium: monitoring for the first ten years?' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 65-71. London: Museum of London Archaeology Service

Pestana, J M, Hunt, C E and Bray, J D 2002 'Soil deformation and excess pore pressure field around a closed-ended pile.' *Journal of Geotechnical and Geoenvironmental Engineering* 128, 1-12

Petrukhin, V P, Isaev, O N, Nayatov, D V and Gil'shtein, S R 2002 'Construction of utility tunnels in Moscow with preservation of existing buildings.' *Soil Mechanics and Foundation Engineering* 39, 128-132

Pickles, A R, Lee, S W and Norcliffe, B A W 2003 'Groundwater and ground movement around deep excavations.' *Proceedings of the Institution of Civil Engineers, Geotechnical Engineering* 156, 147-158

Poh, T Y, Goh, A T C and Wong, I H 2001 'Ground movements associated with wall construction: case histories.' *Journal of Geotechnical and Geoenvironmental Engineering* 127, 1061-1069

Pollard, A M 1998 'The chemical nature of the burial environment.' In Corfield, M, Hinton, P, Nixon, T and Pollard, M (eds) *Preserving Archaeological Remains in situ: Proceedings of the Conference of 1st-3rd April 1996,* 60-65. London: Museum of London Archaeological Service

Poulos, H G and Chen, L T 1997 'Pile response due to excavation-induced lateral soil movement.' *Journal of Geotechnical and Geoenvironmental Engineering* 123, 94-99

Pournou, A, Jones, A M and Moss, S T 2001 'Biodeterioration dynamics of marine wreck-sites determine the need for their *in situ* protection.' *The International Journal of Nautical Archaeology* 30, 299-305

Pugh-Smith, J, Sermon, R and Williamson-Taylor, A 2004 'Archaeology and urban regeneration: lesson from Blackfriars multiplex, Gloucester.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 143-149. London: Museum of London Archaeology Service

Reed, I 2004 'Deposit monitoring in Tønsberg, Norway.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 87-90. London: Museum of London Archaeology Service

Ritz, K, Thompson, T R E, Harris, J A, Heaton, M, Jordan, D and Morton, A 2004 'Post-disturbance changes in archaeology: the potential pitfalls of PARIS.' Paper presented at *The Institute of Field Archaeologists Annual Meeting, Liverpool*, April 2004

Romanoff, M 1969 'Performance of steel piling in soil." *Proceedings of the 25th Conference of the National Association of Corrosion Engineers*.

Rosenbaum, M S, McMillan, A A, Powell, J H, Cooper, A H, Culshaw, M G and Northmore, K J 2003 'Classification of artificial (man-made) ground.' *Engineering Geology* 69, 399-409

Rouffignac, C 1987 *The Effects of Sample Storage Conditions on the Preservation of Human Parasite Remains in Soil Samples from Roman, Mediaeval and Post-Mediaeval Deposits at Watling Court and Monument/Fish Street, London*. Unpublished MA Dissertation, Department of Archaeology and Prehistory, University of Sheffield

Rowsome, P 2000 *Heart of the City: Roman, Medieval and Modern London Revealed by Archaeology at No. 1 Poultry*. London: English Heritage and Museum of London Archaeology Service

Rubnikowicz, M 2002 'Archaeological heritage management and sustainable development.' Paper presented at *The 5th European Commission Conference on Research for Protection, Conservation and Enhancement of Cultural Heritage*, Cracow, Poland

RUFUS (Re-use of Foundations for Urban Sites) European Commission 5th Framework Project. http://www.webforum.com/rufus/home/index.asp?sid=319&mid=1

Sagaseta, C and Whittle, A J 2001 'Prediction of ground movements due to pile driving in clay.' *Journal of Geotechnical and Geoenvironmental Engineering* 127, 55-66

Sheehan, P 2004 'Turning made ground into monuments: preservation of archaeological remains on Old Cairo, Egypt.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 230-236. London: Museum of London Archaeology Service

Sheward, T 2003 'Screw piling in Salisbury.' *New Steel Construction* 11/6, 27-28

Shilston, D T and Fletcher, S L 1998 'Geotechnical engineering for the *in-situ* preservation of archaeological remains.' In Corfield, M, Hinton, P, Nixon, T and Pollard, M (eds) *Preserving Archaeological Remains in situ: Proceedings of the Conference of 1st-3rd April 1996,* 8-15. London: Museum of London Archaeological Service

Shreir, L L (ed) 1976 *Corrosion. Volume 1: Metal/Environment Reactions*. Second Edition. London: Newnes-Butterworths

