Piling and Penetrative Ground Improvement Methods on Land Affected by Contamination: Guidance on Pollution Prevention

National Groundwater & Contaminated Land Centre report NC/99/73

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Statement of use
This report presents initial technical guidance on the potential impact that intrusive ground improvement and piling techniques can have on the environment. It focuses, in particular, on the potential for pollution of groundwater. The information within this document is for use by Environment Agency staff and others involved in the redevelopment of, and construction on, land that has been affected by contamination. The report may be revised in future as additional research and data becomes available, since it is recognised that the current information base on the effects of piling is limited.

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EXECUTIVE SUMMARY

This report presents guidance on assessing risks associated with, and preventing pollution from, piling and penetrative ground improvement methods on land affected by contamination. Government policy favours development on previously used land, including 'brownfield' development sites on which piling and penetrative ground improvement methods are commonly used. However, piling and penetrative ground improvement methods have the potential to create adverse environmental impacts when used on land affected by contamination and the Environment Agency has identified this issue as one of concern.

Data was collated from literature sources, a review of regulatory concerns and a survey of UK piling contractors. This revealed that there was little published research, case studies or monitoring data concerning actual or potential pollution of groundwater caused by piling or penetrative ground improvement methods. A number of (unpublished) examples were, however, identified where environmental issues were identified and addressed as part of the scheme design.

The wide range of commercially available foundation piling and penetrative ground improvement techniques has been classified into three generic classes for the purposes of this report. These are:

- Displacement piling;
- Non displacement piling;
- Penetrative ground improvement.

Six possible pollution scenarios have been identified and described, representing situations where the Environment Agency is concerned that piling or penetrative ground improvement operations have a potential to cause pollution. The six scenarios considered are as follows:

1. Creation of preferential pathways, through a low permeability layer (an aquitard), to allow potential contamination of an underlying aquifer;
2. Creation of preferential pathways, through a low permeability surface layer, to allow upward migration of landfill gas, soil gas or contaminant vapours to the surface;
3. Direct contact of site workers and others with contaminated soil arisings which have been brought to the surface;
4. Direct contact of the piles or engineered structures with contaminated soil or leachate causing degradation of pile materials (where the secondary effects are to increase the potential for contaminant migration);
5. The driving of solid contaminants down into an aquifer during pile driving; and
6. Contamination of groundwater and, subsequently, surface waters by concrete, cement paste or grout.

For each of the six pollution scenarios identified, the likely hazards associated with each generic method of piling and ground improvement are recognised, described and possible mitigation measures are identified. Particular problems and uncertainties are noted and the effects of variations of piling methods within the generic classes are considered.

The report outlines a process to allow designers to select an appropriate piling method and any mitigation and monitoring measures required for piling or penetrative ground improvement on a site affected by contamination. A number of possible mitigation measures that may be applicable in particular circumstances are listed. Quality assurance and quality control, and longer-term monitoring are addressed.

The conclusions and justification are to be presented in the form of a 'Foundation Works Risk Assessment Report', which should present a thorough and auditable risk assessment, describing and justifying fully the decision making process, including a description of any methods rejected after consideration.

Preparation of the Foundation Works Risk Assessment Report, and its examination by Environment Agency and local authority officers, is intended to assist planning authorities to meet their objectives described in Planning Policy Guidance (PPG) 23 in granting permission or enforcing planning conditions. However, submission of a Foundation Works Risk Assessment Report will not absolve the developer and his professional and construction team from their duties not to cause or knowingly permit pollution, harm or nuisance. It is expected that the developer will require the report to form part of the designer's contract obligations.

The report concludes by recognising the limitations in the body of scientific and engineering knowledge concerning the environmental impact of piling and penetrative ground improvement and the resulting interim nature of this guidance. It makes recommendations for further research to address these limitations.

Key words

Piling, ground improvement, contaminated land, groundwater, pollution.

1. INTRODUCTION

1.1 Background

This report reviews and provides guidance on preventing pollution from piling and penetrative ground improvement methods on land affected by contamination. It is based on best current information, but it should be recognised that very limited research has been conducted on this subject. As such the guidance may need to be amended in the future in the light of further research work. The review on which this document is based was carried out between January and August 2000.

Piles are columnar elements in foundations that have the function of transferring loads from structures through weak, compressible (soft) strata onto competent strata or rock. Ground improvement is the enhancement of the properties of weak compressible strata in order to render them competent to carry loads from structures. Penetrative ground improvement methods involve the improvement of vertical annuli of weak compressible soils by their penetration, compaction and addition of material to increase their density locally.

Piling has been used in foundation engineering at least since Roman times and remains a primary method of foundation engineering in soft ground (Chellis, 1961). Penetrative ground improvement is a more recent development of the 20th century and has become widely adopted for the support of lightly loaded structures. Both methods are commonly used in the urban environment, particularly where previous development has resulted in a thickness of artificially filled or "made" ground of poor or variable load bearing capacity.

Both piling and penetrative ground improvement methods are therefore commonly used on 'brownfield' development sites and this situation is likely to persist in the future. Government development policy favours the re-use of previously used land in preference to new construction on 'greenfield' land, particularly in the context of the significant number of new housing units identified as being required within the first two decades of the 21st century.

Piling and penetrative ground improvement methods have the potential, in certain circumstances, to create adverse environmental impacts when used on land affected by contamination. A number of documents giving guidance on the development of derelict and contaminated land (DoE, 1994; CIRIA, 1995 & 1999) make reference to this issue peripherally, identifying it as one that designers need to consider and address. However, none provide detailed guidance or recommendations. The Environment Agency has identified this issue as one of potential concern in the Pollution Prevention Manual (Environment Agency, 1996).

Despite the recognition of potential adverse environmental effects, the published literature is devoid of case studies, research or substantiated reports of actual pollution: on the other hand, neither has there been any demonstration that pollution does not occur during piling installation by means of targeted groundwater monitoring. There is very limited research underway into the potential environmental impacts of piling or penetrative ground improvement. In the absence of any research or robust field data the regulatory approach tends to be based on the precautionary principle. Where groundwater resources are vulnerable, this may result in restrictions or prohibitions being placed on developers and may in the process deter the re-use of brownfield sites.

1.2 Scope of Report

1.2.1 Objectives

This report addresses the following Environment Agency objectives with respect to the use of piles in land affected by contamination:

- To improve the effectiveness of regulation in order to better protect and enhance the environment;
- To ensure all parties, including developers and regulators, base their decisions on best information and knowledge;
- To increase awareness of environmental issues amongst the piling and ground improvement industry, and of geotechnical / engineering issues amongst Agency officers;
- To develop a decision-making framework based on site-specific assessment of risk;
- To identify appropriate and cost-effective risk mitigation measures that minimise constraints on the construction industry, whilst ensuring adequate environmental protection; and
- To identify areas of uncertainty and to make recommendations on future research needs.

1.2.2 Approach

The wide range of commercially available piling and penetrative ground improvement methods were grouped into a number of generic classes with similar properties. The types of piling and ground improvement methods considered has been limited to those used in civil engineering construction of foundations for built development. The study specifically excludes non-foundation piling such as sheet piling (where it is not used for vertical load bearing); the construction of deep basements; in ground methods such as deep soil mixing, intended wholly or partly to treat contaminated soil; and surface based ground improvement techniques such as dynamic compaction or pre-loading.

An initial review was undertaken to assess the degree of regulatory concern with respect to the use of piling and penetrative ground improvement methods on contaminated sites, the use of mitigation methods and whether any pollution incidents had been substantiated. The experiences of UK piling contractors (all members of the Federation of Piling Specialists) were sought by means of a questionnaire. A summary of the responses to the questionnaire is given in Appendix 1.

The most likely causes of pollution or harm to receptors have been identified. Each of these scenarios is discussed within a risk assessment framework in order to determine the likely magnitude of risk associated with each piling or ground improvement method, the certainty with which the risk assessment may be reported and the possible mitigation methods which might be applicable.

Where it is apparent that the assessment of risk for a particular piling or ground improvement method carries a considerable degree of uncertainty, recommendations are made for further research in order to ensure that this uncertainty is reduced.

There are few situations where a blanket prohibition on all types of piling or penetrative ground improvement can be justified, although there may be cases when alternative engineering methods, such as construction on rafts, may be more appropriate and pose a lesser risk to the environment. The report does not set out to provide a prescriptive guide to the applicability or selection of individual piling or ground improvement methods in relation to particular environmental conditions. The nature and magnitude of environmental risks will be highly dependent on site-specific circumstances and there is a wide variety of piling and ground improvement methods from which a method demonstrably posing an acceptable level of risk of harm to sensitive receptors can normally be selected.

Developers should ensure that any risks to human health and the environment are assessed, in order to determine appropriate remediation requirements. The effects of piling and ground improvement works should be incorporated into that process. Guidance on determining remedial objectives to protect water resources is given in Environment Agency R&D Publication 20, *Methodology for the derivation of remedial targets for soil and groundwater to protect water resources* (Environment Agency, 1999).

Environment Agency officers, and other regulators, need to be able to satisfy themselves that the designers of the ground improvement or piled foundations have fully considered the risk that the proposed works pose for the environment, human health and property, in addition to considering load carrying performance, ease of installation and cost.

The risk-based framework proposed is suitable for use by developers and their professional advisers to justify the proposed scheme to regulators. The preparation of such a risk assessment and its examination by Environment Agency and local authority officers will not absolve the developer and his advisers from the duty to prevent pollution, harm or nuisance. Professionals preparing such an assessment on behalf of a developer must demonstrate that reasonable skill and care have been exercised in the fulfilment of their commission, as required by their standard conditions of service and professional indemnity insurance.

The onus for rigorously justifying the proposed method is on the developer's professional advisers and not on the individual regulator, whose expertise may lie outside the realm of geotechnical engineering design. A comprehensive foundation works risk assessment report will be required in sensitive environmental locations, where regulatory concerns are raised. It is hoped that early discussion between the developer and regulators will help to ensure that all parties understand each other's concerns, and that rapid and satisfactory decisions can be made that place the minimum necessary constraint on the developer, whilst ensuring that the environment, human health and property are properly protected.

2. BACKGROUND TO ISSUES CONSIDERED

2.1 Legislative and Regulatory Context

2.1.1 Planning and development control

Redevelopment of land in general is controlled through the Town and Country Planning system, and it is this system that will normally be used to enforce any regulatory requirements or restrictions as sites are redeveloped.

Piling and penetrative ground improvement methods are generally considered in the redevelopment context, to provide foundations for new buildings or other engineering works. In the general case, the recommendations of the Environment Agency concerning water protection issues will be enforced by the planning authority, by the inclusion of planning conditions in its decision notice, or by other controls, such as s106 agreements.

Land contamination, or the possibility of it, is a material consideration for the purposes of the planning process. A planning authority has to consider its implications both during preparation of local or structure plans and when considering individual planning applications. The Environment Agency is a statutory consultee for planning applications that involve land affected by contamination.

Guidance to planning authorities is provided by Planning Policy Guidance 23 (PPG23): Planning and Pollution Control, and the Department of the Environment Circular on the 'Use of Conditions in Planning Permissions' (DoE, 1995). A revision of PPG23 is anticipated in the near future to bring it up to date with the new contaminated land regime (discussed further in section 2.1.3). The planning authority has a duty to satisfy itself of the following:

- that the potential for contamination is properly assessed;
- that the development incorporates the necessary remediation; and
- that risks are assessed, and remediation requirements set, on the basis both of the current site use and the proposed new use.

Where necessary, the planning permission should include conditions that require the developer to carry out appropriate site investigation and remediation. These conditions may also include any restrictions, mitigation or prohibitions on the use of particular foundation methods and in practice it is common for the inclusion of such conditions to be requested by the Environment Agency where risks to the water environment are significant. In some cases, the remediation works themselves may require planning permission as engineering works for development.

The planning process should take account of the requirements of the Environmental Impact Assessment Regulations 1999 and circular (DETR, 1999), for specified development classes.

In addition to the planning system, the Building Regulations 1991 may require that the fabric of new buildings and their future occupants are protected from the effects of contamination. Compliance with the Building Regulations is normally enforced by the building control function of the local authority.

2.1.2 Water Resources Act 1991

The Environment Agency has powers of prosecution under section 85 of the Water Resources Act 1991 (WRA, 1991) where a person "*causes or knowingly permits any poisonous, noxious or polluting matter or any solid waste matter to enter any controlled waters*". Controlled waters are defined under section 104 of the same Act as *"territorial waters, coastal waters, inland fresh waters and ground waters"*. Ground waters are defined as *"any waters contained in underground strata"*.

Where piling and ground improvement works are demonstrated to give rise to pollution of controlled waters (including run-off from arisings), the Environment Agency may seek to prosecute those parties who have caused or knowingly permitted the pollution. This may include any, or all, of: the main contractor, the ground works sub-contractor, site supervisory engineer, design engineer and client. The offence under section 85 is a strict liability offence and contractual arrangements do not offer any party exemption from prosecution.

The current maximum sentence in a magistrate's court for a summary conviction under s85 is a fine of £20,000 or three months imprisonment. Larger sentences can be handed down by higher courts.

Additionally, section 161 A-D of WRA 1991 and the Anti-Pollution Works Notice Regulations 1999 give the Environment Agency powers to remedy or forestall pollution of controlled waters, which includes powers to serve notices that requires remediation of polluted ground waters. In the event that a person has caused or knowingly permitted pollution of controlled waters as a result of piling or ground improvement works, the Environment Agency may serve a 'Works Notice' on that person, which requires the remediation of polluted waters. This notice may be served in addition to prosecution under s85 described above.

2.1.3 Part IIA, EPA 1990:The new contaminated land regime

The new contaminated land regime is primarily concerned with the state of land in its current condition and use. Part IIA of the Environmental Protection Act 1990 (inserted by Section 57 of the Environment Act 1995) provides a new regime for the identification and remediation of contaminated land. Reference should be made to the Contaminated Land (England) Regulations 2000 and the Statutory Guidance (DETR, 2000) or their equivalents applicable to Scotland or Wales (in due course), for definitive details of the new regime.

The main objective of the regime is to provide an improved system for the identification and remediation of contaminated land where existing contamination is causing unacceptable risks to human health or the wider environment, assessed in the context of the current use and circumstances of the land. The Act also sets out a framework for statutory liabilities to pay for remediation of contaminated sites, which is based on the 'polluter pays' principle. In the first instance, any person who caused or knowingly permitted the contaminating substances to be in or under the land will be required to undertake remediation and meet the costs.

'Contaminated land' is tightly defined and requires the existence of a significant pollutant linkage (SPL) that gives rise to a significant risk of significant harm or pollution of controlled waters (or the significant possibility of such), rather than merely the presence of contaminants in the ground. The definition of contaminated land is thus risk-based. The broader definition of 'land affected by contamination' is used in this report to refer to land with contamination present. It relates to land which may or may not pose a significant risk of significant harm or pollution at the current time, but which could give rise to environmental risks if circumstances change, such as during or after piling or penetrative ground improvement activities.

2.2 Environment Agency Concerns

The Environment Agency has expressed concern over foundations and piling as activities with the potential to cause, or allow the migration of, pollution into controlled waters (particularly groundwater). The Agency's approach to date is set out in the Pollution Prevention Manual (Environment Agency, 1996):

"Where sites are underlain by aquifers, piling should be avoided wherever possible, particularly if it would involve penetration of a clay layer previously providing protection to an underlying aquifer. Piling using the vibro-compaction/replacement [ground improvement] methods should always be avoided where contaminants are to remain on site, as the granular columns formed will produce an easy route of pollutants into the underlying formation.

"Where there is an option, concrete raft foundations are the preferred means of foundation on contaminated sites. Where these are not possible and there is no alternative to piling, continuous flight augered piles probably pose the least risk of groundwater pollution, although even these will not be acceptable at some sites without further precautions such as removal of contaminated material from individual pile sites or the use of temporary casing to seal out contaminated water."

This approach is underpinned by the "precautionary principle", supported by UK government policy (This Common Inheritance, Britain's Environmental Strategy, 1990) and articulated in the Rio Declaration on Environment and Development of 1992. Principle 15 of the Rio Declaration states:

"In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."

The starting point for the Environment Agency approach is a recognition of a lack of available scientific knowledge on the environmental implications and effects of piling. The general lack of technical guidance backed by rigorous theoretically based research makes the application of the precautionary principle inevitable where there is a reasonable possibility of serious adverse impacts on human and environmental receptors occuring as a result of activities on land affected by contamination.

The Environment Agency is nevertheless aware that the rigid application of this principle to piling and penetrative ground improvement on land affected by contamination may lead to unnecessarily restrictive requirements or prohibitions being placed on developers. The Environment Agency aims to ensure that the application of this principle is based on as detailed an understanding of the potential risks of adverse environmental impacts as possible given the current state of knowledge, that its decisions are defensible and that any resulting requirements or prohibitions are proportionate to the risks present and clearly explained to those affected.

The Agency concerns are:

- The creation of preferential flow paths, allowing contaminated groundwater and leachates to move downwards through aquitard layers into underlying groundwater or between permeable horizons in a multi-layered aquifer;
- 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;
- Contaminated arisings being brought to the surface by piling work, with the risks of subsequent exposure to site workers and residents, and the need for appropriate handling;
- The effects of aggressive ground conditions on materials used in piles;
- Driving contaminated materials downwards into an aquifer during construction / installation; and
- Concrete or grout contamination of groundwater and any nearby surface waters.

The first of these points is of particular concern to the Environment Agency in relation to the protection of water resources. It relates to the situation in which piling or ground improvement has the potential to create permeable flow paths allowing contaminated water to enter and pollute an underlying aquifer.

Throughout the discussions that follow, it is assumed that appropriate standards of design and workmanship will be applied to the design, method selection and construction of the foundation works considered. The proposed framework for foundation works risk assessment outlined in this report is considered to reinforce high standards of design and workmanship as it requires a detailed understanding of the technical issues involved.

However, a note of caution should be introduced since, as with all construction activities, there is the possibility that low standard work, albeit superficially attractive due to its low cost, may be accepted by a client. This could lead to failures in the structural and environmental performance of the foundations. In all cases, not only on brownfield sites, it is strongly recommended that appropriately qualified professionals, members of relevant professional or trade bodies and with demonstrable experience in the type of work proposed, should be employed.

2.3 Case Studies

There are few reported, and fewer still substantiated, incidents of the use of piling or ground improvement methods on contaminated sites causing pollution. This cannot, however, be taken as *prima facie* evidence that no risk to sensitive receptors is posed by these activities. Pollution could have been attributed to other causes or may have been undetected altogether since targeted groundwater monitoring has rarely been undertaken during piling operations.

Campbell *et al* (1984) identify a chemical works in the southern United States where piling was implicated in vertical migration of contaminants, though the source-pathway-receptor linkage was not conclusively proved.

Driven pre-cast concrete piling (the West Shell system) was originally designed in the 1920s to form foundations for town gas works (West, 1972). Despite the gross contamination associated with many of these sites and the elapsed time since their original construction, driven piling has not been clearly implicated in the migration of gasworks contaminants into underlying aquifers. One of the case studies described in Appendix 2 relates to the redevelopment of a gas works site where the original piled foundations were encountered.

Although there is no documentary evidence that links piling activities to pollution of groundwater on a large scale, despite the extensive use of piles in urban areas over the past century, at the majority of sites there is insufficient data to show that the piles did not contribute to contamination. The Environment Agency considers that developers are in general reluctant to undertake groundwater monitoring, particularly for extended periods that would be necessary to prove whether ground works have caused contaminant movement.

It is this lack of appropriate monitoring data, rather than an inherent distrust of the piling and ground improvement technologies themselves, that causes the Environment Agency to tend to adopt the precautionary approach when considering piling on contaminated sites. Regulatory concern has been raised at a large number of sites which has resulted in changes to the piling design or method selected, or where appropriate mitigation methods have been used. Several case study examples are summarised in Appendix 2.

2.4 Research Carried Out or Underway

The majority of the research carried out into the performance of piling and penetrative ground improvement methods has focussed on the structural performance and behaviour of the foundations. Particular attention has been paid to the mechanisms of load transfer from structures to ground, failure mechanisms, ultimate and serviceability limits for bearing capacity, and settlement and construction issues such as driveability of driven piles and integrity of cast-in-place piles (Fuller, 1983; Tomlinson, 1994; Whittaker, 1970).

A parallel strand of research has considered the long-term durability and hence structural performance of piles in the ground. Sulphate minerals are common in many soils (natural as well as from man-made sources) and concrete has a particular susceptibility to attack from sulphates. Other sources of aggressive chemical attack have also been studied, for example acids, alkalis, organic solvents and inorganic salts (Barry, 1983; Paul, 1994; Environment Agency, 2000a).

Academic research specifically carried out into the environmental impacts of piling systems is virtually non-existent in the UK and very limited in the United States and this remains the case at the present time. The Engineering and Physical Sciences Research Council (EPSRC) is not currently funding any such research. An internet search carried out in early 2000 of UK university departments with particular interest in either piling or groundwater protection did not indicate any research interests or projects underway in this specific area.

In the United States, Hayman *et al* (1993) and Boutwell *et al* (2000) have published results of bench scale laboratory testing which examined the possible impact of displacement piling on 'dragdown' of contaminated soils, vertical contaminant migration along the pile-soil interface and, for timber piles, contaminant migration through the material of the pile itself.

Their research tends to indicate that the potential for vertical contaminant migration is limited, being a function of the pile material and the magnitude of the horizontal displacement. Both sets of authors agree that the potential for 'dragdown' of contaminants during pile driving is finite and in most cases insignificant, and can be mitigated effectively by the use of a conical pile shoe. In the case of untreated timber piles, vertical contaminant migration by capillary action ('wicking') within the pile material itself is identified as a possible pathway.

Some of the research carried out into the structural performance of piling and ground improvement methods may nevertheless be of use in considering environmental performance of piles, albeit with the limitation that the research was not designed specifically to address environmental issues. For example, research into stress distributions and density changes in soils surrounding displacement piles could be re-examined to enable the impact on soil permeability to be determined.

Research into the durability of piles in aggressive ground is particularly relevant to the use of these methods on contaminated sites. A number of research bodies have examined these material durability issues. Early work commissioned by the Construction Industry Research and Information Association (CIRIA) into material durability in aggressive ground (Barry, 1983) identified the contaminants of concern and outlined the mechanisms of attack on structural materials in the ground. The Building Research Establishment (BRE) carried out a major study which considered aggressive contaminants in contaminated land, the mechanisms of corrosion and degradation and acceptance criteria for use of structural materials in these situations (Paul, 1994). The BRE is continuing this work under a further DETR project investigating the corrosion behaviour of steel piles in the presence of various contaminants. This project is titled 'Contaminated land risk assessment for building materials' and is due to report during 2001.

Research into corrosion attack on steel piles is currently being carried out by the Steel Construction Institute and contaminated and aggressive ground is one of the issues under investigation (Johnson, 1995). The results of this research have not yet been published.

Quantitative data are, however, available for a range of contaminants and building materials, the most well-known being BRE Digest 363 on 'Sulphate and Acid Resistance of Concrete in the Ground' (BRE, 1996). Qualitative data also exist, to a lesser extent, on the aggressivity of chemicals towards materials other than concrete, most notably metals and materials used for the distribution of water (Paul, 1994, and references therein).

In addition, some studies have been carried out on redundant piles which have been in service in contaminated land for an extended period. For example, Matheson & Wain (1989) investigated the effects of corrosion on concrete piles that had been installed at two former gasworks sites for between 15 and 29 years. Conditions at both sites are considered extremely aggressive to concrete, with high sulphate concentrations and acidic conditions recorded at a site in Camberley and high sulphate, chloride and phenol concentrations recorded at a site in Beckton. Analysis of concrete samples from the core and surface of piles at both sites showed that, other than some surface corrosion (corroded zone 1mm in depth), the concrete showed no signs that disruptive chemical reaction had taken place.

Therefore the conclusions from the majority of the research carried out indicate that whilst the theoretical possibility of attack on concrete or steel piles has been identified, in practice their confinement in a comparatively stable subsurface environment tends to limit the magnitude of any attack on the piles.

Individual piling technology providers commission research on occasion, particularly when introducing new pile construction and installation methods. Much of this research is commercially sensitive and consequently is not disseminated or peer reviewed as rigorously as would be the case for independent academic or research body directed research. Such research is commonly focussed on the structural performance of the proprietary method. Nevertheless such research may provide a practical means for piling and ground improvement companies to demonstrate the environmental effect (or absence of such) of the use of their proprietary methods.

3. REVIEW OF PILING AND GROUND IMPROVEMENT METHODS

3.1 Introduction

There is a considerable variety in the materials, design and installation methods used in piling and penetrative ground improvement (BRE, 1986). As a result a number of different approaches to creating a generic classification system may be taken. Piles may be classified by material used in the piles, by the mechanism for load transfer between the foundations and the ground by the installation methodology used or by the effect of the installation on the soil mass.

Table 3.1 Possible classification scheme for ground works

Classification	Subdivisions
Materials	Timber, concrete, steel, composite, stone etc
Load transfer	End-bearing, friction, combination
Installation	Bored, driven, cast-in-place
Effect of installation on soil mass	Displacement, non-displacement/replacement and subdivisions according to installation method

It is common industry practice to use the latter approach (Tomlinson, 1994) and this has been followed in preparing this report. Pile foundations are divided into two basic types; displacement and non-displacement (replacement), and further subdivided according to the methods of construction and installation used. As will be illustrated by the description below, the difference between displacement and non-displacement methods has a potential effect on the environmental impact of the piling method used.

Penetrative ground improvement methodologies are difficult to classify in comparison with piling methods, as they function in an essentially different way. Whilst piles are designed to transfer loads through poor ground to a competent founding level, ground improvement techniques aim to improve poor ground (by densification, or by a combination of densification and addition of stiffer granular material) so that it is made competent to support conventional foundations. However, some ground improvement techniques such as vibrated concrete columns are more similar in form to piles than to ground improvement by densification.

There are a number of factors that determine the choice of piling or ground improvement method for a particular project. These include the support requirements (both bearing capacity and settlement) for the structure, the subsoil stratigraphy, the load transfer mechanism from the pile to the ground (friction or end bearing), ease of quality control, effect on adjacent structures, comparative material and installation prices and speed of installation (Prakash and Sharma, 1990). The decision may be empirical, it having been found on previous projects in a particular area or geotechnical context that a particular method is trouble free, reliable and cost effective.

In urban areas the potential for noise and vibration created by the piling operations is often a major concern to the local planning authority and local residents. Piling driven by percussion hammers can create particular disturbance and in noise and vibration sensitive locations the choice of piling or ground improvement methods may be considerably constrained.

In considering the potential for environmental impacts from piling and ground improvement methods, it must be recognised that structural, geotechnical and noise considerations will have a major bearing on the type of piling method preferred by a project's client and his professional advisers. This guidance recommends that potential environmental impacts should be considered at all stages of method selection.

It should be noted that there are a large number of proprietary systems and variants on the generic piling and penetrative ground improvement methods described and new approaches are continually being developed and brought to market. New methods may be introduced which represent hybrids of the methodologies described here and it is even possible that completely new methods may be introduced which do not fit comfortably into the classification presented.

General characteristics of displacement and non-displacement piling methods and penetrative ground improvement methods are described in sections 3.2 to 3.4. Detailed descriptions of specific methods are given in Appendix 3 and are summarised in the table below.

Table 3.2 Types of piling and penetrative ground improvement methods considered in this report

Generic methodology	Methods that are discussed in Appendix 3
Displacement piles	Pre-formed hollow pile (A3.1.1)
	Pre-formed solid pile (A3.1.2)
	Displacement cast-in-place pile (A3.1.3)
Non-displacement piles	Non-displacement cast-in-place pile (A3.2.1)
	Partially pre-formed pile (A3.2.2)
	Grout or concrete intruded pile (A3.2.3)
Penetrative ground improvement methods	Vibro replacement stone column (A3.3.1)
	Vibro concrete column (A3.3.2)

3.2 General Characteristics of Displacement Piling

Small displacement piles comprise steel sheet, H, I, hollow tube sections, or hybrids such as the auger pile. Large displacement piles may consist of pre-cast concrete elements, closed-end steel tube or timber sections, or may be cast in situ inside a casing or in a pre-formed void. Displacement piling methods involve the pile being formed by displacing soil from the space to be occupied by the pile without the removal of soil to the ground surface.

Soil displacement occurs generally in a radial horizontal direction; there is little downwards vertical movement of soil under the toe of the pile. In some cases, for example large displacement driven piles, the radial horizontal movement of soil can displace overlying soil upwards, leading to some heave at ground level. Some vertical downwards movement of soil due to frictional dragdown can occur along the sides of the pile shaft but this is typically of a limited extent both horizontally and vertically (FPS, 2000; DoE and CIRIA, 1980).

In general the mechanism of radial soil displacement leads to a volume reduction for a given unit weight of soil within the soil surrounding the pile. This corresponds to densification of the soil surrounding the pile and generally this will lead to a reduction in permeability of the penetrated soil (FPS, 2000). The radial movement of the soil will also create a stress field in the zone of influence that will tend to make the soil close up around the pile after the driving is complete, especially in cohesive materials.

3.3 General Characteristics of Non-Displacement Piling

Non-displacement piling techniques involve the extraction of a core of soil and its subsequent replacement by the pile. The pile is typically formed by casting concrete in situ. Displacement of the soil surrounding the pile is minimised and there is minimal radial or vertical soil movement or densification as a result of this method. Excavated soil is brought to the ground surface in the form of arisings, sometimes mixed with grout or concrete from the pile formation itself.

Since non-displacement piling methods involve the formation of an excavated hole in which the pile is formed or placed, the temporary support of the hole prior to placing the pile is often a requirement. A variety of methods have been developed for providing this temporary support, including temporary and permanent casings and the use of bentonite (DoE and CIRIA, 1977). The installation of these casings may cause the same effects on the soil as for small displacement piles, as noted in section 3.2.

3.4 General Characteristics of Penetrative Ground Improvement

Ground improvement generally involves the improvement of the physical characteristics related to load bearing and settlement performance of the soil in order for it to form a competent bearing material in its own right. Penetrative ground improvement methods involve the penetration to the full depth of soil to be improved by equipment used for the ground improvement, by contrast with non-penetrative methods that involve the application of compactive loads at the ground surface.

The physical properties of the ground may be improved by densification alone, or by a combination of densification and introduction of granular material which improves the stiffness of the ground. Introducing columns of granular material can also speed up settlement as the length of the drainage path is reduced by allowing faster dissipation of excess soil pore water pressures. A comparatively recent development is the introduction of concrete, rather than granular material, a method that may be considered a hybrid between ground improvement and displacement piling.

4. HAZARD IDENTICATION: POTENTIAL ADVERSE ENVIRONMENTAL IMPACTS

4.1 Pollution Problems Considered

It is important to consider the potential pollution hazards associated with piling and ground improvement works in the context of the environment in which sites are located. For example, some ground works have the potential to create pathways for contaminant migration, but an unacceptable risk of pollution can only occur if there is also a source of contamination and a receptor that could be harmed by exposure to those contaminants. This is often termed a Source-Pathway-Receptor (S-P-R) linkage. The overall level of risk is a product of the probability of harm occurring and the consequence of that harm (Environment Agency, 2000b).

The presence of contaminant sources will normally depend on the past uses of the site. The presence of environmental receptors that could be harmed by ground works is essentially defined by the hydrogeological properties of the underlying strata, the proximity to surface water bodies and the use and occupation of the site and its surroundings.

In many instances, the risks to groundwater quality will be the principal concern of Environment Agency officers. The Agency's *Policy & practice for the protection of groundwater* (Environment Agency, 1998) describes an approach that allows sites to be ranked on the basis of their sensitivity to groundwater pollution. Groundwater resource classification (Major, Minor and Non-aquifer) from groundwater vulnerability maps, combined with the modelling of Source Protection Zones around groundwater abstractions can be used to assess and rank the overall sensitivity of that groundwater to pollution arising from activities near the ground surface.

In the case of piling and ground improvement works, concerns about water protection are likely to be most acute when:

- Contaminants are present on the site and ground works could allow them to migrate;
- Piling would breach a low permeability layer or connect two previously discrete aquifers;
- The site overlies a Major or Minor Aquifer;
- The site is located within a Source Protection Zone;
- Groundwater is currently of good quality;
- The water table is shallow or likely to be intersected by piles;
- The geological strata are fractured or fissured;
- Works are close to a surface water body and run-off from arisings could pollute those waters.

The Agency's response to proposals for piling on contaminated sites will be based on the overall level of risk that piling is likely to present, the techniques, any mitigation measures and the quality assurance and control (QA/QC) methods proposed. Where the hydrogeological setting is not sensitive (e.g. the site is located on a thick sequence of clays classed as a Non-aquifer) and the Agency is satisfied that risks are low, then special precautions or design constraints are unlikely to be necessary. In sensitive situations the Agency may require a risk assessment to be undertaken and mitigation measures (including groundwater monitoring) to be incorporated. In the most sensitive situations, the Agency will object to proposals that it considers present an unacceptable risk of pollution.

In this report six potential S-P-R linkages have been considered. This is not an exhaustive list and others may be identified in particular circumstances. The six scenarios considered relate to:

1. Creation of preferential pathways, through a low permeability layer (an aquitard), to allow potential contamination of an underlying aquifer;

2. Creation of preferential pathways, through a low permeability surface layer, to allow upward migration of landfill gas, soil gas or contaminant vapours to the surface;

3. Direct contact of site workers and others with contaminated soil arisings which have been brought to the surface;

4. Direct contact of the piles or engineered structures with contaminated soil or leachate causing degradation of pile materials (where the secondary effects are to increase the potential for contaminant migration);

5. The driving of solid contaminants down into an aquifer during pile driving; and

6. Contamination of groundwater and, subsequently, surface waters by concrete, cement paste or grout.

These scenarios are discussed in detail in the following boxes.

Pollution Scenario: 1

Creation of preferential pathways, through a low permeability layer (an aquitard), to allow potential contamination of an aquifer.

Source/Contaminant:
Contaminated made-ground or waste, or contaminated perched groundwater.

Pathway:
Pile stone column, pile/soil interface or disturbed ground around pile.

Receptor:
Groundwater in aquifer - typically in solid strata in which pile is founded.

Description:
A typical situation is where filled (contaminated) ground is situated above clay drift deposits that in turn sits on solid strata such as the Chalk (DoE and CIRIA, 1978). This situation is common in eastern and southern England. Frequently perched water exists within the made ground, with the drift deposits inhibiting downward movement of the perched groundwater. Disturbance of this aquitard layer has the potential to create a migration pathway, provided that a downward hydraulic gradient exists between the perched groundwater and the aquifer.

A similar situation could arise if a closed landfill, with a basal liner, was to be redeveloped, with structural loads supported on piles founded in solid strata below the basal liner.

Cases of known/inferred pollution or research findings suggesting possibility of pollution:
It has been reported (though further investigation is proposed to substantiate the details) that installation of piles through 5 – 15m of clay into an underlying sandstone at a chemical works in northern England has caused contaminated groundwater perched in a superficial aquifer to migrate into the deeper Major Aquifer. Campbell *et al* (1983) report a case of a site in the southern United States where vertical migration of contaminants around piles is implicated in groundwater pollution.

Hayman *et al* (1993) and Boutwell *et al* (2000) report on bench scale model testing which showed that steel ‘H’ section piles could create migration pathways along the pile/soil interface, and untreated timber piles could allow transmission through the material of the pile itself. Cylindrical section driven piles, however, showed no adverse impact, presumably due to the large displacements and confining pressures generated.

Cases where regulatory concern has been expressed:
A number of cases have been reported. Typically these involve proposals for piled foundations on ‘brownfield’ sites when the Chalk is the desired founding stratum and is overlain by clays. Frequently, initial proposals are bored or driven piles but regulatory

intervention has led to the adoption of auger based piles. Cases are also noted where vibro stone columns have been replaced by vibro concrete columns.

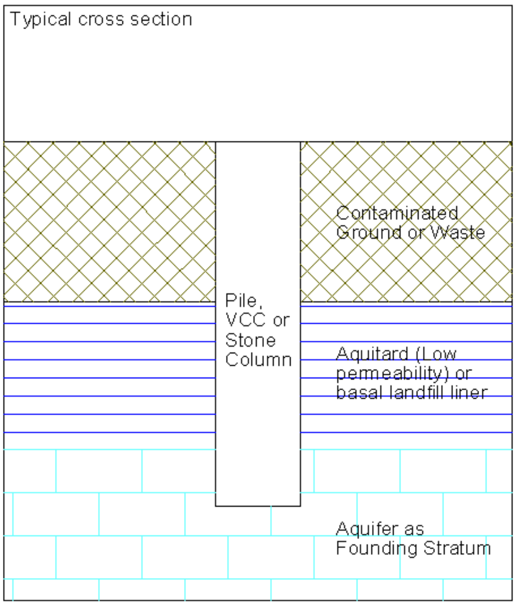

Figure 4.1 Pollution scenario 1: breaching an aquitard

Pollution Scenario: 2

Creation of preferential pathways, through a low permeability surface layer, to allow migration of landfill gas, soil gas or contaminant vapours to the surface.

Source/Contaminant:
Gassing (e.g. methanogenic) landfilled waste or contaminated ground.

Pathway:
Pile/stone column, pile/soil interface or disturbed ground around pile.

Receptor:
Users of built development; structures.

Description:
This situation may be encountered where development is proposed on an old landfill, or a 'brownfield' site when ground levels have been raised using contaminated (gas-generating) fill. Alternatively this may occur where land has been contaminated with volatile compounds, such as petroleum spirit. Frequently an impermeable cap is present as part of the remediation solution to manage the existing gassing regime.

Disturbance of this capping layer has the potential to create a migration pathway for landfill gas, or could create air-flow pathways that might render an active gas extraction system ineffective. The introduction of air may affect the existing gas generation within the fill, for example, increasing the rate of degradation and increase the volume of gas generated.

Cases of known/inferred pollution or research findings suggesting possibility of pollution:
None reported, however, this cannot be taken as evidence for non-existence of cases. It is noted that migration of soil gas through stone filled columns is directly comparable to landfill gas interception trenches that are designed to vent migrating landfill gas to atmosphere.

Cases where regulatory concern has been expressed:
Few cases reported. It is assumed that the severity of the consequences of failure of gas protection measures are such that designers will normally adopt a precautionary approach and design appropriate mitigation measures to avoid such an occurrence.

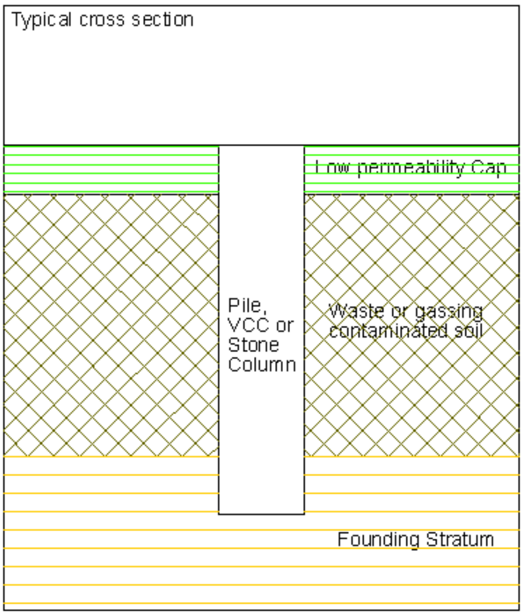

Figure 4.2 Pollution scenario 2: vapour migration to surface

Pollution Scenario: 3

Direct contact of site workers and others with contaminated soil arisings that have been brought to the surface.

Source/Contaminant:
Contaminated soil or waste.

Pathway:
Direct contact with excavated arisings, run-off to surface waters.

Receptor:
Human receptors (construction workers, site users etc) and surface water.

Description:
Where pile excavation creates arisings, there is a potential for such arisings to contain contaminated soil which is brought into contact with sensitive receptors.

The piling process is likely to mix contaminated and uncontaminated soils, leading to an increased volume of contaminated materials for disposal. If the soil contains asbestos or other forms of relatively non-mobile but hazardous contaminants (e.g. PCBs and dioxins) the creation of arisings may be particularly undesirable. Contaminated piling arisings may also cause cross-contamination to isolation layers.

Cases of known/inferred pollution or research findings suggesting possibility of pollution:
None reported, however, this cannot be taken as evidence for non-existence of cases.

Cases where regulatory concern has been expressed:
Concern is likely in cases where arisings may contain particularly hazardous materials, for example fibrous asbestos or PCBs. For example, use of rotary displacement piling was used to drive piles through a landfill containing asbestos waste whilst minimising surface arisings. Air monitoring at the site was undertaken to confirm that airborne asbestos fibre concentrations were always within safe limits.

Where arisings fulfil the definition of controlled waste, there is a 'duty of care' on the operator to ensure the safe disposal of that material.

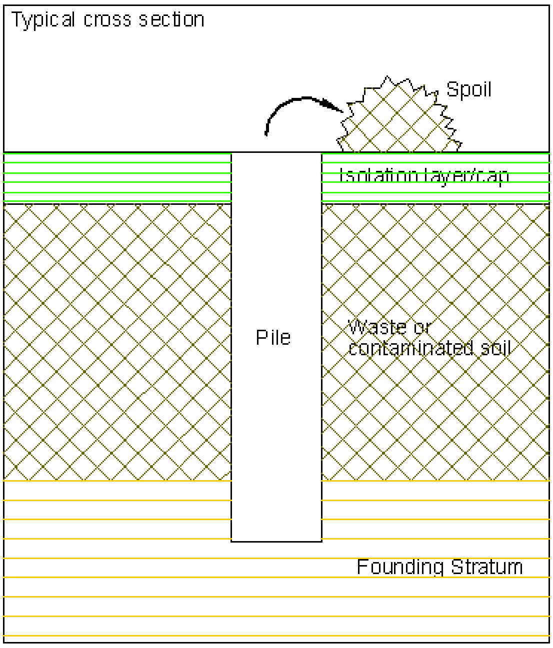

Table 4.3 Pollution scenario 3: contaminated arisings exposed as surface

Pollution Scenario: 4

Direct contact of the piles or engineered structures with contaminated soil or leachate causing degradation of pile materials.