Sidell, E J, Higuchi, T, Allison, R J and Long, A J 2004 'The response of archaeological sediments and artefacts to imposed stress regimes as a consequence of past, present and future anthropogenic activity.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 42-49. London: Museum of London Archaeology Service

Simonini, P 1996 'Analysis of behaviour of sand surrounding pile tips.' *Journal of Geotechnical Engineering* 122, 897-905

Simpson, I A 1998 'The physical nature of the burial environment in archaeological sites and landscapes.' In Corfield, M, Hinton, P, Nixon, T and Pollard, M (eds) *Preserving Archaeological Remains in situ: Proceedings of the Conference of 1st-3rd April 1996,* 55-59. London: Museum of London Archaeological Service

Skal'nyi, V S, Kosygin, E V and Sorochan, E A 2002 'Monitoring foundation deformations of the buildings housing the bishop chambers in the Suzdal Kremlin.' *Soil Mechanics and Foundation Engineering* 39, 60-64

Slocombe, B C, Bell, A L and Baez, J I 2000 'The densification of granular soils using vibro methods.' *Géotechnique* 50, 715-725

Smit, A 2004 'Measuring the burial environment at archaeological sites to judge the in situ conservation potential: a PLANARCH Project to facilitate planning decisions.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 168-172. London: Museum of London Archaeology Service

Steenfelt, J S, Randolph, M F and Wroth, C P 1981 'Instrumented model piles jacked into clay.' *Proceedings of the 10th International Conference on Soil Mechanics and Foundations in Engineering* II, 857-864. Stockholm, Sweden.

Stockwell, M 1984 'Foundation preparation and the archaeologist.' in Addyman, P V and Black, V E (eds) *Archaeological Papers from York presented to M.W. Barley*, 158-162. York: York Archaeological Trust

Stoffyn-Egli, P, Buckley, D E and Clyburne, J A C 1998 'Corrosion of brass in a marine environment: mineral products and their relationship to variable oxidation and reduction conditions.' *Applied Geochemistry* 13, 643-650

Suh, M, Koo, M, Choi, S and Song, I 2004 'Instability of an underground ancient tomb due to excavation and its relationship to the temperature and ground water.' *Geotechnical and Geological Engineering* 22, 269-283

Tedd, P, Charles, J A and Driscoll, R 2001 'Sustainable brownfield re-development – risk management.' *Engineering Geology* 60, 333-339

Teh, C I and Wong, K S 1995 'Analysis of down-drag on pile groups.' *Géotechnique* 45, 191-207

Teller, J and Warnotte, A 2003 *The Enhancement of Archaeological Remains in an Urban Context*. Accessibility Projects: Sustainable Preservation and Enhancement of Urban Subsoil Archaeological Remains. APPEAR Position Paper 1

Thorne, R 1988 *Guidelines for the Organisation of Archaeological Site Stabilization Projects: a Modelled Approach*. Technical Report EL-88-8, US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

Thorne, R 1991a *Intentional Site Burial: A Technique to Protect Against Natural or Mechanical Loss*. Brief No. 5, DOI Departmental Consulting Archaeologist/NPS Archaeology and Ethnography Program, National Parks Service, Washington DC

Thorne, R 1991b *Site Stabilization Information Sources*. Brief No. 12, DOI Departmental Consulting Archaeologist/NPS Archaeology and Ethnography Program, National Parks Service, Washington DC

Tilly, G P 1998 'Engineering methods of minimising damage and preserving archaeological remains *in situ*.' In Corfield, M, Hinton, P, Nixon, T and Pollard, M (eds) *Preserving Archaeological Remains in situ: Proceedings of the Conference of 1st-3rd April 1996,* 1-7. London: Museum of London Archaeological Service

Tomlinson, M J 1995 *Foundation Design and Construction*. 6th Edition. Harlow: Longman Scientific and Technical

Ulitskii, V M and Alekseev, S I 2002 'Preservation of buildings during the installation of foundation pits and the laying of utilities in Saint Petersburg.' *Soil Mechanics and Foundation Engineering* 39, 133-138

Ullen, I, Nord, A G, Fjaestad, M, Mattsson, E, Borg, G and Tronner, K 2004 'The degradation of archaeological bronzes underground: evidence from museum collections.' *Antiquity* 78, 380-390

Vähäaho, I 1999 'Helsinki Geotechnical Database.' *Proceedings from COST C7 Workshop in Thessaloniki*, 1-2 October 1999

Van de Noort, R 1998 'Assessment and management of sites in wetland landscapes: four cases studies from the Humber wetlands.' In Corfield, M, Hinton, P, Nixon, T and Pollard, M (eds) *Preserving Archaeological Remains in situ: Proceedings of the Conference of 1st-3rd April 1996,* 133-143. London: Museum of London Archaeological Service

Van de Noort, R 2004 'Sutton Common (South Yorkshire): a monument at risk in England's wetlands.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 79-86. London: Museum of London Archaeology Service

Van de Noort, R, Chapman, H P and Cheetham, J L 2001 '*In situ* preservation as a dynamic process: the example of Sutton Common, UK.' *Antiquity* 75, 94-100

Wainwright, G J 1989 'Archaeology in towns.' *Conservation Bulletin* 9, 1-2

Watson, B, Bingham, T and Dyson, T 2001 *London Bridge: 2000 Years of a River Crossing*. London: Museum of London Archaeological Service Monograph 8

Welch, J and Thomas, S 1998 'Groundwater modelling of waterlogged archaeological deposits.' In Corfield, M, Hinton, P, Nixon, T and Pollard, M (eds) *Preserving Archaeological Remains in situ: Proceedings of the Conference of 1st-3rd April 1996,* 16-20. London: Museum of London Archaeological Service

Westcott, F J, Lean, C M B and Cunningham, M L 2001 *Piling and Penetrative Ground Improvement Methods on Land Affected by Contamination: Guidance on Pollution Prevention*. Environment Agency: National Groundwater and Contaminated Land Centre report NC/99/73

Westcott, F J, Smith, J W N and Lean, C M B 2003 'Piling in contaminated ground: environmental impacts, regulatory concerns and effective solutions.' *Engineering Geology* 70, 259-268

White, D J and Bolton, M D 2004 'Displacement and strain paths during plane-strain model pile installation in sand.' *Géotechnique* 54, 375-397

Williams, J and Corfield, M 2002 'Construction impacts on *in situ* preservation of archaeological sites and artefacts.' Paper presented at *The 5th European Commission Conference on Research for Protection, Conservation and Enhancement of Cultural Heritage*, Cracow, Poland

Williams, J and Chaddock, S 2003 'Protecting the buried archaeological resource: the re-use of foundations.' *Proceedings of the 7th International Symposium of the Organization Of World Heritage Cities*. Rhodes, Greece

Wilson, L and Pollard, M 2004 'Making sense of diagenesis? The development of integrated laboratory and geochemical modelling strategies in studies of diagenetic change.' In Nixon, T (ed) *Preserving Archaeological Remains in situ? Proceedings of the 2nd Conference 12-14 September 2001*, 40-41. London: Museum of London Archaeology Service

Wong, I H and Chua, T S 1999 'Ground movements due to pile driving in an excavation in soft soil.' *Canadian Geotechnical Journal* 36, 152-160

Wong, I H and Law, K H 1999 'Corrosion of steel H-piles in decomposed granite.' *Journal of Geotechnical and Geomorphological Engineering* 125, 529-532

Woodiwiss, S 1998 'The rural context: a view from the sticks.' In Corfield, M, Hinton, P, Nixon, T and Pollard, M (eds) *Preserving Archaeological Remains in situ: Proceedings of the Conference of 1st-3rd April 1996,* 31-38. London: Museum of London Archaeological Service

Yang, J S and Wang, M C 2002 'Evaluation of tunneling-induced downdrag on end-bearing piles.' *Electronic Journal of Geotechnical Engineering* 7, paper 0214. At http://www.ejge.com/2002/Ppr0214/Ppr0215.htm

LIST OF JOURNALS SEARCHED

The following journals were searched for relevant papers:

Archaeological

American Antiquity vol. 60 (1995) – vol. 63 (1998)
Archaeometry vol. 39.1 (1997) – vol. 46.1 (2004)
European Journal of Archaeology vol. 3.1 (2000) – vol. 6.2 (2003)
Geoarchaeology vol. 15.1 (2000) – vol. 19.5 (2004)
International Journal of Historical Archaeology vol.3 (1999) – vol. 7 (2004)
International Journal of Nautical Archaeology vol. 22.3 (1993) – vol. 32.2 (2003)
Internet Archaeology vol.1 (1996) – vol.15 (2004)
Journal of Archaeological Method and Theory vol. 4 (1997) – vol. 11.1 (2004)
Journal of Archaeological Research vol. 6.2 (1998) – vol. 12.2 (2004)
Journal of Archaeological Science vol.20 (1993) – vol.31.7 (2003)
Journal of Field Archaeology vol.1 (1974) – vol.28.4 (2001)
Norwegian Archaeological Review vol. 32.1 (1999) – vol. 36.2 (2003)
World Archaeology vol.1 (1969) – vol.32 (2000)