Source/Contaminant:
Contaminated soil, waste or leachate.

Pathway:
Direct contact with pile.

Receptor:
Built development (and users).

Description:
Some contaminants or constituents of contaminated soil or leachate may be aggressive to materials used in piles. This has the potential to cause degradation to the piles, reducing or eliminating their load carrying capacity, and possibly creating migration pathways.

In an extreme case, this could lead to catastrophic failure of building structures, although a building designer and local authority building control officer should be expected to take into account any aggressive properties of the ground in preparing and approving their designs.

From a purely environmental point of view, the most significant impact could be created by subsequent remedial works designed to maintain the building's stability.

Cases of known/inferred pollution or research findings suggesting possibility of pollution.
None reported, however, this cannot be taken as evidence for non-existence of cases.

Cases where regulatory concern has been expressed:
None reported by the Environment Agency, though a number of cases are reported where geotechnical designers or piling specialist contractors have selected particular methods or taken particular design measures to protect piles from chemical attack.

The Environment Agency's interest in this issue is primarily where corrosion of the pile would subsequently lead to opportunity for pollution migration. Responsibility for assessing the risks to buildings normally lies with the local authority.

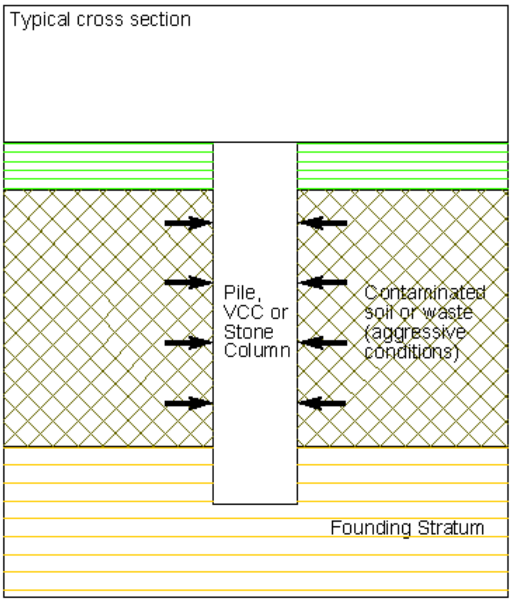

Figure 4.4 Pollution scenario 4: corrosion of pile leading to creation of flow paths

Pollution Scenario: 5

The driving of solid contaminants down into an aquifer during pile driving.

Source/Contaminant:
Contaminated soil.

Pathway:
Driving down of soil in contact with the sides and butt end of the pile, or 'plugging' of an open-ended pile.

Receptor:
Groundwater in aquifer, typically in solid strata in which pile is founded.

Description:
The primary movement of soil during piling is in a lateral direction, but there is potential for soil in contact with the sides of a driven pile and material below the butt end of a solid or closed-end pile to be dragged down slightly before it is displaced laterally.

There is also a potential for open-ended tubular piles to become 'plugged' with soil, enabling material captured near the surface to be transported downwards within the tube towards the founding level. This is most likely to occur when stiff or dense soils are present.

Cases of known/inferred pollution or research findings suggesting possibility of pollution.
None reported from the field, however, this cannot be taken as evidence for non-existence of cases. Hayman *et al* (1993) report on bench scale model testing that demonstrated that this mechanism was possible, though the magnitude of the impact was unlikely to be significant. Boutwell *et al* (2000) present a volumetric calculation which confirms that the magnitude of the impact of this mechanism is unlikely to be significant in most cases, and that any impact will be reduced by between one and three orders of magnitude by the use of a conical driving shoe.

Cases where regulatory concern has been expressed:
None reported by the Environment Agency. The use of a pointed or convex driving shoe can be used to avoid this problem.

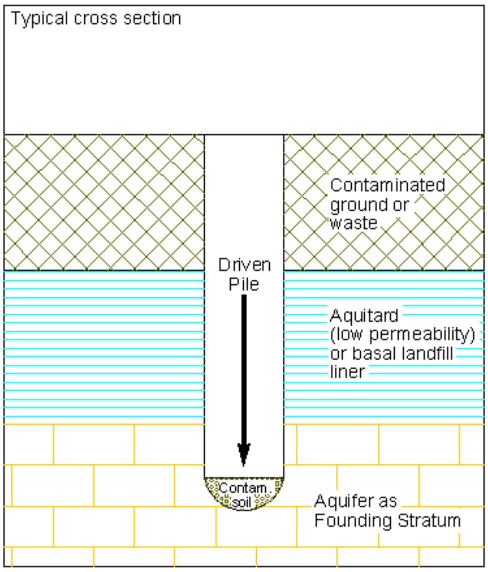

Figure 4.5 Pollution scenario 5: Driving contaminated material into aquifer

Pollution Scenario: 6

Contamination of groundwater and, subsequently, surface waters by wet concrete, cement paste or grout.

Source/Contaminant:
Concrete, cement paste or grout introduced to the ground during piling/penetrative ground improvement operations.

Pathway:
Flow within highly permeable or fractured strata.

Receptor:
Groundwater and surface water.

Description:
Loss of wet concrete, cement paste or grout may occur in fast-flowing groundwater, probably associated with fractured or jointed rocks such as limestones and the Chalk or permeable gravel formations. Migration may occur until setting of the concrete, cement paste or grout occurs; this would generally occur on a timescale of a few minutes. Use of retarder additives could extend this timescale to a few hours, although their effectiveness would be reduced by dilution. In most circumstances, therefore, the impact, if any, is likely to be localised.

Cases of known/inferred pollution or research findings suggesting possibility of pollution.
Injection of grouts into mine workings to improve ground stability has resulted in pollution of a nearby river and pond in at least one reported case, as grout migrated through the workings and fractures, and subsequently through the bed of the watercourse.

Cases where regulatory concern has been expressed:
None reported by the Environment Agency. For geotechnical and economic as well as environmental reasons, a piling method which avoids the risk of loss (e.g. use of permanent casing or pre-formed piles) would generally be chosen when piling through highly fissured or permeable strata.

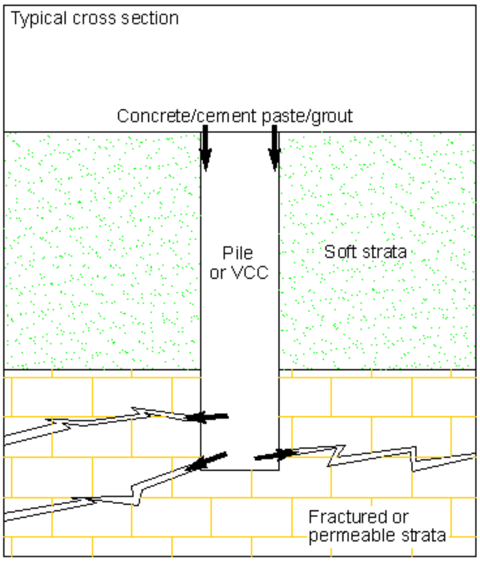

Figure 4.6 Pollution scenario 6: injection of grouts or pastes into groundwater

5. HAZARD ASSESSMENT

5.1 Approach

This section describes the likely hazards associated with each generic method of piling and ground improvement (described in Section 3). The critical assumptions relating to each method of piling or ground improvement are given and possible mitigation measures are described.

The limitations of any generic assessment should be recognised. It takes no account of any site-specific conditions and these are likely to have a major influence on the processes of design, method selection, risk assessment and mitigation that would be required on a given site. The hazard assessment is therefore presented to illustrate the sort of considerations that need to be taken into account: it should not be taken as a definitive specification of 'suitable' or 'unsuitable' methods for a given case.

5.2 Pollution Scenario 1: Creation of Preferential Pathways, through a Low Permeability Layer, to Cause Contamination of Groundwater in an Aquifer

5.2.1 Assessment of applicability of displacement piling methods

General applicability

The soil surrounding the pile is densified and high stresses are induced in the surrounding ground when driving displacement piles. These stresses increase with size of pile and magnitude of displacement. In most soils these stresses will tend to force the soil to close up around the pile shaft, which means that the development of preferential flow paths around the outside of the piles is, in general, unlikely. However the magnitude of these beneficial effects may be reduced in cases where the lateral displacement is small, for example, cruciform or 'H' section piles.

Specific problems and uncertainties

In stiff over-consolidated clays such as those associated with glacial till the driving may create cracking in the upper levels due to upwards expansion, though this is less likely where the stiff clay is confined by overlying soil.

Piles with small cross sections may be prone to a "whipping" action when driven percussively, especially in soft soils. This could conceivably cause soil to be displaced further outwards than necessary to make room for the pile. In soft clays, where whipping is likely to be an issue, it is unlikely to be a problem as the surrounding soil will deform with the pile. The reduction in shaft adhesion with increasing undrained sheer strength (Tomlinson, 1994) shows that there may not always be continuity between the pile and stiff clays.

However, as areas of soil are likely to remain in contact with the shaft during installation and will relax back to the pile in time, there is unlikely to be a continuous pathway formed due to this action. It should be noted that the SCI have made it known that they consider that issues relating to whipping are overstated and that, by careful selection of pile, it can be eliminated in soft soils (SCI, 2001).

Laboratory tests have shown that soil may not close-up around piles with re-entrant angles in cross section (for example, cruciform, H or I piles) (Hayman *et al*, 1993; and Boutwell *et al*, 2000). However, there is little evidence of this occurrence in the field.

In general, it is considered that provided the aquitard layer is of a reasonable thickness and the piles driven through have a cross section without re-entrant angles, the likelihood of creating preferential flow paths for downward migration of leachate is very low. This hypothesis is consistent with the results obtained by Hayman *et al* (1993) and Boutwell *et al* (2000). Thin aquitards, and in particular thin stiff clay layers, may provide some cause for concern over preferential flow paths. It is, however, by no means certain that this situation would actually arise in practice. The magnitude of the effects due to whipping and piles with re-entrant angles together with their possible impact on flow paths is not known and would benefit from further research.

Where a hole is pre-formed through a body of contaminated groundwater or leachate to allow the subsequent insertion of a pile there is a possibility of short-term rapid liquid flow through the pre-formed hole during the pile installation. This situation would be undesirable from a geotechnical as well as an environmental standpoint, as the water flow would be likely to soften or weaken the soil. In most conventional piling a positive hydrostatic head is maintained in the pre-formed hole to prevent water flowing from the ground into the hole.

In some circumstances maintenance of this positive head may not be possible. In such a situation, if the area of the pile cannot be completely de-watered prior to installation the selection of an alternative piling method should be considered.

Piling method variations

The above considerations apply to driven displacement cast-in-place piles where the concrete ‘shell’ or casing is left in place. Where casing is removed, the plastic concrete is forced, by its hydrostatic pressure into intimate contact with the surrounding soil. This should ensure that the formation of preferential seepage paths is avoided.

The bored displacement auger pile behaves in a somewhat different manner. Since the installation is by a rotary boring method, there is no prospect of drag down of soil and whilst the lateral displacement of the soil is not great, there is an increase in stress which will act to ensure that the soil closes up around the pile. To minimise the torque required to screw these piles into place, the disposable base has a slightly larger diameter than that of the drive tube. Consequently, there is potential for creation of a temporary pathway around the peripheral zone of soil. The helical shape of the pile will serve to lengthen considerably any potential seepage along the pile-soil interface. However, pile installation time will be of the order of a few minutes and concreting will close this pathway. It is therefore considered that, in the absence of a head of contaminated liquid, seepage of a significant volume of contamination is unlikely to occur along this pathway.

In the particular case of timber piles, Hayman *et al* (1993) and Boutwell *et al* (2000) identify capillary transmission ('wicking') through the material of the pile itself as a possible migration pathway.

5.2.2 Assessment of applicability of non-displacement piling methods

General applicability

Non-displacement piling methods involve the extraction of soil prior to the placing of the pile. Theoretically therefore there is no disturbance of the surrounding soil and provided that the pile is formed or placed in intimate contact with the surrounding soil there should be no formation of preferential pathways.

Specific problems and uncertainties

Avoidance of disturbance to the surrounding soil does, however, require a high standard of workmanship in the construction process. Any lack of support due to poor working practices, however short term, during boring or augering could lead to collapse of soil or piping into the hole, leading to loss of density in the surrounding soil and possibly void formation. The result of poor workmanship could be the creation of preferential flow pathways. Under-reaming of pile bases has particular potential for the collapse of soil into the bore and the formation of voids if not correctly executed. Appropriate QA/QC methods should be incorporated into the works to enable workmanship to be monitored and verified.

Where a hole is pre-formed through a body of contaminated groundwater or leachate to allow the subsequent formation of a pile there is a possibility of short term rapid liquid flow through the pre-formed hole during the pile installation. This situation would be undesirable from a geotechnical as well as an environmental standpoint, as the water flow would be likely to soften or weaken the soil. In most conventional piling, a positive hydrostatic head is maintained in the pre-formed hole to avoid water flowing from the ground into the hole.

In some circumstances maintenance of this positive head may not be possible. In such a situation, if the area of the pile cannot be completely dewatered prior to installation the selection of an alternative piling method should be considered.

Subject to these caveats relating to support and workmanship, it is considered that there is a negligible risk of creating preferential pathways by the use of the non-displacement piling methods.

Piling method variations

Partially preformed piles involve the placing of a preformed section within a larger hole and the grouting of the annulus between the preformed hole and the soil. Because this grout is non-load-bearing it is likely to be regarded as less critical during installation and the result may be that soil surrounding the hole is allowed to loosen before grouting. If this method is used it is important that the grouting operation is carried out with the importance of the prevention of seepage pathways recognised during construction.

Continuous flight augers rely on the retention of soil on the auger flights to provide support to the surrounding soil until the auger is withdrawn and the concrete or grout intruded. It is vital that the intruded material is placed under pressure at a rate consistent with that of the withdrawal of the auger to ensure that the hole is supported.

5.2.3 Assessment of applicability of penetrative ground improvement methods

General applicability

As ground improvement methods commonly involve a shallower depth of penetration than piling (the maximum penetration is typically of the order of 5m) and cannot be used to penetrate stiff or dense soils, there is less likelihood of penetrating to a deep aquifer, subject to local geological circumstances. However, there is the potential for shallow groundwater movement to be affected.

Ground improvement method variations

Vibro-replacement stone columns and vibro-concrete columns are installed by displacement methods so soil surrounding the columns will be densified, reducing the permeability of the surrounding soil. However, if the top feed process is used the introduction of water may flush fines from the surrounding soil and this could increase its permeability.

Stone columns are filled with uniformly graded stone of coarse gravel or cobble grading. Although this infill is compacted to a high density the permeability of the completed column is likely to be high, so the column itself is likely to form a preferential pathway. The bottom feed process can be adjusted to allow for mitigation measures. These include the placing of a concrete plug in the base of the stone column to reduce the vertical permeability of the structure and hence the potential for downward movement of leachate, subject to the stratigraphy of the surrounding materials. Alternatively the grouting of the stone column itself with cementitious grout can reduce its permeability, but it is necessary to consider the applicability of grouts to any contaminants present at the site.

With vibro concrete columns the infill concrete is effectively impermeable and cast in contact with the surrounding soil and formation of preferential pathways is not likely.

5.3 Pollution Scenario 2: Creation of Preferential Pathways to Allow Migration of Landfill Gas or Contaminant Vapours to Surface

In general it is unlikely that a gas impermeable clay cap will be used exclusively to protect built development above, without a permeable granular gas blanket and venting system, and overlying gas proof membrane provided to ensure that any gas escape can be satisfactorily vented. If such a cap is used as part of a gas protection system, it clearly must be designed to take account of any penetration by foundations.

5.3.1 Assessment of applicability of displacement piling methods

General applicability

Similar considerations apply as to the previous pollution scenario. A low permeability cover layer is likely to be near surface and the possibility of disrupting the layer by heave is consequently greater. Conversely, mitigation measures are correspondingly easier to implement.

Specific problems and uncertainties

In heavily compacted clay cover, pile driving may cause cracking in the upper levels due to upwards expansion, though this is less likely where the stiff clay is confined by overlying soil. As discussed in section 5.2.1, piles with small cross sections may be prone to a 'whipping' action when driven percussively, especially in soft soils, causing soil to be displaced further outwards than necessary to make room for the pile. Soil may not close up around piles with re-entrant angles in cross section (for example, cruciform or H or I section piles). The magnitude of these effects and their possible impact on gas flow paths is not known and would benefit from further research.

It is difficult to predict what implications displacement piling through a low gas permeability cover layer might have on rates of gas flow and this is an area that could benefit from research. It is prudent, however, for any built development located above potentially gassing ground to be protected by at least an underfloor granular gas collection blanket with a passive venting system, covered by a gas impermeable membrane. These measures, which can be characterised as normal gas protection measures, should be sufficient to mitigate risks associated with upward migration in the case described. Detailed description or specification of such measures is outside the scope of this report and should be the responsibility of the scheme designer.

Piling method variations

No variations are considered significant for this pathway.

5.3.2 Assessment of applicability of non-displacement piling methods

General applicability

Non-displacement piling methods involve the extraction of soil prior to the placing of the pile. Theoretically therefore there is no disturbance of the surrounding soil and provided that the pile is formed or placed in intimate contact with the surrounding soil there should be no formation of preferential pathways for upward gas migration.

Specific problems and uncertainties

Avoidance of disturbance to the surrounding soil does, however, require a high standard of workmanship in the construction process, and these methods have the potential to create near ground disturbance. The result of poor workmanship could be the creation of preferential flow pathways. Good working practices include the maintenance of a positive hydrostatic head in the bore. In practice this involves the addition of water to the bore and this may increase the leaching of contaminants in the soil.

It is difficult to predict what implications non-displacement piling through a low gas permeability cover layer might have on rates of gas flow and this is an area that could benefit from research. It is prudent, however, for any built development located above potentially gassing ground to be protected by at least an underfloor granular gas collection blanket with a passive venting system, covered by a gas impermeable membrane. These measures, which can be characterised as normal gas protection measures, should be sufficient to mitigate risks associated with upward migration in the case described. Detailed description or specification of such measures is outside the scope of this report and should be the responsibility of the scheme designer.

Piling method variations

Partially preformed piles involve the placing of a preformed section within a larger hole and the grouting of the annulus between the preformed hole and the soil. Because this grout is non-load-bearing it is likely to be regarded as less critical during installation and the result may be that soil surrounding the hole is allowed to loosen before grouting. If this method is used it is important that the grouting operation is carried out with the importance of the prevention of gas migration pathways recognised during construction.

Continuous flight augers rely on the retention of soil on the auger flights to provide support to the surrounding soil until the auger is withdrawn and the concrete or grout intruded. It is vital that the intruded material is placed under pressure at a rate consistent with that of the withdrawal of the auger to ensure that the hole is supported. This can be difficult to achieve near to the surface.

5.3.3 Assessment of applicability of penetrative ground improvement methods

General applicability

Similar considerations apply to the previous pollution scenarios. The penetrative ground improvement methods considered are displacement methods and densification of soil may be expected to reduce permeability. If the low permeability cover layer is densely compacted, localised cracking or heave could occur, though in practice it is unlikely that a vibrating poker could penetrate such a layer.

Ground improvement method variations

The relatively high permeability of the granular stone columns may make them a preferential migration route for ground gas. Indeed stone columns have been used specifically for purposes of gas venting. If this method is to be considered further gas protection measures for any built development will be essential. If the gas flow is particularly high, the gas protection measures may need to be specially designed and enhanced. If an active gas extraction system is already installed the provision of stone columns may allow ingress of air into the ground, with deleterious effects (in terms of gas generation). Stone columns may also allow increased infiltration of surface water, increasing the possibility of contaminant leaching, though the built development cover often serves to limit this. A possible mitigation measure applicable to stone columns constructed by the bottom feed process is the use of grouting.

With vibro concrete columns the infill concrete is relatively impermeable and cast in contact with the surrounding soil. Considerations in this case are similar to those for displacement piling.

5.4 Pollution Scenario 3: Direct Contact with Contaminated Soil Arisings that have been Brought to the Surface

Soil arisings generated by piling works may be particularly difficult to manage within a land remediation scheme since they tend to be generated after the major remedial works and site platform formation have been completed. This often leads to a requirement for arisings to be disposed off-site, even if the contaminant concentrations would allow its re-use on-site, with a cost implication. Since piling is a development, not a remediation, activity, there is no exemption from landfill tax for these contaminated materials.

Any off-site disposal of contaminated arisings is required to be to an appropriately licensed waste management facility in accordance with Part II of EPA 1990 and supporting regulations. This will necessitate characterisation of the arisings, which are likely to consist of a mixture of soil types often including cementitious material and grout. Implications of handling this material on site, including possible impacts on development construction workers and the public in the site surroundings, need to be addressed and operators must ensure they comply with their 'duty of care' under the Environmental Protection Act 1990 and relevant heath and safety requirements. Detailed description or specification of such measures is outside the scope of this report.

The avoidance of soil arisings may be particularly beneficial in the case of buried contaminants such as fibrous asbestos and low mobility, but highly toxic, organic contaminants such as PCBs and dioxins. Such contaminants may not pose a significant risk as long as they remain buried and isolated below ground but could create particular concerns over handling, disposal and public contact if brought to the surface.

5.4.1 Assessment of applicability of displacement piling methods

General applicability

Displacement piles by their nature do not generate soil arisings at the ground surface, though ancillary works such as casting of pile caps may do so. Some soil arisings could be created by large displacement piles due to ground heave, especially if near-surface deposits are loose, but this is likely to be limited in volume and is in any case likely to be avoided for geotechnical reasons. Driven cast-in-place piles involving the grabbing-out of "plugging" soil from the base may give rise to some arisings.

The risk from contaminated soil arisings in the case of displacement piling is considered to be negligible in most instances.

5.4.2 Assessment of applicability of non-displacement piling methods

General applicability

Non-displacement piling methods necessitate bringing to the surface a volume of soil excavated from within the hole created to form the pile. The soil arisings consist of a heterogeneous mixture of all soil types encountered in the boring, and usually have a high moisture content (both from groundwater and from water added to maintain a positive hydrostatic pressure in the bore). They may also contain cementitious grout and concrete from the pile installation works.

The volume of arisings on a major development may be significant. A single 6m long 450mm diameter pile will generate $1m^3$ of arisings. These arisings may be contaminated and their handling, transport and disposal need to be addressed with appropriate care.

5.4.3 Assessment of applicability of penetrative ground improvement methods

General applicability

The penetrative ground improvement methods discussed in this report involve the horizontal displacement of soil by the vibrating poker and as such does not lead to soil arisings. The risk from contaminated soil arisings in the case of vibroreplacement and vibro concrete columns is in general considered to be negligible.

5.5 Pollution Scenario 4: Direct Contact with Contaminated Soil or Leachate Causing Degradation of Pile Materials

Different piling methods are not considered in detail in this case as the main determinant of susceptibility to attack from aggressive ground is the materials out of which the pile is manufactured. Steel, concrete, grouts and timber can all be affected by chemicals and acidity in the ground. The issue of durability in aggressive ground conditions is one that has been the subject of a significant body of research by the Construction Industry Research and Information Association (CIRIA), the Building Research Establishment (BRE) and others. Their publications should be referred to for detailed information on this specialist field.

Since durability has a structural as well as an environmental implication it is expected that a prudent foundation designer will address this issue in method selection and design of piles. The local authority building control officer will seek to ensure that these issues are satisfactorily addressed.

The main environmental implications of aggressive ground conditions affecting piling are likely to be the following:

- Limitation in the choice of piling methods (possibly introducing constraints that could affect the ability to mitigate other pollution risks);
- Degradation of pile materials leading to increase in permeability of the piles themselves (and even formation of voids), creating migration pathways;
- Failure of piles after building construction leading to the need for remedial works which might involve a limited choice of piling methods (possibly introducing constraints that could affect the ability to mitigate other pollution risks); and
- Reaction with pile materials causing materials to fail to cure, affecting both structural and environmental performance (e.g. bentonite grouts in the presence of phenol contamination).

Mitigation measures to deal with aggressive ground conditions might include the use of permanent casing (displacement and non displacement piles), the use of protective coatings (displacement non-cast-in-place piles only) and the use of a higher quality of concrete (more easily achieved with pre-formed concrete piles). The use of partially pre-formed non-displacement piles with a bentonite-cement slurry grout might also be considered, although bentonite should not be used where chemicals are present in the subsurface that could affect its performance. Steel piles may be protected by use of anti-corrosion products and cementing with adjacent soils.

Stone columns are not excluded from consideration of aggressive ground conditions. Certain types of stone, derived particularly from limestone and other calcareous rock, may be susceptible to attack in some cases (i.e. under acidic conditions). Selection of a durable and chemical resistant stone, for example flint (silica-based) gravel, may be an appropriate mitigation measure.

5.6 Pollution Scenario 5: The Driving of Solid Contaminants Down into an Aquifer during Pile Driving

5.6.1 Assessment of applicability of displacement piling methods

General applicability

Driven displacement piles may drag down contaminated material as they penetrate underlying strata. This drag down may occur by a frictional mechanism along the shaft of the pile, or by pushing material ahead of the pile shoe. However, geotechnical research on driven piles has shown that the magnitude of these effects is normally low (Hayman *et al*, 1993; Boutwell *et al*; 2000). Material dragged down by shaft friction is unlikely to be displaced by more than a few centimetres, and theoretical calculations by Boutwell *et al* (2000) indicate that at most a few kilograms of soil may be pushed ahead of the pile shoe, as the primary mechanism of soil displacement during pile driving is horizontal. However, this would also imply that soft material is carried with the pile right to set and would bring the load-bearing capacity of the pile into doubt. It is therefore considered unlikely that, in practice, this occurs.

Boutwell *et al* (2000) suggest that the use of a pointed or convex shoe should reduce the volume of material being pushed down ahead of the pile by between 1 and 3 orders of magnitude. This potential problem will also be minimised by using small displacement piles because small sections tend to cut through or push material aside.

Piling method variations

Open-ended tubular piles may become plugged with soil from the upper layers of the ground through which the piles are driven and this plug of soil may be driven down to the lower levels. The piles can be fitted with a driving shoe to avoid this problem.

5.6.2 Assessment of applicability of non-displacement piling methods

General applicability

Non-displacement methods, which involve the extraction of the soil prior to placing the pile, will not in normal circumstances lead to soil being dragged downwards.

5.6.3 Assessment of applicability of penetrative ground improvement methods

General applicability

Penetrative ground improvement methods involve horizontal displacement and densification of the soil through which the column is constructed. In normal circumstances this will not lead to soil being dragged downwards.

5.7 Pollution Scenario 6: Contamination of Groundwater and Subsequently Surface Waters by Concrete, Cement Paste or Grout

5.7.1 Assessment of applicability of displacement piling methods

General applicability

Where displacement piling methods involve the driving of steel piles, pre-cast concrete pile elements or permanent casings inside which concrete is cast, there is in general no risk of contamination as all concrete in direct contact with groundwater is hardened before being introduced into the ground. However if the method involves the use of bentonite slurry as a lubricant there is the potential for contamination of fast flowing groundwater.

Piling method variations

The screw or bored displacement auger pile method involves the casting of concrete directly against soil and there is the potential for leaching of wet concrete, cement paste or grout into fast flowing groundwater. However in these circumstances this piling method is unlikely to be selected due to geotechnical considerations.

5.7.2 Assessment of applicability of non-displacement piling methods

General applicability

Where non-displacement piling involves the casting of concrete directly against soil, or the use of bentonite slurry as a lubricant (for example, a number of variants of the continuous flight auger method) there is the potential for the leaching of wet concrete, cement paste or grout into fast flowing groundwater. Where a permanent casing protects the wet concrete from contact with the groundwater until it has been allowed to set, this potential is reduced or eliminated.

5.7.3 Assessment of applicability of penetrative ground improvement methods

General applicability

The installation of stone columns will not lead to the leaching of wet concrete, cement paste or grout into fast flowing groundwater. Vibro-replacement concrete columns, on the other hand, are placed in direct contact with the surrounding ground and leaching of wet concrete, cement paste or grout into fast moving groundwater is possible.

5.8 Summary

A general summary of the applicability of the generic piling and ground improvement methods, with and without appropriate mitigation measures, against the identified pollution scenarios is given in table 5.1. This table should be used with care and not in a prescriptive manner as it is not based on site-specific considerations. For a particular site, circumstances may be such that generic methods indicated in this table as being applicable to the pollution scenario are not appropriate to conditions at the site, or vice versa. This table does not consider structural or geotechnical issues.

Table 5.1 Indicative hazards associated with piling and penetrative ground improvement methods

Pollution scenario	Displacement piles	Non-displacement piles	Penetrative ground improvement
1: Creation of preferential pathways, through a low permeability layer, to cause contamination of groundwater in an aquifer.	**B-D** (dependant on details of method)	**B-C** (dependant on details of method)	**D** (stone columns) **B** (VCC)
2: Creation of preferential pathways to allow migration of landfill gas or contaminant vapours to surface.	**B**	**B**	**C** (stone columns) **B** (VCC)
3: Direct contact with contaminated soil arisings which have been brought to the surface.	**A**	**B-C** (dependant on contaminant)	**A**
4: Direct contact with contaminated soil or leachate causing degradation of pile materials.	**B-C** (dependant on pile materials and contaminants)	**C** (dependant on pile materials and contaminants)	**B-C (**dependant on pile materials and contaminants)
5: The driving of solid contaminants down into an aquifer during pile driving.	**B**	**A**	**A**
6: Contamination of groundwater and, subsequently, surface waters by concrete, cement paste or grout.	**A**	**C-D** (dependant on details of method)	**A** (stone columns) **D** (VCC)

VCC = vibro-concrete columns

Key:

A: Pollution scenario not likely to be an issue if using this method provided workmanship and QA/QC measures are appropriate.

B: Subject to appropriate workmanship, mitigation and QA/QC measures, to be outlined in the Foundation Works Risk Assessment report (see chapter 6) and incorporated in the design and contract specification, this method is likely to be acceptable.

C: This method may be considered acceptable, depending on specific type used and subject to appropriate workmanship, mitigation and QA/QC measures, to be outlined in the Foundation Works Risk Assessment report. However a more suitable piling or ground improvement method may be available.

D: This method should normally be avoided on sites where this pollution scenario is likely to be an issue.

6. RECOMMENDED RISK ASSESSMENT FRAMEWORK

6.1 Approach

The objective of this section is to propose a robust, effective and transparent decision-making process that allows designers (including specialist contractors offering design services) to select an appropriate piling method and mitigation measures, if required, when piling on contaminated sites.

It is assumed that sufficient information (for example, site investigation data, contamination assessment etc) is available to the designer in order to allow him to make judgements regarding the applicability of each potential *S-P-R* linkage at the site and the potential for the preferred piling or ground improvement method to create additional linkages.

It is assumed that remediation works to an appropriate standard have been carried out in order to allow building works to be undertaken. An assessment of the risks arising from contamination on the site should have been undertaken and the results of this risk assessment should be made available to the contractor. If there is any doubt, the parties responsible for design and construction of piling should seek advice from a suitably experienced and qualified contaminated land specialist.

6.2 Mitigation Measures

In many cases it will be possible to remove a potentially adverse impact by the design and specification of mitigation measures. These could be based, for example, on changes to the pile installation method, or could involve additional separate processes such as grouting being employed. Because of the variety of possible mitigation measures and the site-specific nature of their potential applicability, it is not possible to produce general recommendations in this report. However, a number of issues that need to be addressed in considering the applicability of mitigation measures can be summarised as follows:

- Do the mitigation measures themselves have any adverse environmental impacts?
- Are the proposed mitigation measures adequate to remove significant adverse environmental impacts?
- How will the mitigation measures be specified to ensure that they are incorporated and verified during the installation works?
- What monitoring requirements are there?
- Who will verify the inclusion and adequacy of the mitigation measures?
- Could the mitigation measures be adversely affected by subsequent building works and, if so, how will this be prevented?

Potential mitigation measures that could be used to address some of the issues described in the preceding sections are noted in the table below. It should be noted that this list suggests a number of mitigation methods which might be applicable in appropriate circumstances. This cannot be considered as a comprehensive list, and not all of the measures will be appropriate to a particular set of circumstances on site.

Table 6.1 Suggested potential mitigation measures

Mitigation measure	**Relevant pollution scenarios**
Use alternative piling / ground improvement method or variant	PS1, PS2, PS3, PS5, PS6
Design piles to avoid reaching aquifer or penetrating aquiclude (found at shallower level)	PS1, PS5, PS6
Remediate shallow groundwater prior to piling	PS1
Permanently lower shallow groundwater prior to piling (to remove positive hydraulic gradient)	PS1
Immobilise or remediate contaminants in soil through which piles pass	PS1, PS3, PS5
Isolate contamination around piles from groundwater flow and infiltration (e.g. surface cover, in ground barriers)	PS1
Use of Bentonite during boring or driving	PS1, PS2
Grout pile or stone column after installation	PS1, PS2, PS4
Provide gas collection/venting system, gas impermeable membranes etc under building floors	PS2
Establishment of appropriate health and safety and waste management procedures for working with contaminated soil and disposal of arisings	PS3
Use alternative piling / column material or improved material specification (e.g. sulphate resisting cement)	PS4
Coating of pile / column with protective product	PS4
Use of a permanent or temporary casing	PS4, PS6
Use pile with pointed or convex butt end or driving shoe	PS5

6.3 Quality Assurance and Quality Control

In general, all site works should be carried out under an appropriate quality assurance and quality control (QA/QC) regime, which should be rigorously specified in the contract. This is normally the case with geotechnically and structurally significant aspects of piling and ground improvement, where dependent on the detail of the installation method a number of parameters are normally monitored.

In the case of potential environmental impacts, appropriate methods and measures for quality assurance and quality control need to be considered specifically in the context of the avoidance and mitigation of the environmental impact. This is likely to result in a number of QA/QC procedures relevant to geotechnical and structural issues will also be relevant to environmental impacts. For example, poor workmanship in installation of non displacement piles, which could lead to loss of load bearing capacity, could also lead to the creation of preferential migration pathways, where a pile is not in intimate contact with the surrounding soil.

It is important that the environmental QA/QC procedures are rigorously specified and carried out according to the specification, and that those responsible for workmanship are made aware of the reasoning behind the required procedures. Ignorance of the need for these procedures may lead to omission.

Where a more immediate form of QA/QC procedure cannot be found, the establishment of a comprehensive long-term groundwater monitoring programme may need to be instigated in order to detect any detrimental effects. Installation of monitoring facilities, such as suitably designed boreholes, should ideally pre-date the piling works in order to determine baseline conditions. Groundwater monitoring may be necessary where the overall risks to groundwater are greatest, taking account of the level and mobility of contamination, engineering techniques applied and environmental setting. Groundwater monitoring will generally only be required on areas of Major Aquifer, or within Source Protection Zones unless there are specific issues of local concern that justify monitoring in others locations.

The Environment Agency is likely to have a view concerning the appropriate coverage and time period for such monitoring, in order to have regard to likely contaminant transport times, and should be consulted concerning the scope of the monitoring system. Groundwater monitoring should be undertaken in accordance with ISO 5667-18 (ISO, 2000) and other relevant guidance.

6.4 Piling, Ground Improvement Works and the Duty of Care

This section is relevant to the situation where arisings are generated as a result of piling or ground improvement works. Section 34 of the Environmental Protection Act 1990 places a duty on any person who produces, carries, keeps or disposes of controlled waste. It requires that person to take reasonable steps to ensure that the waste is managed properly and disposed of safely, by themselves and any other person with responsibility for the waste. Breach of this duty of care is an offence subject to a fine not exceeding £20,000 on summary conviction or unlimited on indictment.

A Code of Practice has been published to help holders of controlled waste comply with the duty (HMSO, 1996). Contaminated soil is controlled waste, and arisings from piling works will have to be kept, carried and disposed of safely. Issues that the contractor and site engineer should consider include:

- Does the waste need a special container to prevent its escape or protect it from the elements?
- Is it likely to be a special waste subject to the Special Waste Regulations 1996?
- Is it likely to change its physical state during transport?
- Can it be disposed of safely in a landfill site with other waste?

The transfer of controlled waste, for example from site to a transfer station or disposal site, should be accompanied by a written description of the waste or a Consignment

Note if the waste is special waste. It is recommended that waste management issues are addressed at an early stage in order to prevent contravention of the duty of care.

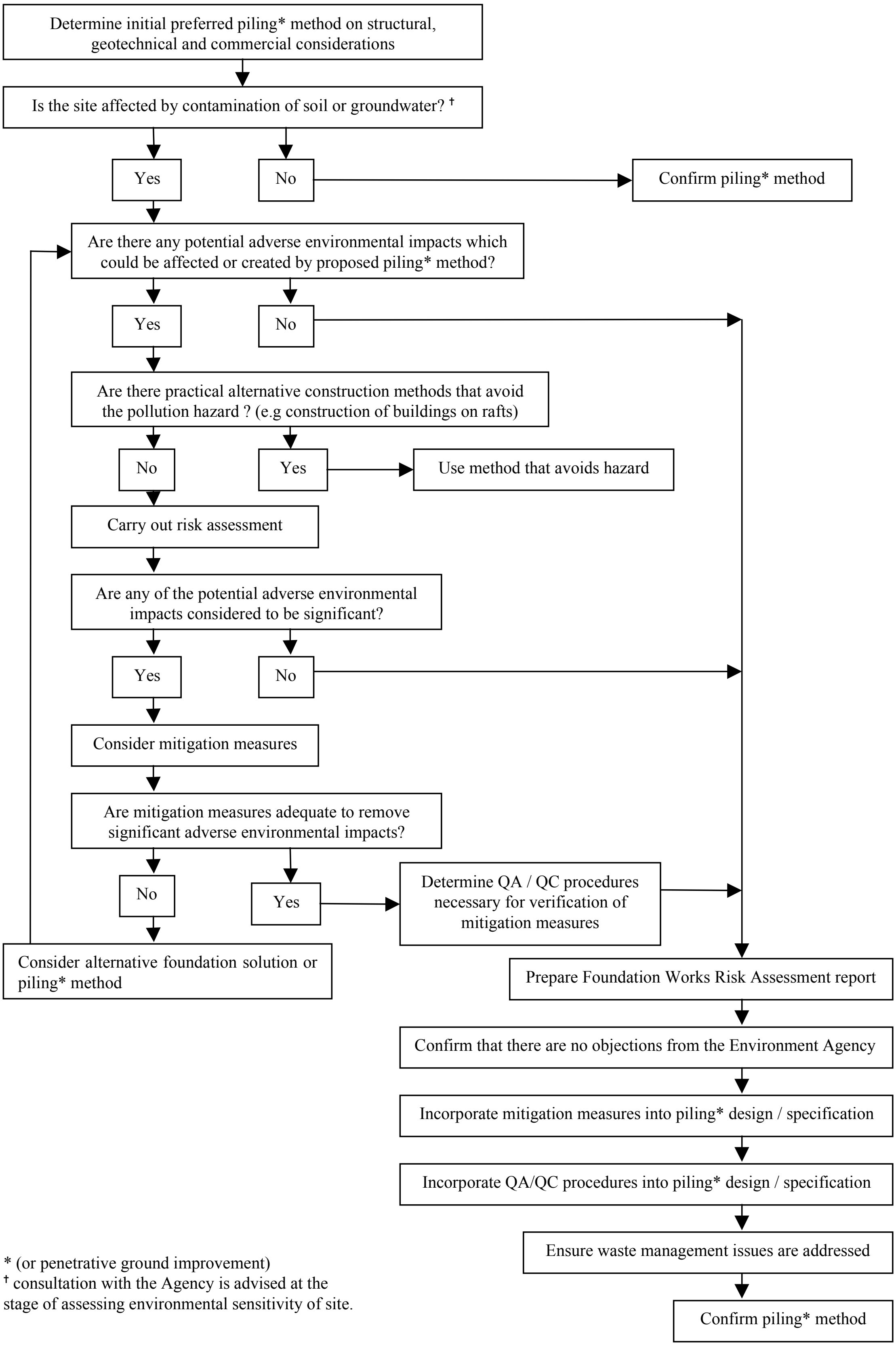

Figure 6.1. Risk assessment flowchart

6.5 The Foundation Works Risk Assessment Report

The recommended risk assessment process to be carried out by the scheme designer is given in Figure 1. It provides a framework for the designer to carry out a risk assessment enabling him to select an appropriate piling or ground improvement method and justify this choice, with mitigation, if required, and appropriate QA/QC measures. The justification may be presented in the form of a ‘Foundation Works Risk Assessment Report’.

Submission of a ‘Foundation Works Risk Assessment Report’ will not absolve the developer and his professional and construction team from their duties not to cause or knowingly permit pollution, harm or nuisance. It is expected that the developer will require the report to form part of the designer’s contract obligations. The designer will be expected to exercise reasonable skill and care in the preparation of the report and may be held liable, subject to legal action by relevant parties, if this can be demonstrated not to have occurred.

It is envisaged that the issues outlined in Box 6.1 below should be addressed in the Foundation Works Risk Assessment Report in order to present a rigorous and comprehensive risk assessment. The entire decision-making process should be described in a rigorous and justifiable manner, including a description of any methods that were considered and rejected.

Box 6.1 Suggested contents of Foundation Works Risk Assessment Report

1. Introduction. An introductory section should describe the site setting in terms of geology (including stratigraphic logs), hydrogeology, soil or groundwater contamination, existence of any landfill, topography, geotechnical considerations and requirements for piling or ground improvement methods.