Engineering/geotechnical

Canadian Geotechnical Journal vol. 33.6 (1996) – vol. 41.2 (2004)
The Electronic Journal of Geotechnical Engineering vol. 1 (1996) – vol. 9.b (2004)
Engineering Geology vol. 50 (1998) – vol. 73.2 (2004)
Ingenia issue 2 (1999) – issue 19 (2004)
Soil Mechanics and Foundation Engineering vol. 35.1 (1998) – vol. 40.6 (2003)
Geotechnical and Geological Engineering vol. 15 (1997) – vol. 22.2 (2004)
Journal of Geotechnical and Geoenvironmental Engineering vol. 123 (1997) – vol. 130.5 (2004)
Geotechnique vol. 45 (1995) – vol. 54.4 (2004)
Proceedings of the Institution of Civil Engineers, Geotechnical Engineering vol. 107 (1994) – vol. 157.1 (2004)

British and Irish Archaeological Bibliography search terms

corrosion
engineering
engineering and development
geotechnique
hydrology
mitigation
piles
preservation *in situ*
soil chemistry
urban soils
water table

GLOSSARY

Displacement – the distance by which the soil is moved due to stresses created by construction activities

Drag load – compressive force on piles from sediment settling around it

Down-drag – settlement on pile due to drag load

Drag-down - vertical displacement seen in the soils adjacent to a pile caused by the action of driving the pile

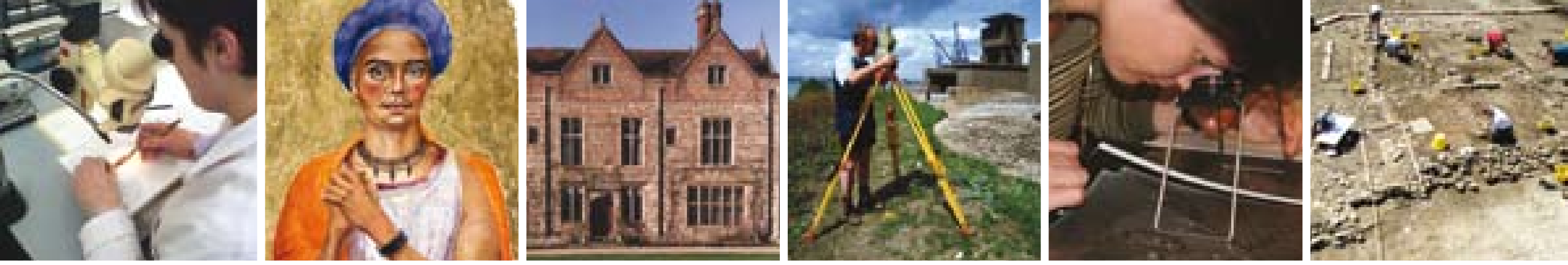
Ground Heave – vertical displacement (upwards) of ground caused by engineering activities, eg displacement piling

Return deflection – the distance by which soil returns towards its original location following displacement, this can be caused by the dissipation of excess pore water pressure

Secant Pile Wall – wall constructed from a line of touching piles

Stress – pressure applied to an object or material (force/area)

Strain – deformation of an object or material as a result of applied stress or force (extension/length)



ENGLISH HERITAGE RESEARCH DEPARTMENT

English Heritage undertakes and commissions research into the historic environment, and the issues that affect its condition and survival, in order to provide the understanding necessary for informed policy and decision making, for sustainable management, and to promote the widest access, appreciation and enjoyment of our heritage.

The Research Department provides English Heritage with this capacity in the fields of buildings history, archaeology, and landscape history. It brings together seven teams with complementary investigative and analytical skills to provide integrated research expertise across the range of the historic environment. These are:

* Aerial Survey and Investigation
* Archaeological Projects (excavation)
* Archaeological Science
* Archaeological Survey and Investigation (landscape analysis)
* Architectural Investigation
* Imaging, Graphics and Survey (including measured and metric survey, and photography)
* Survey of London

The Research Department undertakes a wide range of investigative and analytical projects, and provides quality assurance and management support for externally-commissioned research. We aim for innovative work of the highest quality which will set agendas and standards for the historic environment sector. In support of this, and to build capacity and promote best practice in the sector, we also publish guidance and provide advice and training. We support outreach and education activities and build these in to our projects and programmes wherever possible.

We make the results of our work available through the Research Department Report Series, and through journal publications and monographs. Our publication Research News, which appears three times a year, aims to keep our partners within and outside English Heritage up-to-date with our projects and activities. A full list of Research Department Reports, with abstracts and information on how to obtain copies, may be found on www.english-heritage.org.uk/researchreports

For further information visit www.english-heritage.org.uk

ENGLISH HERITAGE