2. Initial selection of piling method: Justification, on geotechnical, structural and noise/vibration grounds, of the initially preferred method proposed.

3. Identification of potential adverse environmental impacts that may be caused by the proposed works.

4. Site-specific assessment of the magnitude and consequences of the identified risks to the environment, workers and residents, both in terms of existing problems and new *S-P-R* linkages that could be created during site works.

5. Identification of any changes to preferred method. Consideration of mitigation measures that may be required to prevent pollution, harm or nuisance occurring.

6. Identification of QA/QC methods and measures.

7. Justification of finally selected methodology, including mitigation, QA/QC and monitoring measures, with regard to geotechnical, financial and environmental considerations.

6.6 Examples of Issues to be Addressed in Report

Reference is made to the potential environmental problems considered in Chapters 4 and 5 of this report for examples of issues to be addressed in the Foundation Works Risk Assessment report:

6.6.1 Pollution scenario 1: Creation of preferential pathways, through a low permeability layer (an aquitard), to allow potential contamination of an aquifer.

- Are there polluting substances in the ground that are in a leachable or mobile form?
- Is the groundwater directly underneath the site, or in strata penetrated by engineered structures, considered to be in a Major or Minor Aquifer or is the groundwater in hydraulic continuity with a surface water body?
- Will the piling or ground improvement method of choice breach a low permeability layer (aquitard) or the basal liner of a closed landfill site, or penetrate an aquifer?
- Is there a hydraulic gradient that could cause contaminants in near surface deposits to migrate into an underlying aquifer or surface water body?
- Is the pile made out of a material (e.g. timber) that could allow passage of contaminants?
- Will the piling or ground improvement method of choice have the potential to create a preferential flowpath for the migration of contaminated perched water or leachate into an aquifer or surface water body?

6.6.2 Pollution scenario 2: Creation of preferential pathways, through a low permeability surface layer, to allow migration of landfill gas, soil gas or contaminant vapours to the surface.

- Is the contamination considered to present a potential source of either landfill gas (for example, waste materials giving rise to methane, sulphur dioxide and carbon dioxide) or volatile organic compounds (for example, BTEX volatilising from hydrocarbon contaminated soils)?
- Will the piling or ground improvement method of choice have the potential to create a preferential flowpath for the migration of gas or vapour to surface?
- Will the risks arising from accumulation of landfill gas or contaminant vapours in enclosed spaces in the proposed development be mitigated by the incorporation of standard gas protection measures into the building design?
- Is the release of gases to atmosphere acceptable from an air quality point of view?

6.6.3 Pollution scenario 3: Direct contact of site workers and others with contaminated soil arisings, which have been brought to the surface.

- Are contaminants present in the soil or groundwater at sufficient concentrations to pose a hazard to human health or the environment?

- Will the piling or ground improvement method of choice have the potential to bring potentially contaminated soil arisings to the surface?
- Are measures in place to contain and dispose of arisings in a safe manner?

6.6.4 Pollutant scenario 4: Direct contact of the piles or engineered structures with contaminated soil or leachate causing degradation of pile materials.

- Does the nature of the soil or leachate contamination present a risk to the performance or durability of the pile material?

6.6.5 Pollutant scenario 5: The driving of solid contaminants down into an aquifer during pile driving.

- Are there polluting substances in the ground that are in a leachable or mobile form?
- Is the groundwater directly underneath the site, or in strata penetrated by engineered structures, considered to be in a Major or Minor Aquifer or is the groundwater in hydraulic continuity with a surface water body?
- Will the piling or ground improvement method of choice breach a low permeability layer (aquitard) or the basal liner of a closed landfill site or penetrate an aquifer?
- Does the chosen piling method involve use of blunt-ended solid or closed-end piles that could drag down soil or open-ended tubular piles that could become 'plugged' with soil?

6.6.6 Pollutant scenario 6: Contamination of groundwater and, subsequently, surface waters by concrete, cement paste or grout.

- Does the chosen piling or penetrative ground improvement method involve the introduction of wet concrete, cement paste or grout into the ground?
- Is the groundwater directly underneath the site, or in strata penetrated by engineered structures, considered to be in a Major or Minor Aquifer or is the groundwater in hydraulic continuity with a surface water body?
- Is the aquifer characterised by highly fissured or granular strata?
- Is the groundwater in the aquifer fast-flowing?

6.7 Procedure for Presentation of Report

It is envisaged that any requirement for a Foundation Works Risk Assessment will normally be enforced through the planning system. The Environment Agency, as a consultee on planning application matters affecting contaminated land would normally, by means of its consultation response, seek to have the planning authority place relevant conditions on the planning permission. Such conditions might be to the effect that no piling, ground improvement or building construction shall take place until a Foundation Works Risk Assessment report has been submitted to the planning authority and its detail and recommendations accepted by the planning authority in consultation with the Environment Agency.

The procedure for the consideration of the Foundation Works Risk Assessment report would be similar to that by which the regulatory authorities consider remediation proposals as part of planning applications. This is likely to involve dialogue between the developer and his professional advisers, the Environment Agency and the Planning Authority. **As with any works that could adversely affect the environment, informal discussions between all parties prior to submitting planning applications are prudent.**

Following acceptance by the relevant authorities it will be necessary, prior to commencing works on site, for the designer to ensure that any proposed mitigation and QA/QC measures are fully designed, specified and actually implemented on site.

7. RECOMMENDATIONS FOR FURTHER RESEARCH

As noted in Chapter 2, the issue of adverse environmental impacts caused by piling or penetrative ground improvement works is one that has largely been neglected in the research arena. As a result it has not been possible in all the scenarios considered to determine unequivocally the significance of the risks to the identified receptors that might arise from piling. In these cases it is apparent that there would be benefit from further research into the pile and surrounding soil behaviour in the individual cases.

The research may take a number of forms:

- Documentation and recording of site based case studies;
- Computationally based numerical modelling, possibly using existing test data from previous structural research;
- Scale model testing, though Hayman *et al* (1993) observe that scaling of hydrogeological systems is extremely difficult;
- Full scale trial pile installation and monitoring;
- Retrospective investigation of sites where piles have been used in the past;
- Detailed instrumentation and monitoring of developments involving piling on contaminated sites.

There is a considerable cost implication to some of these options and it is likely to be necessary to adopt a staged approach to this research, using less expensive approaches to identify any particularly difficult issues that may require more detailed consideration. One approach may be to carry out comparative studies between different pile types, though it is expected that the key comparison will be with the soil in its undisturbed state. Research into the effectiveness of mitigation measures could be based on comparison with the unmitigated case.

One of the key areas of uncertainty identified in this study is the impact of displacement piling on aquitard strata or low permeability cover layers. Whilst a concern has previously been identified that the action of pile driving could serve to disrupt and increase the permeability of the aquitard layer, consideration of the densification of the soil caused by displacement tends to indicate a reduction in permeability in the immediate vicinity of the pile. It is likely that the effect on a thick aquitard layer will be different from the effect on a thin layer and the research should consider both cases. Both permeability to water (including leachate) and gas permeability should be considered.

Research should consider in particular the effect of displacement piling on stiff overconsolidated clayey soils such as are commonly encountered in glacial tills. The phenomenon of frictional drag down of soils in contact with the circumference of the pile shaft should be examined to determine the effect on the vertical permeability of the soil. The particular case of the impact of driven piles such as steel H-piles with a re-entrant cross section on an aquitard layer should be considered.

The behaviour of the soil at the interface with a non-displacement pile should also be examined for the range of non-displacement pile types and casing systems. As the nature of the soil interface is likely to be determined to a large degree by the method of temporary support and permanent installation it is likely that such research may need to be based on full scale testing or monitoring.

Research into non-displacement piling systems should also examine the risks of transmission of groundwater through the bored hole in the temporary case prior to the casting of concrete, and taking into consideration the effect of construction measures such as the maintenance of a positive hydrostatic head in the borehole during construction.

A further development of the research might involve the determination of quantitative measures, for example, if increased flow rates of leachate due to the impact of piling were measured. These quantitative measures could be used as the basis for risk modelling using contaminant fate, transport and attenuation modelling approaches.

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GLOSSARY OF TERMS

AQUIFER	A permeable geological stratum or formation that is capable of both storing and transmitting water in significant amounts.
AQUITARD	A low permeability unit that can store groundwater and also transmit it slowly from one aquifer to another.
AUGER	Hand or mechanical equipment used to extract soil by method of a drilling motion.
BROWNFIELD	Abandoned, idle or underutilised industrial or commercial facilities where expansion or redevelopment is complicated by real or perceived environmental contamination
CASING	Steel tube driven into the pile borehole to temporarily support the sides of the bore, it is removed during the concreting operation.
COMPETENT STRATA	Soil of high bearing capacity.
CONTAMINANT	A substance which is in, on or under the land which has the potential to cause harm or to cause pollution of controlled waters.
CONTAMINANT FATE	The combined effects of chemical, biological and physical processes on a pollutant in the environment.
CRAWLER	Tracked construction vehicle (e.g. crane or dozer). Piling rigs are often 'crawler-mounted' as this means that the heavy equipment is spread over a wide area meaning that it can safely stand on the soft ground.
DYNAMIC LOADING	Repeated or cyclic loading imposed on a pile, for example by machinery, traffic or wind.
GROUND IMPROVEMENT	The improvement of soil properties near the surface enabling the use of shallow foundations where otherwise they would not have been suitable.

GROUNDWATER	The mass of water in the ground below the water table (vadose zone) occupying the total pore space in the rock and moving slowly down the hydraulic gradient where permeability allows.
GROUNDWATER PROTECTION ZONE (GPZ)	An area designated around a groundwater source, the maximum extent of which is the catchment area for the source and within which there are limits to the processes and activities that can occur within that area.
HYDRAULIC CONDUCTIVITY	A coefficient of proportionality describing the rate at which water can move through a permeable medium. The density and kinematic viscosity of the water must be considered in determining hydraulic conductivity.
KELLY or TORSION BAR	The sliding shaft on a boring rig that transmits the torque to the boring tool from a driven rotary table.
LEACHATE	The liquid that has percolated through solid materials and contains dissolved soluble components.
MANDREL	A cylindrical rod round which metal or other material is forged or shaped.
NECKING	Thinning of the pile where the concrete has not completely filled the pre-formed shaft.
PATHWAY	The route or means by or through which a receptor is being, or could be, exposed to, or affected by, a contaminant.
PERMEABILITY	Measure of the ability of a permeable medium to transmit water. It is defined as the volume of water passing through $1m^3$ of aquifer under unit hydraulic gradient.
PILE	Long, slender structural member, used to transmit loads applied at its top to the ground at lower levels.
PLASTIC CONCRETE	Concrete that has yet to set and, whilst may not be fully fluid, is still malleable.

POKER or SONDE	Vibrating rod, used to push trapped air from setting concrete.
S-P-R LINKAGE	The relationship between a source, a pathway and a receptor. (cf. Pollutant linkage under EPA90, Part IIA).
PRE-STRESSED CONCRETE	Concrete incorporating pre-stressed reinforcement bars.
RAFT FOUNDATION	Raft foundations are foundations that cover large areas laterally, greatly reducing differential settlement.
RECEPTOR or TARGET	A particular entity, which is being or could be harmed by a pollutant, or controlled waters which are being or are likely to be polluted.
REINFORCED CONCRETE	Concrete that is strengthened by an internal steel frame
SHOE	A metal plate that is cast onto the toe of concrete piles whether driven in hard or soft conditions.
SPALLING	Flaking of the concrete surface.
STATIC LOADING	The load applied to a pile in its normal service life. Usually split into 'dead', i.e. the weight that is always applied due to the weight of the structure, and 'live', i.e. the loading due to moveable objects (e.g. vehicles, people and furniture).
TACK WELD	A weld temporarily holding something together that can be broken easily.
TORSIONAL LOADING	The load applied to a pile by imposing a moment on it, i.e. a twisting force in either direction.
TREMIE PIPE	A pipe that is made up from a number of lengths of 200 – 300mm diameter steel pipes, which is used to place concrete underwater or at depth.
WHIPPING	The lateral movement of a pile as it is being driven.

APPENDIX 1

SUMMARY OF REPLIES TO QUESTIONNAIRE

A1.1 Piling and Ground Improvement Contractors who Responded to the Questionnaire

Aarsleff Piling
Amec Piling
Keller Ground Engineering
May Gurney Limited
Norwest Holst Soil Engineering Limited
Roger Bullivant
Rock & Alluvium Limited
Stent Foundations Limited
Taranto De Pol
The Expanded Piling Company Limited
Westpile Limited

A1.2 Methods of Piling and Penetrative Ground Improvement Available From Respondents

Driven cast-in-place piles
Bored cast-in-place replacement piles
Driven pre cast piles
Driven cased piles
Rotary bored replacement piles
Continuous flight auger piles
Continuous helical displacement piles
Displacement flight auger piles
Pre-cast reinforced concrete piles
Steel sheet piles
Steel H section piles
Steel tube piles
Tripod bored piles using cable percussive methods
Timber piles
Lime / cement columns
Vibro stone columns – dry top feed
– dry bottom feed
– wet top feed

A1.3 Details Of Sites/Projects in which the Contractor Has Been Involved or Are Aware Where the Actual Installation of Piling Has Been Implicated in the Migration of Contaminated Water or Ground/Landfill Gas

No information supplied by any contractor.

A1.4 Details of Sites/Projects in Which the Contractor Has Been Involved or Are Aware Where the Proposed Installation of Piling Has Raised Concerns Over the Migration of Contaminated Water or Ground/Landfill Gas with Planning, Building Control or Environmental Regulators

- At a large number of sites in southern England, there has been concern over the effect of piles penetrating the Chalk. In these cases, the Environment Agency has generally preferred continuous flight auger piles over, for example, driven pre-cast concrete piles. Continuous flight auger piles are generally specified in order to reduce the possibility of transporting contaminated soil from the upper layers into the aquifer and because they do not provide an easy contamination path for surface water to reach the lower strata.

- At a site in the north of England, the National Rivers Authority (one of the Agency's predecessors) had reservations about migration of contaminants into the sandstone due to piling. Initially the piling was priced on the basis of a "double-casing" method. On agreement that the risks from conventional construction were low, the "double casing" method was kept as insurance in the event that particularly highly contaminated areas were encountered. The water level and quality were monitored during piling operations and no significant effect from the piling work was noted.

- At a site where fill materials lay directly either over chalk or over stiff clays above the Chalk, the Environment Agency were concerned at contaminants migrating into the Chalk aquifer. There was evidence of solution features within the Chalk surface. After further investigation, the Environment Agency reduced their concern, and the solution features were treated by compaction grouting.

- At a site in southern England, the use of driven pre-cast concrete piles was not permitted for fear of taking contamination down into the underlying chalk aquifer and creating groundwater migration pathways. The use of continuous flight auger piles was acceptable to the Environment Agency, but would have had the disadvantage of creating significant quantities of contaminated spoil. For these simple commercial reasons, the use of a continuous helical displacement system was chosen at this site as it produces virtually no spoil and was not thought likely to take contamination into the underlying aquifer. This method also reduces the permeability of strata in the immediate vicinity of the pile and produces no obvious pollution pathways for water to migrate into the lower strata.

- At a site where a former landfill site was underlain by a variable thickness of boulder clay overlying the chalk aquifer, the preferred option for construction would have involved piling due to the potential for long-term compaction of the landfill. However, due to fears of allowing contaminated landfill leachate to reach the aquifer, a method combining dynamic compaction with the use of very heavy foundations was adopted. Measures were put in place to monitor and intercept any possible lateral migration of contaminated leachate during and subsequent to the dynamic compaction operation.

- At a contaminated site where driven cast-in-situ piles were to be used, concerns were raised about high groundwater levels and the proximity of the site to a nearby watercourse. A solution involving installation of an HDPE membrane with monitoring facilities was instigated. Monitoring confirmed that no rise in groundwater level or deterioration of stream quality had occurred during operations. Contaminated spoil was removed to a specially licensed tip.

- Stone columns can sometimes be perceived as offering a pathway for the downwards migration of leachate. At a number of sites where this has proved cause for concern, either a concrete plug at the base of stone columns formed with the dry top-feed technique or the grouting of stone columns formed using bottom-feed construction has been used to inhibit leachate migration.

- The matter of downward migration was brought to the attention of the Environment Agency on a site in the south of England. The Environment Agency were concerned with the potential for piling to allow migration of contaminated groundwater from an upper aquifer into an underlying aquifer that was separated from the contaminants by a clay aquiclude. Following discussions, it was decided that the clay would form a seal around the pile to prevent downward contamination. Furthermore, the size of the pile was increased in order to reduce penetration into the clay.

- Common methods of overcoming concerns with regard to piling through contaminated soil include:
  a) Designing the piles to stop short of an aquifer.
  b) Removing contaminated ground from pile positions by bulk excavation and replacing with clean fill.
  c) Removal of contaminated ground by pre-boring with the piling rig and casing or filling the casing with bentonite prior to its removal in advance of the main piling operation.
  d) Citing the flow of soil up and away from augers and the seal around bored piles in order to overcome fears of migration of contamination (most common means of overcoming concerns according to one respondent).
  e) Use of bored displacement piles.
  f) Installation of a mix in place impermeable barrier with permeable ‘active’ gate to filter contaminants from groundwater leaving the site.

A1.5 Details of Any Issues Concerning the Disposal of Contaminated Soil Arisings from Replacement Piling that the Contractor May Have Encountered on Particular Sites/Projects

- Where spoil is classified as 'special waste', disposal is usually undertaken by a specialist sub-contractor.

- Specialist piling contractors may consider that disposal of contaminated spoil is not an issue related to the piling operation. Main contractors are generally responsible for the clearance of spoil arisings.

- Where contamination is present, waste is classified and may require disposal to licensed tip relevant to classification.

- Disposal of spoil containing even relatively low levels of contamination can have significant cost implications.

- There is a Health and Safety risk to other road users when there are a large number of trucks travelling to licensed landfills.

- There are concerns with regard to the effective sealing of tipper lorry tail-gates on wet days and when spoil is wet, giving rise to the potential for spread of contamination.

- Bentonite contaminated spoil is deemed to be 'contaminated', although it is a non-toxic natural clay unlike industrial waste. Contractors may consider it messy rather than a contaminant.

A1.6 Details of any Material Durability Issues that the Contractor May Have Encountered When Considering the Design and Specification of Piles in Contact with Aggressive Contaminated Ground

- A major concern is the high sulphate content and low pH values in contaminated soils. BRE Digest 363 provides guidelines that are universally used.

- Corrosion of steel joints in pre-cast piles may also be an issue.

- The presence of phenols may affect the setting and strength of concrete and slurries. Sleeving of piles is sometimes specified, however, one respondent queried that there is little or no evidence to prove this.

- One contractor reported the results of trials on the site of a former tank farm that had a long-term history of hydrocarbon contamination. Tests on slurry mixes were undertaken. When contaminant was mixed directly with slurry, the slurry strength was halved. To combat the effect, the cement content of the slurry was increased.

- Occasional instances of concern with regard to contact with other contaminants have been recorded, for example sugar contamination.

- Extreme conditions may require the use of permanently cased piles to prevent contact with contaminated soils.

- In some cases specific protection can be achieved by coating or painting the pile with proprietary products to provide the necessary protection level.

A1.7 Other Information Supplied that is Considered of Relevance to the Study

- There is a lack of information / guidance relating to piling on contaminated sites and the whole subject area appears to be very much in its infancy. One respondent noted that 70% of their work is undertaken without any formal site investigation other than basic trial pits.

- 'Most concerns regarding the pile as a conduit for downward migration of contamination ignore the action of the auger, and the densification and/or void filling characteristics of displacement auger and continuous flight auger piles. Also ignored is the short construction period for the piles. Unless the auger is bored in and left stationary whilst large volumes of surface water flow down it, dissolving soluble contaminants on the way, little migration is possible at all.'

- 'Prior to piling, the site has often been subject to small diameter site investigation boreholes. The site investigation stage can be a cause of cross contamination and is often not subject to the same controls as the piling operations.'

- The 'main risk to aquifers probably badly backfilled boreholes rather than piles'.

APPENDIX 2: CASE STUDY EXAMPLES

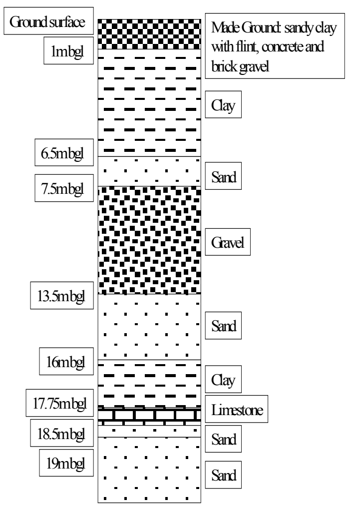
5. CASE STUDY 1: PILING DESIGN FOR RESIDENTIAL DEVELOPMENT ON FORMER INDUSTRIAL SITE.

Description of site and proposed development:

A residential development was proposed for a former industrial site in the south of England. Piled foundation was required to support the structural loads from the proposed buildings, which were to be 5 to 7 storeys high.

Site investigation revealed elevated concentrations of a range of contaminants in the made ground which were considered to pose a risk to the integrity of underground structures. Landfill gas was also considered to represent a potential hazard.

Stratigraphy:



Local hydrogeology and environmental setting:

The stratigraphic sequence present at the site is shown and comprises about a metre of made ground, consisting of sandy clay with occasional flint, brick and concrete, overlying over 5m thickness of alluvial clay. Underlying the alluvium were approximately 6m of dense sands and gravels (River Gravel deposits) and, underlying these, a stiff silty clay with dense silty sands comprising the Woolwich and Reading Beds.

The alluvial clay may be considered to be an aquiclude, while the Woolwich and Reading Beds have variable permeability. The River Gravel deposits are considered to be a Minor Aquifer. Underlying the site, below the Woolwich and Reading Beds, is the Upper Chalk, which is considered to be a Major Aquifer.

Implications for piling and ground engineering:

A review of piling options concluded that driven cast-in-situ piles would be the best solution because the direct contact with the ground and uneven surface of the pile would give full adhesion of the clay to the shaft. It had been known that the Environment Agency had preferred use of this method on adjacent sites to minimise the risk of groundwater contamination to deeper aquifers. Also, the amount of contaminated spoil generated is minimised by the use of driven cast-in-situ piles. The pile was to be installed by driving a heavy gauge steel tube into the stratum of gravel until a set was obtained. High slump concrete was then placed and the tube withdrawn. The piles were to be founded in the gravel.

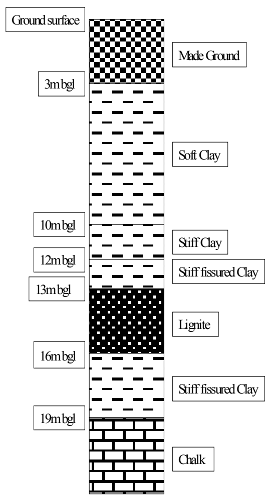
Gas protection measures were recommended for incorporation in the buildings in order to mitigate the effects of migration of landfill gas. The risk that the piles would form migration pathways for gases could therefore be discounted.
Area-specific assessments of concrete specification were required to protect the piles from degradation to take into account sulphate, pH and ammonium ion aggressivity.

6. CASE STUDY 2: PILING DESIGN FOR WASTE WATER TREATMENT WORKS

Description of site and proposed development:

A waste-water treatment works was constructed on a former industrial site in the south of England. Site investigation revealed elevated concentrations of several toxic metals, including arsenic and selenium, within the soil. Elevated concentrations of several phytotoxic metals, which are deemed non-hazardous to human health, were also recorded. Methane gas was also recorded in the landfill material at concentrations in excess of the lower explosive limit of 5% volume.

Stratigraphy:



Local hydrogeology and environmental setting:

The stratigraphic sequence present at the site is shown opposite. Made ground beneath tidal storage tanks on the site consisted of 1-1.5m of PFA sand. Below this a 0.5-1.0m thick grey-brown mottled clay with sand and fragments of glass, brick and flint was present. An organic, potentially hydrocarbon, odour was noted in this horizon.

The made ground was underlain by alluvium comprising very soft light grey/green clay. Plant remains were observed at up to 10m depth in this material and an organic odour was noted. The alluvium was underlain by a stiff organic clay comprising the Woolwich and Reading Beds. The alluvial clay and the Woolwich and Reading Beds may be considered to comprise aquicludes. The site is underlain by Chalk at a depth of approximately 19 mbgl. The Chalk is considered to be a Major Aquifer.

Implications for piling and ground engineering:

Suggested piling methods involved piles to be founded in the Chalk. It was highlighted that piling may raise concern with the Environment Agency as the Chalk is a major aquifer and the piles could be perceived as providing a potential pathway. It was suggested that piling could be carried out using similar protection measures as British Drilling Association recommendations for borehole operations. However, this would significantly increase the cost of the piling work.

Continuous flight auger piles were recommended to give the best option for reducing any potential cross contamination. Care was taken to ensure that water and concrete pressures were balanced in order to minimise concrete losses in all permeable horizons (the gravels and fissures within the Chalk).

Typical methods of gas protection were to include a gas proof membrane in the base slabs together with a passive venting layer below. Careful detailing of services connections to buildings was necessary to avoid the creation of gas pathways.

7. CASE STUDY 3: PILING RECOMMENDATIONS FOR A RIVERSIDE DEVELOPMENT

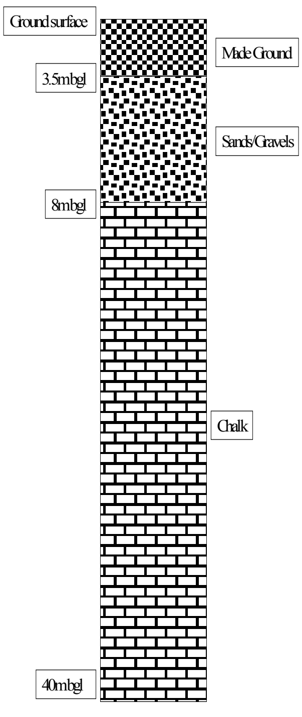
Description of site and proposed development:

A riverside site, containing elevated concentrations of a variety of inorganic and organic contaminants, was to be redeveloped.

Elevated concentrations of petroleum hydrocarbons and heavy metals were identified in the soil. Contaminants were also suspected to have migrated along the length of the river wall. The presence of free-phase hydrocarbons was also suspected within perched groundwater.

Remediation was undertaken at the site, involving removal of 'hotspots' of soil containing highly elevated concentrations of petroleum hydrocarbons and the removal of free-phase hydrocarbons. However, site clean-up criteria were set for soil remaining undisturbed, and concerns were raised relating to the potential for piling to mobilise the remaining contamination.

Stratigraphy:



Local hydrogeology and environmental setting:

The stratigraphic sequence for the site is summarised opposite. In summary, the site comprises a maximum of 3.5m of made ground overlying alluvial sands and gravels. Pockets of peat were also present. Underlying the site, at a depth of approximately 8mBGL, was the Chalk.

The underlying Chalk is a Major Aquifer from which groundwater is used for public drinking supply. The adjacent river was also considered to be a potential receptor for contamination.

Implications for piling and ground engineering:

It was noted that when piling is performed soil may become agitated and pore water pressures increased. This may encourage the remaining contamination to mobilise. Therefore, whilst the soil was considered to have been remediated to concentrations generally below the site remediation criteria, remaining contamination may still provide a risk to the underlying Chalk major aquifer and the adjacent river if disturbed during piling.

The Environment Agency required the following assessments to be undertaken:

- A risk assessment considering dissolved phase contamination, fate and transport and natural attenuation; and
- An assessment at every piling location to find the potential for any cross contamination from the sand and gravel to the Chalk aquifer. If it was considered that a risk may be present the Agency required that auger piling techniques were to be used.

Continuous flight auger piles were considered to be the most acceptable pile type in order to protect the Chalk aquifer.

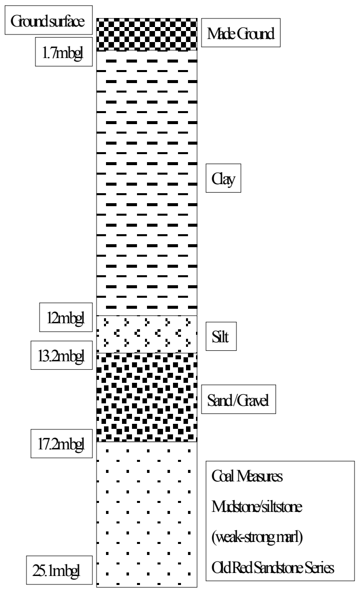
8. CASE STUDY 4: PILING FOR MOTORWAY TUNNEL CONSTRUCTION

Description of site and proposed development:

The proposed work included the drilling of 1.2m diameter rotary piles bored through made ground, alluvial clay and silt, alluvial gravel and Mercia Mudstone.

Contaminated ground was encountered beneath the topsoil at several locations. Contaminants included hydrocarbons and polychlorinated biphenols, which are considered hazardous to human health.

Stratigraphy:



Local hydrogeology and environmental setting:

The stratigraphic sequence encountered at the site is summarised opposite. In summary, ground conditions comprised made ground overlying alluvium (soft clay, silt and sands and gravels). The site is underlain by the Mercia Mudstone.

Due to the substantial thickness of alluvial clay, groundwater contamination was not considered to be a major issue.

Implications for piling and ground engineering:

Piling was put in abeyance for three to four months while the contamination problem was assessed. At two areas, the contaminated soil was removed to a licensed tip and the excavation backfilled with the piles bored through the clean fill. At two other areas, oversized diameter boreholes were constructed through the contaminated fill (about 6m) using temporary casing. The bore was filled with a weak slurry mix and the 1.2m diameter pile bored through the set slurry.

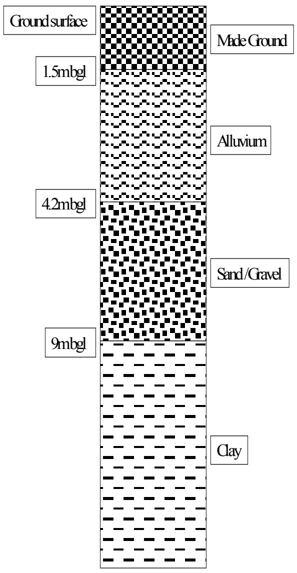
9. CASE STUDY 5: PILING DESIGN FOR A FACTORY DEVELOPMENT ON A FORMER INDUSTRIAL SITE

Description of site and proposed development:

Piles were required for a factory development in southern England. Pile working loads varied from 200kN to 875kN. Made ground on the site contained elevated concentrations of a range of organic and inorganic contaminants.

Site investigation revealed elevated concentrations of arsenic, lead, boron, copper, zinc, selenium, zinc, phenols and petroleum hydrocarbons within the made ground. Elevated carbon dioxide concentrations were also recorded.

Stratigraphy:



Local hydrogeology and environmental setting:

The stratigraphic sequence found at the site is summarised opposite. Made ground was encountered at the site to a depth of 1.50m and typically comprised sandy clay with a little to some flint and brick gravel. The made ground also contained concrete and brick cobbles, ash and wood fragments and clinker.

Alluvium was present below the made ground, comprising a variable sequence of clay, peaty clay and peat. The peat often had a hydrogen sulphide odour. Flood Plain Gravel was encountered below the alluvium and, underlying the gravel, was the London Clay.

Groundwater was encountered at the top of the Flood Plain Gravel.

Implications for piling and ground engineering:

It was recommended that continuous flight auger piles of nominal 300mm and 400mm diameter were used, founded in the London Clay. Continuous flight auger piles were recommended due to concerns that contaminated soil might be transported from the upper layers into an aquifer and because they do not provide an easy contamination path for water from the surface to the lower strata.

Due to high concentrations of carbon dioxide recorded, gas protection measures were recommended, comprising passive venting of the under floor void and the incorporation of a gas impermeable membrane into the floor slab design.

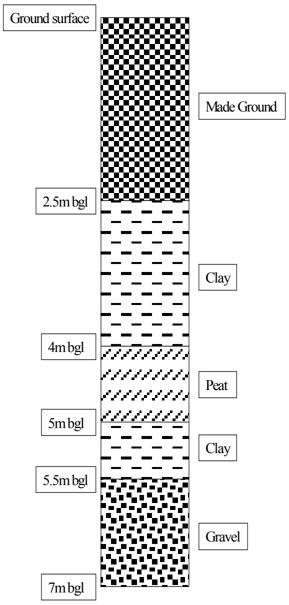
10. CASE STUDY 6: PILING DESIGN FOR RESIDENTIAL PROPERTIES ON A FORMER INDUSTRIAL SITE

Description of site and proposed development:

A combination of residential properties, landscaped areas and service properties was proposed for a site in southern England. The residential areas were expected to comprise either one and two storey houses or, possibly, three and four storey blocks of flats.

Site investigation revealed elevated concentrations of arsenic, cadmium, lead, selenium, sulphate, boron, copper, nickel and zinc within the made ground. Pulverised fuel ash found with a petrochemical odour returned elevated toluene and cyclohexane extract concentrations. Elevated carbon dioxide levels were also recorded.

Stratigraphy:



Local hydrogeology and environmental setting:

The stratigraphic sequence present at the site is summarised opposite. Made ground was found over much of the eastern half of the site, consisting of 0.4-3.2m of pulverised fuel ash (PFA). The PFA varied in thickness between 1 to 2 m. In localised areas, clayey ash gravel grading to PFA with depth was found at thicknesses up to 7.4m. Foundations to demolished structures were known to exist.

Underlying the made ground are alluvial deposits comprising soft to firm silty clays and peat. Underlying the alluvium is the Thames Gravel which is encountered at a depth of approximately 5 mbgl.

Groundwater was encountered the gravels. Perched water was also noted as seepages in the superficial natural clays and the PFA.

The leaching potential of contaminants was found to be low. However, perched water within the made ground contained slightly elevated levels of boron, chloride, copper, nickel, selenium, and zinc. Groundwater from the Thames Gravel displayed similar or lower levels of the same determinands.

Implications for piling and ground engineering:

Continuous helical displacement piles founded in the Thames Gravel were accepted at this site, however, the work has not yet been undertaken. The use of pre-cast concrete piles is not considered acceptable to the client due to the potential for creating preferential pathways for the migration of contaminants.

Due to the concentrations of carbon dioxide recorded, gas protection measures have been recommended.

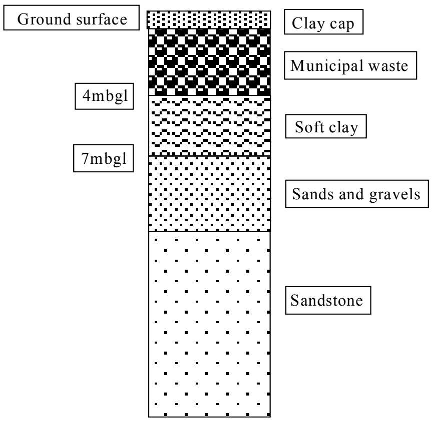
11. CASE STUDY 7: PILING DESIGN FOR HEAVY INDUSTRIAL STRUCTURES ON A CLOSED LANDFILL SITE

Description of site and proposed development:

A closed landfill site in the north of England, occupying a former sand pit, was to be developed for industrial use. The proposed development of heavy industrial structures required the use of large diameter bored piles founded into the sandstone.

The site had undergone limited remediation, but localised hot spots of heavy metal and hydrocarbon contamination were present.

Stratigraphy:



Local hydrogeology and environmental setting:

A schematic stratigraphic sequence is shown opposite. Typical soil conditions comprise 3-4 metres of fill material overlying 3m of soft (alluvial) clay over sands and gravels. Underlying the sands and gravels is the Sherwood Sandstone.

The Sherwood Sandstone is considered to be a Major Aquifer in the vicinity of the site.

Implications for piling and ground engineering:

The National Rivers Authority (now incorporated within the Environment Agency) initially expressed major reservations about migration of contaminants into the sandstone due to piling. The Sherwood Sandstone in the north-west of England is classified as a major aquifer which is widely used for industrial and potable water abstraction. However, after discussions it was decided that the risks from conventional construction were low and therefore conventional piling methods were used. Double casing methods were to be used as a contingency in the event that hot spots were encountered. Visual inspection of arisings took place. During piling operations, groundwater level and quality were monitored at three borehole locations. No measurable effect from the piling work was noted.

12. CASE STUDY 8: PILING DESIGN FOR HOUSES ON A FORMER INDUSTRIAL SITE

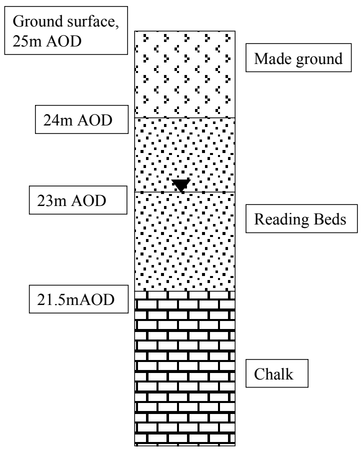
Description of site and proposed development:

Planning permission was granted, subject to conditions, for the redevelopment of a former engineering works to housing, comprising a number of houses with gardens and a single block of 6 flats surrounded by soft landscaping and car parking.

Site investigations demonstrated the presence of hydrocarbons (diesel and lube oils) and heavy metals (most notably mercury, lead, copper and zinc) throughout the made ground and in the upper 0.5 metres of the natural ground (Reading Beds). Elevated concentrations of these substances were identified in both 'total' and 'leachability' testing of the made-ground and underlying strata.

The developer proposed to excavate the made ground in areas proposed for gardens, but retain the contaminated materials below buildings, roads, car parks and open spaces. Half a metre of clean cover (soil) was proposed to 'cap' areas of open space. The developer proposed to use vibro-stone piles, extending 2 metres into the Reading Beds (i.e. below the winter watertable) to provide foundations for all of the buildings.

Stratigraphy:



Local hydrogeology and environmental setting:

The stratigraphic sequence present at the site is shown opposite, and comprises about a metre of made ground (brick, slag, sand) overlying 2.5 metres of Reading Beds (a poorly consolidated silty sand), which in turn overlies a thick sequence of the Upper Chalk.

The Reading Beds are classified by the Agency as a Minor Aquifer, whilst the underlying Chalk is a Major Aquifer and is used locally for public water supply. This site lies within the catchment (SPZIII) of a public water supply abstraction borehole. The Reading Beds are known to be in hydraulic continuity with the underlying Chalk aquifer and there is a vertical hydraulic gradient downwards from the Reading Beds into the Chalk.

Implications for piling and ground engineering:

Conceptualisation of the situation gave the Agency concerns that the use of vibro-stone columns would create new permeable vertical pathways for the migration of contaminants from the made-ground into groundwater in the Reading Beds and subsequently the Chalk. It was known that the contamination present in the made ground was in a leachable form.

Following discussions with the developer's engineers, a revised scheme was developed which included the use of shallow raft foundations for the houses, while the larger block of flats, which could not be supported by raft foundations, was founded on vibro-concrete piles. This approach avoided the use of penetrative foundations below the houses, whilst the use of vibro-concrete piles for the flats reduced the risk of groundwater pollution by creating piles that were impermeable following curing of the concrete.

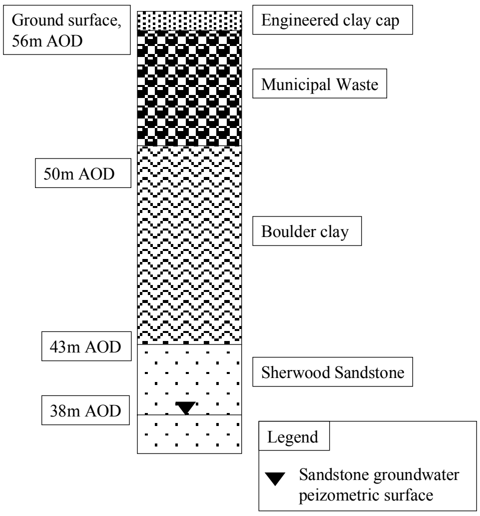
13. CASE STUDY 9: INDUSTRIAL DEVELOPMENT ON A CLOSED DOMESTIC LANDFILL SITE

Description of site and proposed development:

It was proposed to redevelop a closed municipal landfill site in northern England for light industrial uses, comprising a number of industrial units and hard paved areas for vehicle parking and loading.

Leachate and gas monitoring undertaken in and around the landfill for regulatory purposes during its operational life, and additional site investigation undertaken in preparation for the redevelopment confirmed the presence of typical landfill pollutants, which were present as solid materials, leachate and gas. The landfill was originally developed on a 'dilute and disperse' basis, resting on a thick sequence of boulder clay. Following completion of landfilling the site was capped with a mineral liner to reduce the potential for generation of further leachate. Investigations indicated that pollutants present in the waste were in a leachable form and that restricted (perched) bodies of landfill leachate were present within the body of the waste, however, there was no significant head of leachate at the base of the site. Groundwater monitoring in the Triassic Sandstone indicated that leachate had not impacted groundwater quality in the underlying aquifer, and it was inferred that attenuation of leachate within the boulder clay prevented migration into the aquifer.

Stratigraphy:



Local hydrogeology and environmental setting:

A schematic stratigraphic sequence is shown opposite and comprises a metre of clay over 5 metres of domestic waste materials. The landfill is founded on 7 metres of boulder clay, which overlies the Permo-Triassic Sherwood Sandstone, a major aquifer.

The aquifer is not used locally for potable supply at the current time, but groundwater discharges as baseflow into a high quality river that supports a salmon fishery.

Groundwater monitoring indicates that the Triassic Sandstone is currently unpolluted by the landfill, and that groundwater levels are typically 5 to 7 metres below the base of the boulder clay.

Implications for piling and ground engineering:

The developer identified the potential for piling through a former landfill to create new environmental risks. Following discussion the following risks were considered most likely:

(1) breaching of the protective boulder clay by piles, with subsequent pollution of the aquifer;
(2) disturbance and mobilisation of the perched leachate within the landfill, and hence increased potential for pollution of water resources;
(3) penetration of the clay cap, with resultant increase in leachate generation, and;
(4) potential for piles to allow migration of landfill gas up into the atmosphere and buildings.

As a result, possible piling solutions based on end bearing piles into the sandstone, driven pre-cast concrete piles, and vibro replacement techniques were discounted. An agreed piling design using continuous flight auger piles, terminating within the boulder clay, and using temporary casing to minimise leachate migration was adopted.

14. CASE STUDY 10: PILING DESIGN FOR ASBESTOS WASTE LANDFILL

Description of site and proposed development:

Piling was required for the construction of a bridge on part of a landfill containing a variety of domestic and construction waste, including suspected high quantities of asbestos waste. The landfill had been capped and sealed, however, penetration of the landfill was required in order to found the piles into the Chalk bedrock.

Local hydrogeology and environmental setting:

The landfill is 20m thick and has been capped and sealed. Records of fill materials are incomplete, however, the presence of asbestos in a number of forms was suspected.

The landfill was founded directly on the Chalk. There is no engineered liner of low-permeability strata.

Housing is located 170m from the site.

Implications for piling and ground engineering:

A piling method was required that brought no spoil up to the surface in order to prevent a hazard to the health of site workers and nearby residents. There was also a requirement for minimal noise and vibration.

Following extensive discussions between the piling contractor, the consultant, the Environment Agency and the Health and Safety Executive, the preferred piling method was chosen to be a form of rotary displacement piling which used a cone-shaped screw to force aside the fill materials. Hollow casing, lowered immediately behind the cone, allowed a conventional pile to be formed within it and bored into the chalk. A fine mist was sprayed into the casing in order to suppress dust. Soil arisings were negligible.

During the piling works, continual monitoring of air quality was undertaken. The maximum recorded asbestos dust concentrations at the site boundary were less than half of the permitted safe limit.

APPENDIX 3

DESCRIPTION OF PILING AND GROUND IMPROVEMENT TECHNIQUES

A3.1 Types of Displacement Piles

Displacement piles can be formed by using pre-fabricated piles driven directly into the ground, or by driving a casing into the ground and filling the hole so created with concrete. The principal difficulty encountered in driving piles or casings into the ground is the application of sufficient energy to the driving process to penetrate to the bearing depth: the range of displacement pile types reflects the different technical approaches adopted within the industry to surmount this problem.

Materials used can include non-reinforced, reinforced and pre-stressed concrete, tubular steel sections, steel angle sections and timber. The pile or casing may be introduced into the ground by hammering (dynamic loading), by jacking (static loading) or by vibration. A variant of static loading is the formation of screw piles by torsional loading.

In this study three sub-types of displacement piles are considered:

- pre-formed hollow;
- pre-formed solid; and,
- displacement cast-in-place.

A3.1.1 Pre-formed hollow

Pre-formed hollow piles consist of cylindrical steel or concrete elements that are driven into the ground to the required depth and are subsequently filled with concrete or cementitious grout (Figure A1). The cylindrical elements may be prepared to the required length or may be made up of a number of jointed elements. Some systems involve the driving loads being applied to the top of the cylindrical elements, whilst others apply the driving force directly to a shoe at the base of the cylindrical column.

In some cases, the tubes may be driven open ended, with soil entering the base of the tube being grabbed out or removed prior to driving by pre-boring: in this case the piles can not be regarded as pure displacement piles. In other cases, particularly when the pile is designed as end bearing onto a competent stratum, a driving point or shoe is used to close the end of the pile, so that all soil is displaced sideways by the driving of the pile.

Hollow concrete piles are formed from tubular sections and are sometimes described as cylinder piles. The concrete used to infill the piles can be reinforced or post tensioned, therefore having good resistance to bending forces or tension (Fleming *et al*. 1992; CIRIA, 1988). As large displacement of soil occurs, the use of these piles is preferred in low-density applications and in areas where ground heave is not a disadvantage.

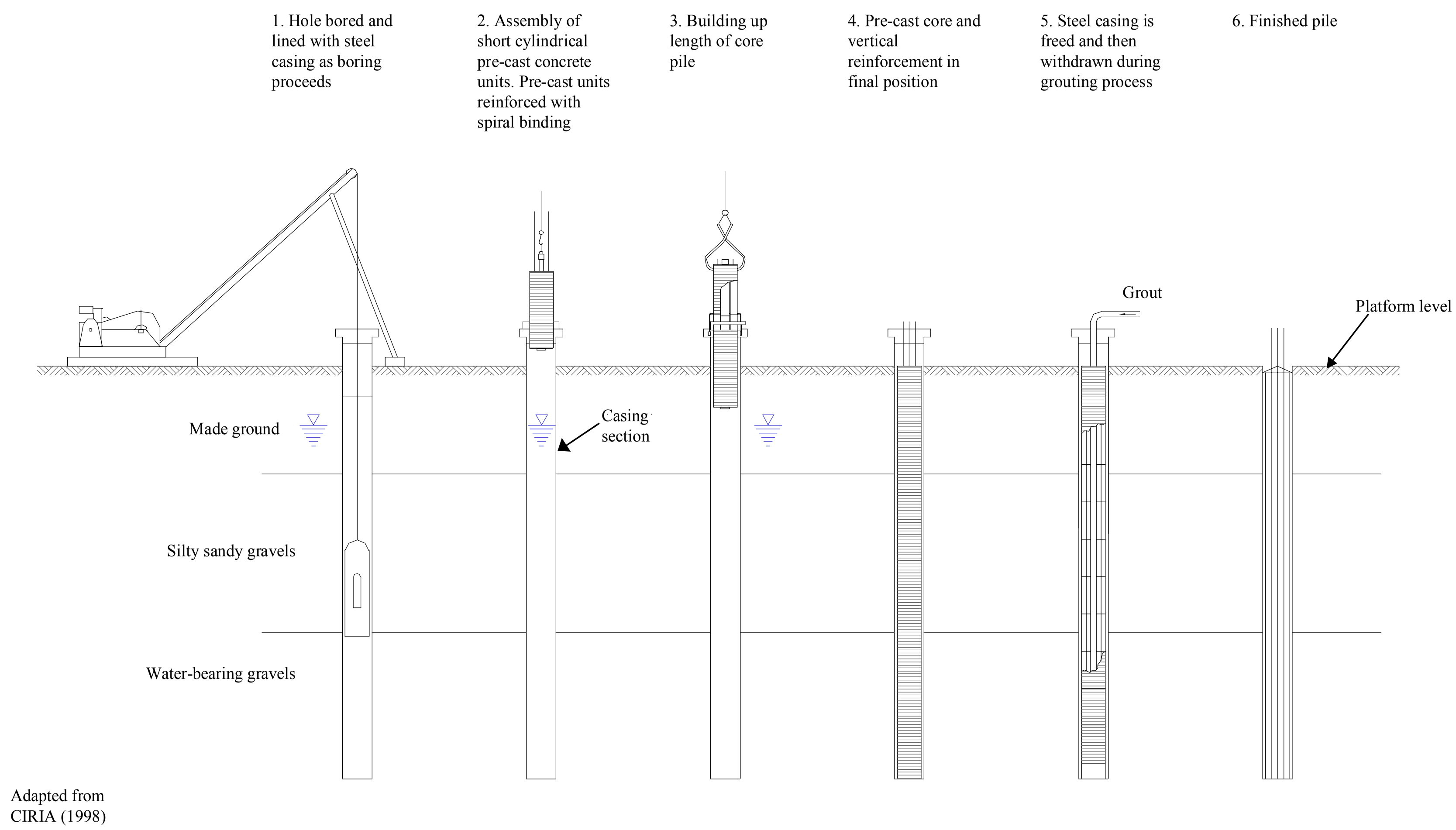


Figure A1. Installation of pre-formed hollow piles

Hollow steel piles may be formed from tubular or box profile hollow sections. To overcome plugging of material at the open end as the pile is advanced, soil can be grabbed out at the base or pre-bored to some depth. Otherwise a closed end can be used, which resists impact and bending loads, or a driving shoe fitted. After driving, the hollow sections are usually filled with concrete or grouted to form a solid core with the segmented sleeve in contact with the surrounding material.

In both cases the completed installation consists of a monolithic composite structure with the original driven cylinder bonded to the concrete or cementitious grout infill. The composite structure so formed constitutes an important part of the pile's load carrying capacity.

A3.1.2 Pre-formed solid

Solid concrete piles can be either pre-cast reinforced or pre-stressed concrete. These may be pre-cast to the correct driving length or may be made up of a number of jointed segments. Non-jointed piles are usually square and generally of larger dimension, however piles of this type have largely been replaced by segmental concrete piles (CIRIA, 1988).

Segmental piles may be formed in a variety of sections (square, hexagonal, circular) and have the advantages of standardised manufacturing length, ease of transport and reduction of stress on the pile during handling. The segments are held together during driving by proprietary jointing systems, ranging from simple male-female socketed joints to more complex systems that prevent rotation of segments relative to each other. Once installed and carrying their service load the compressive forces in the pile will ensure that the joints remain tight.

Pre-cast concrete piles may be reinforced or pre-stressed and can be installed at sub vertical angles and to depths greater than 50m. High cement concrete mixes are used and concrete cover is at a minimum thickness over reinforcing to reduce the risk of spalling. Each section incorporates a steel jointing piece at either end. The main benefit of pre-stressing concrete piles is that tensile stresses are reduced during driving, thereby minimising the chances of cracking the pile. However a pre-stressed pile is more vulnerable if it hits an obstruction (Fleming *et al*., 1992; CIRIA, 1988).

Pre-casting can be carried out in factory, rather than site conditions, thereby improving quality control, and installation in most ground conditions is relatively rapid. The main constraint (on the basis of nuisance) is likely to be from noise due to percussive driving.

Pre-formed solid steel displacement piles include the Universal Bearing (UB) or 'H' pile and 'I' sections. The main advantage of these piles is the small displacement of soil during driving and the ease of handling of the piles. Susceptibility to corrosion is believed to have led to a reluctance to use steel piles in land affected by contamination. However, as yet unpublished research undertaken by the BRE for the DETR suggests that steel piles perform well in contaminated soils (SCI, 2001).

The pile can withstand hard driving and penetrate hard strata or natural obstructions. The pile can have a tendency to wander off line and it is suspected that 'whipping' of the relatively slender pile shafts (Fleming *et al*., 1992) during driving may reduce soil adhesion with the surrounding ground, and increase the potential for voids to form along the length of the pile. However, any such pathway should be localised. High stresses developed at the pile point may lead to the disturbance of weakly cemented sandstones or loss of bearing capacity with time after driving. The finished steel pile provides a continuous column of steel with a large surface area giving high friction and adhesion potential.

Timber piles are suitable for modest loads to depths of approximately 12m (Fleming *et al*., 1992) and are favoured in some marine applications due to their resistance to saline conditions. They are not otherwise greatly used in the UK due to the lack of suitable timber, but are more commonly used in Scandinavian countries, North America and West Africa. Timber piles are used for their special properties, ease of handling and flexibility (Fleming *et al*., 1992, CIRIA, 1988).

A3.1.3 Displacement cast-in-place piles

Displacement cast-in-place piles make use of a tube or void former to create a cylindrical 'void' into which concrete is placed. In fact the use of the term 'void' is in some cases misleading as it is common practice for the concrete to be introduced under pressure as the tube or void former is withdrawn from the hole, so that an actual 'void' is not formed (Figure A2).

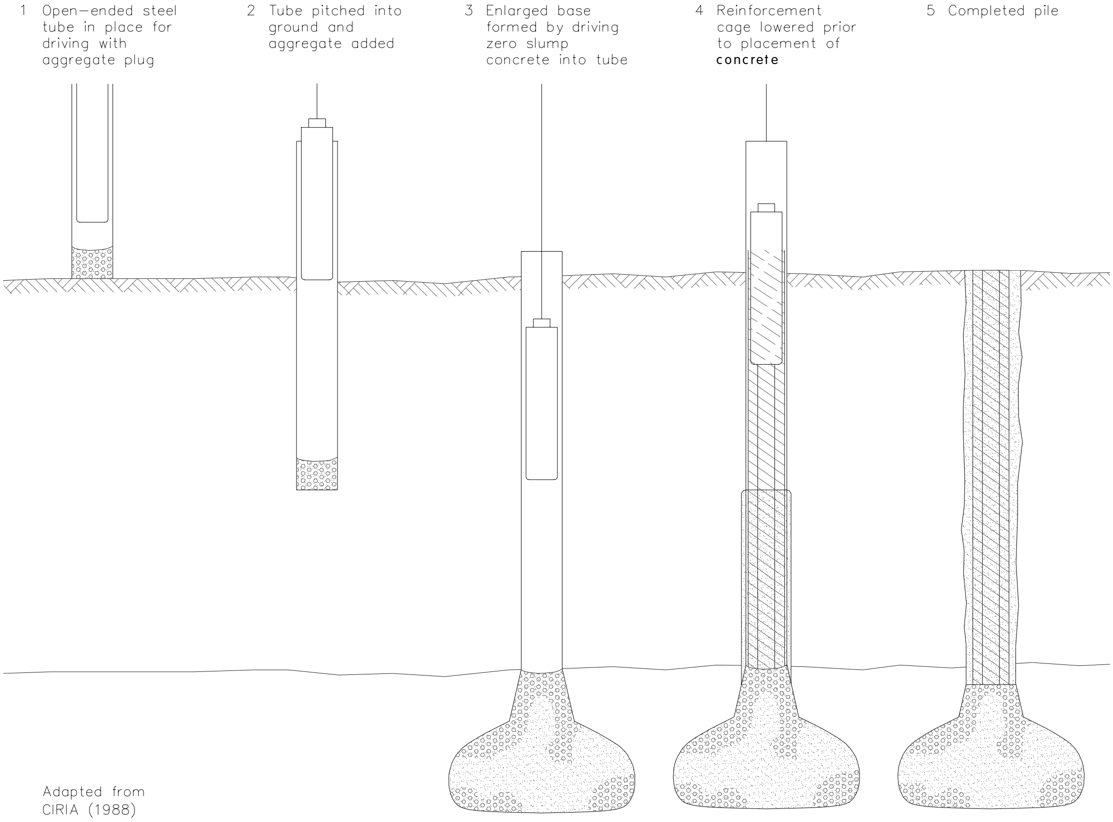


Figure A2. Displacement cast-in-place piles

The tube or void former may be driven or bored. In the case of driven casing the tube is either withdrawn, as the concrete is being poured or left in place to form a permanent casing. The concrete infill is load supporting, which distinguishes this pile type from the pre-formed hollow pile where the hollow section supports load compositely with its infill. A steel plate closes at the end of the pile enabling it to be bottom driven using an internal hammer. Where the tube is retrieved an expandable blanking plate or shoe is used and is left once the tube is removed.

The concrete Shell pile is a type of driven cast-in-place pile. Lengths of concrete shell are top driven into the ground, with a shoe or point at the leading section. The pile point and shell are simultaneously driven by the hammer via a mandrel. After driving, the hollow section is filled with concrete or grouted. Reinforcement may be installed before the concrete is poured.

Steel tubes may also be used to form driven cast-in-place piles. They may be closed or open-ended. A closed end eliminates the use of an enlarged base. The steel tube may be of constant section or taper with depth (CIRIA, 1988). Open-ended installation requires the use of a detachable shoe. The shoe may be either conical or flat and remains closed during driving. The pile base is filled with concrete and the outer casing, mandrel and pile shoe are top driven by a hammer. Once the required depth is reached the mandrel and hammer are raised and more concrete is added. The concrete is then driven out by the hammer hitting the mandrel, as the outer casing is raised. This way a bulb is formed between the detached shoe and the pile shaft. Full length reinforcing is usually attached to the shoe prior to driving (CIRIA, 1988).

The finished pile is a continuous solid concrete column with or without reinforcement. The surface of the pile if the tube has been retrieved may vary in roughness depending on the nature of the surrounding material. The base of the pile may be enlarged to provide greater stability at the base of the pile.

Another variant on the driven cast-in-place pile is the expanded pile. Driven expanded piles typically have a cruciform cross section (other forms are used) with an example being the Burland 'wedge pile'. A closed sleeve with four steel angle sections is driven. A mandrel is then forced down the sleeve splitting the tack welds giving an expansion of about 10% and increasing the shaft friction (Fleming *et al*., 1992). Once the mandrel is removed the remaining void is grouted.

The use of augered techniques allows displacement cast-in-place piles to be bored as well as driven. Several proprietary techniques exist for forming this type of pile, but all involve the use of a disposable auger head, carried on a hollow stem, being screwed into the ground to the required depth. Unlike the continuous flight auger, the head is not rotated at speed to cut and lift the soil. At the required depth, the boring head is counter rotated and withdrawn at a consistent speed to avoid cutting the soil. During the withdrawal of the boring head, concrete is introduced through the hollow stem to fill the void created. This method creates a pile with a particularly strong interlock with the surrounding soil.

A3.2 Types of Non-Displacement Piles

Non-displacement piles involve the excavation of soil (as distinct from its lateral displacement) to form a void into which a pile is formed. Commonly the pile is formed in concrete that is placed in a plastic state into the void so that it forms a close contact with the surrounding soil. As the void is formed by excavation of soil there is normally no disturbance or densification of the surrounding soil as a result of the installation.

Excavated material is brought to the surface as arisings, often in a state of high moisture content (if excavated below groundwater level) including concrete and cement paste as well as soil. These arisings need to be re-used or disposed of in an appropriate manner if they are not suitable for re-use within the site earthworks.

The three main types of non-displacement piles considered (Fleming *et al*., 1992; CIRIA, 1988) include:

- non-displacement cast-in-place piles;
- partially pre-formed piles; and
- grout or concrete intruded piles.

The first two methods produce little or upwards soil displacement and it is possible, though undesirable, that granular deposits may be loosened. The irregular interface between the pile and the soil improves load transfer and the difference in skin friction between the two types is small. In the third method, relaxation or collapse of the walls is inhibited by the auger, which, loaded with soil, supports the hole until its withdrawal allows concrete under pressure to enter the hole and provide support.

A3.2.1 Non-displacement cast-in-place piles

Non-displacement cast-in-place piles range in size from small diameters of less than 600mm to large diameters of 3.0m or more. Concrete, or cementitious grout, is used to fill the hole for the bored pile and transfer the load. The concrete in the pile can be reinforced by the insertion of a prefabricated cage into the hole before placing the concrete. A number of boring and support methods and tools are used but they all have the following elements in common:

- A cutting tool or tools, either cable hung percussion operated or rotary augering/drilling driven by a torsion or kelly bar;
- An arrangement to provide temporary casing and to allow its withdrawal on formation of the pile;
- The use of positive hydrostatic pressure to prevent inflow of groundwater into the base of the hole and consequential loosening of the soil; and
- Placement of plastic concrete from the base of the pile upwards, allowing fluid in the bore to be displaced upwards. Once concrete is placed, its weight supports the hole, even whilst still plastic.

Small diameter percussion bored piles in clay soils are installed by creating a void using an open cylindrical “shell” or a cruciform section cutter. A little fluid may be added for lubrication and is found to not reduce soil strength significantly. Little disturbance is experienced in clays. Casing, which is withdrawn on placing concrete, may be used to provide temporary support to the hole, (Figure A3).

There is possibility of the removal of material in granular soils due to ‘piping’ as groundwater flows into the hole. A shell is used in granular soils and the risk of piping requires the maintenance of a positive hydrostatic head. In granular soils below the water table, casing (or support by dense fluid such as bentonite or bentonite-cement slurry) is essential.

Large diameter bored cast-in-place piles are formed by drilling or surging a casing into the ground with material from the base of the hole grabbed out with a clamshell grab or augered out. The same issues concerning hydrostatic head apply as for the smaller diameter piles (i.e. piping and necking). Percussion chiselling or rotary drilling may be employed to form sockets into weak rock. The finished pile is a continuous concrete column with or without reinforcement. After the casing is removed the concrete fills the annular space formerly occupied by the casing, so the completed pile is in direct contact with the surrounding material.

Rotary bored cast-in-place piles ranging from 450mm to 1500mm are installed using lorry or crawler mounted rigs. Auger heads may be used for boring but this method is not comparable with the continuous flight auger technique. Shaft diameters, nominal loads and concreting procedures are the same as for small diameter percussion bored piles. Most larger-diameter piles are bored using rotary methods and in the UK, augers with diameters up to 3000mm are available.

A number of techniques may be used to improve the end bearing performance of the piles. Under-reaming provides an enlarged base, making improved use of the bearing capacity of the strata. This technique is only feasible in stiff to hard clays and above the water table.

Drilled piles are installed by use of a version of the rock roller drilling bit for large diameter pile bores through rock. Holes up to 2m in diameter can be drilled to depths of more than 30m.

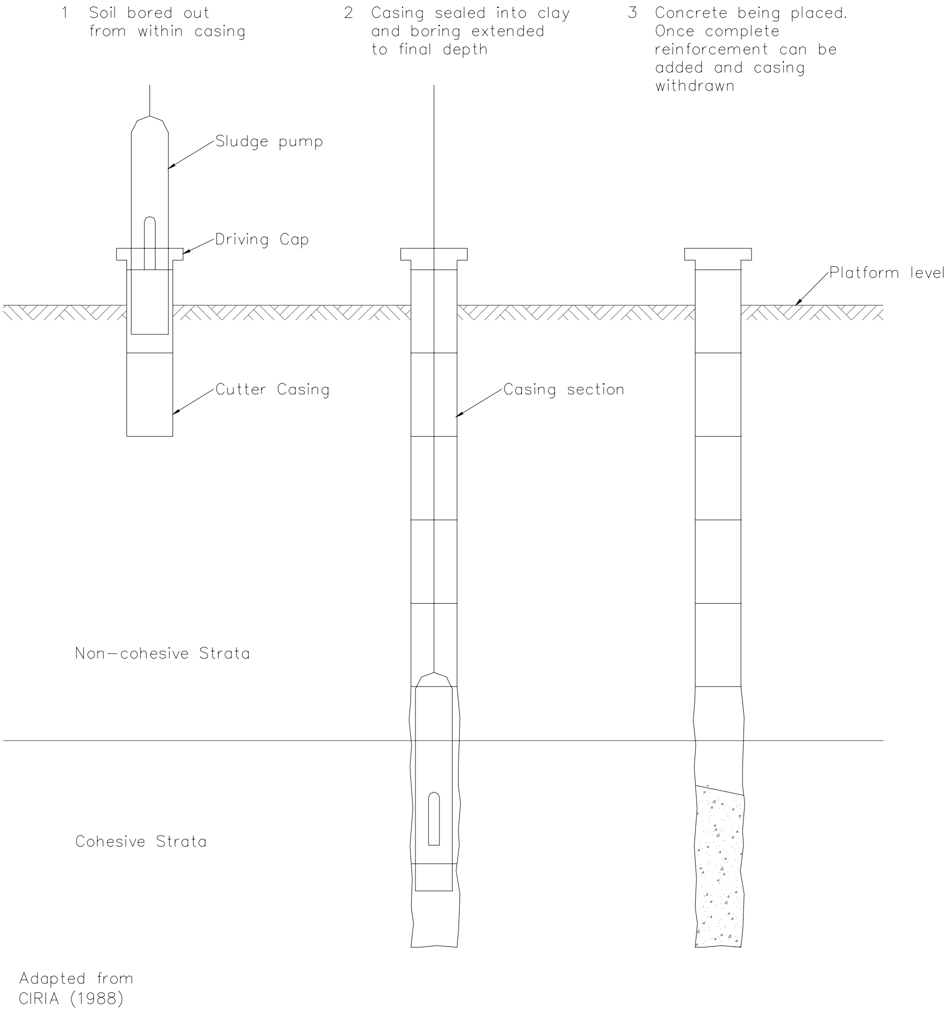


Figure A3. Non-displacement cast-in-place piles

A3.2.2 Partially pre-formed piles

Partially pre-formed non-displacement piles are installed in a hole bored in the same manner as described for non-displacement cast-in-place piles above (Figure A3). The pile is formed by the installation of a series of pre-cast reinforced or pre-stressed concrete elements introduced. Steel column sections (H or I sections) can also be used. The casing is removed as the annulus between the units and the subsoil is grouted to form a solid pile keyed into the solid strata. This pile is suitable for waterlogged ground provided that positive hydrostatic pressure is maintained throughout boring.

The finished pile takes the form of a series of reinforced or pre-stressed pre-cast units, or a steel column, which serves to transmit the foundation loads. The pre-cast units are surrounded by a layer of grout of varied thickness, in direct contact with the pre-cast units and the surrounding material.

A3.2.3 Grout or concrete intruded piles

This method uses a hollow stemmed continuous flight auger to excavate the pile bore and fill the bore with cement or grout. The auger is introduced into the ground by rotary methods at a speed and pitch that minimises soil displacement. The soil retained on the auger flights supports the sides of the borehole (Figure A4).

On achieving the required depth cementitious grout or plastic concrete is introduced under pressure via the hollow stem into the base of the borehole. The auger is withdrawn at a controlled rate whilst maintaining the concrete or grout at a positive pressure. Spoil is withdrawn from the hole on the auger flights and the concrete fills the hole under the auger head, the positive pressure forcing it into contact with the surrounding soil.

The plastic concrete in the hole is maintained at a positive hydrostatic pressure that supports the hole during the time taken for the concrete to cure. Once the complete auger string has been removed from the hole the spoil arisings are cleared away and a reinforcing cage can, if required, be introduced into the plastic concrete in the pile, assisted by vibration.

A variant of this method is mixed-in-place piles which are suitable for use in granular material. Grout is mixed with the existing material within the pile borehole whilst the auger is drilled into the ground. Grout continues to be intruded as the auger rotation is reversed. Reinforcing cannot be used in this type of pile and its strength, bearing capacity and porosity is dependent on the grading and nature of the original material. As material is not brought to the surface this is not a true non-displacement pile.

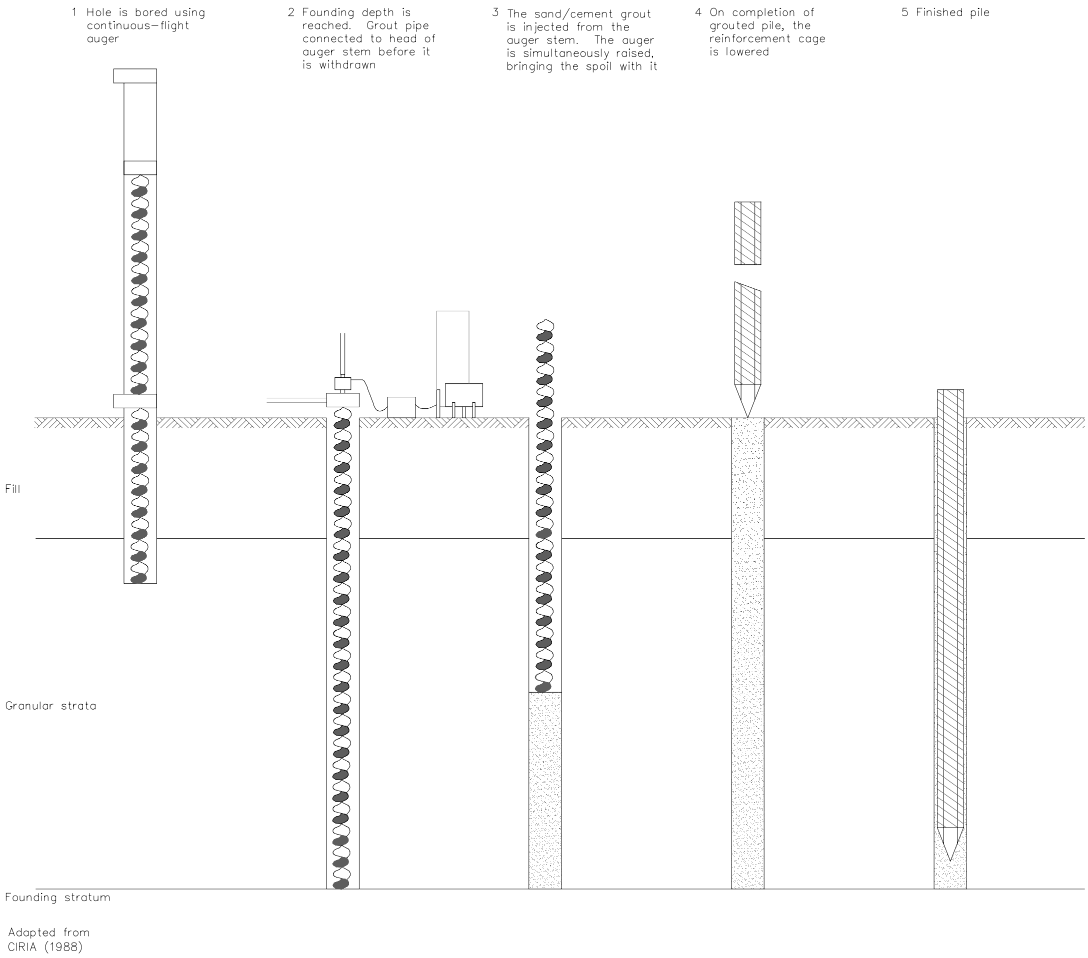


Figure A4. Intruded piles

A3.3 Types of Penetrative Ground Improvement Methods

This report considers two penetrative methods of ground improvement. These are generally carried out by the insertion of a vibrating sonde or poker from a track mounted rig, the vibration causing densification of the soil surrounding the poker. Originally this method was used as a purely densification exercise for granular sandy and gravely soils. In this method, known as vibro-compaction, the vibrating poker is withdrawn in stages and the sandy soil (topped up as necessary) descends to fill the hole vacated by the poker. This method is still commonly used in parts of Europe where appropriate soil types exist but it is not normally suitable for UK subsoil conditions and this variant of the method is not discussed further in this report.

The variants of this method commonly used in the UK involve the filling of the hole created by the poker with introduced material and this generic approach is referred to as vibro-replacement. This approach is suitable for a wider range of soils, including some with a silty or cohesive component, than is the case for vibro-compaction. The two variants use different materials to fill the hole created by the poker.

A3.3.1 Vibro-replacement stone columns

This method involves the displacement and densification of the weak ground into which the poker is inserted and the filling of the hole created by the poker with coarse gravel or cobble sized stone. Initially the poker is allowed to penetrate to the design depth and the resulting cavity filled with the stone, which is compacted in stages. Although the stone is compacted to a high density and the surrounding ground is densified, the stone column itself has a relatively high permeability by virtue of its comparatively uniform grading.

Two main methods are used. In the top feed process the vibrating poker and compressed air jetting is used to form an open hole to the design depth. Water is sometimes added. The vibrator is then removed and a charge of stone placed in the hole. The stone is then compacted in the hole by the vibrator. The stone is forced outwards and tightly interlocked with the surrounding ground. This process is repeated until several layers of stone are compacted to build up a dense stone column to ground level (Figure A5).

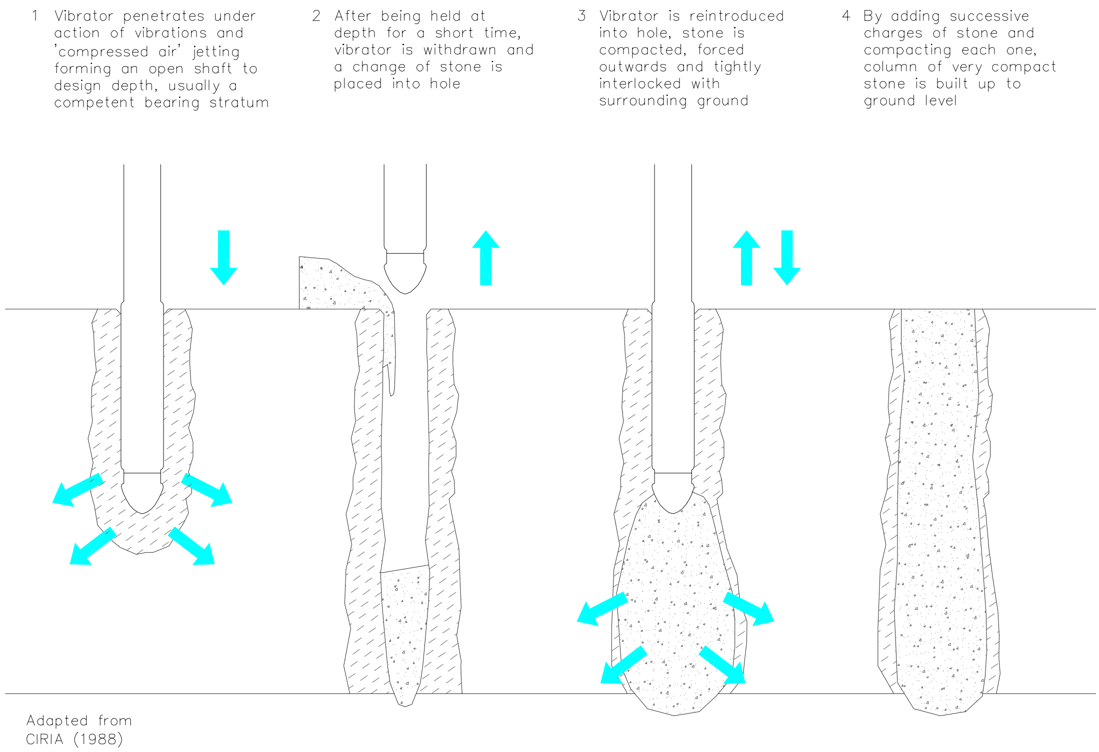


Figure A5. Vibro-replacement stone columns

The bottom feed process uses a hollow vibrating poker, with compressed air as before, to form a void to design depth. At the required depth the stone is released through the vibrator and compacted with small reciprocating vertical movements. This process is repeated as necessary until the column is formed. In some situations the initial basal filling of the void can be of concrete, in order to reduce the potential for downward flow of groundwater through the base of the stone column, although the bulk of the column remains permeable (Figure A6).

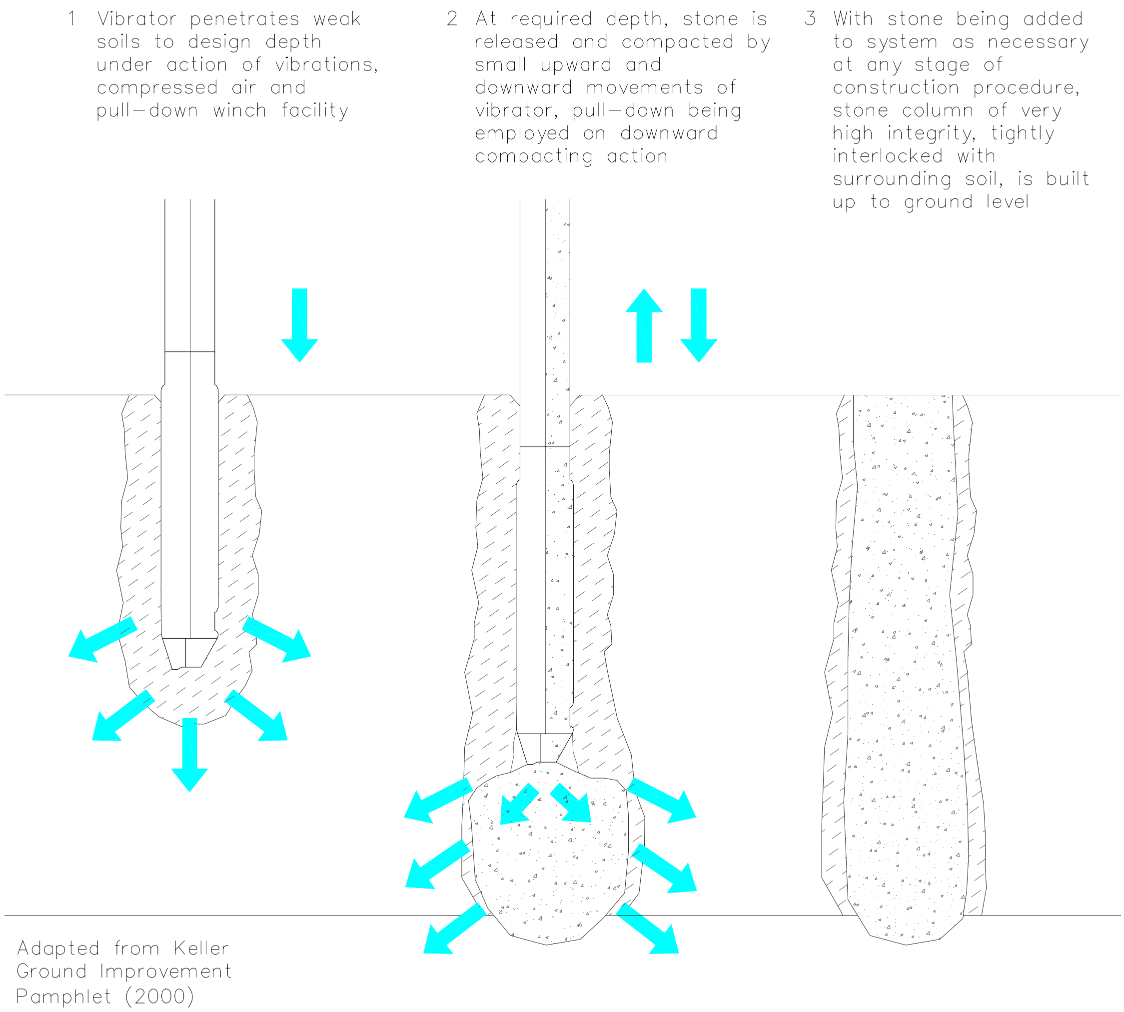


Figure A6. Vibro-replacement stone columns with concrete plug

A3.3.2 Vibro concrete columns

This method is suitable for use in weak alluvial soils such as peats and soft clays overlying competent stratum such as sands and gravels and solid strata. This method may be regarded as a composite between displacement piling and ground improvement as the primary means of load transfer is via the concrete columns. Vibro concrete columns can attain their full working loads at shallow installation depths, reducing the depth of penetration required. The low permeability of the concrete combined with the bulb end of the column and the tight interlock of concrete to soil is claimed to minimise the potential for vertical migration of contamination to underlying aquifers, or upward migration of vapours.

As with vibro-replacement stone columns, a hollow stemmed poker penetrates the soil until the required depth is reached. Pre-loaded concrete is then pumped via a tremie pipe running through the hollow stem of the poker. The poker is raised and lowered into the concrete, displacing the concrete into a bulb. The poker is then withdrawn at a set rate whilst concrete is pumped into the hole at a positive pressure. Once completed the columns can be trimmed and reinforcement placed. An enlarged column head can be formed by reintroducing the poker at the top of the column (Figure A7).

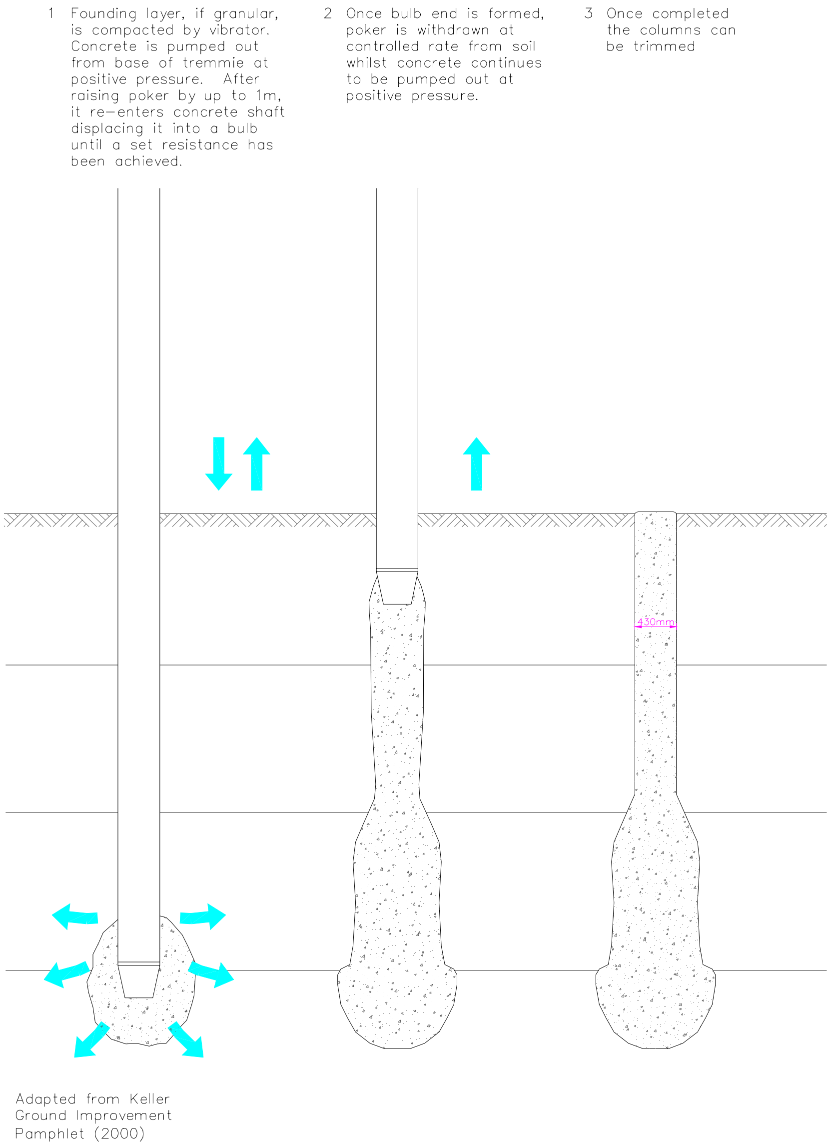


Figure A7. Vibro-concrete columns