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

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CL:AIRE

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Statement of use

This report presents up to date technical guidance on the potential impact that intrusive ground improvement and piling techniques can have on pollution of the groundwater environment and migration of ground gas. The information within this document is for use by Environment Agency, Natural Resources Wales, Scottish Environment Protection Agency and Northern Ireland Environment Agency staff and others involved in piling works that may affect groundwater quality with particular focus on their use on land that has been affected by contamination.

Report Citation

It is recommended citation to this report is made as follows:

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Disclaimer

Executive Summary

This report presents guidance on assessing risks associated with, and preventing pollution from piling and penetrative ground improvement methods, with a specific focus on their use on land affected by contamination. It also covers some specific aspects that are not solely related to contaminated sites, including the issues of turbidity from piling and the risk of it affecting water quality at abstraction wells, as well as the use of support fluids.

Developments are often on previously used land, including 'brownfield' development sites on which piling and penetrative ground improvement methods are commonly used. Increasingly developments are also constructed within the source protection zones for water supply boreholes. However, piling and penetrative ground improvement methods have the potential to create adverse environmental impacts when used on land affected by contamination or in sensitive areas. Specific issues include increased contaminant migration to groundwater, ground gas migration up piles and increase in turbidity from piling.

This report was first published in 2001 by the Environment Agency. Since that time there has been a reasonable amount of research into the effects of piling on contaminant migration. Work has also been undertaken that allows a better understanding of the risk posed by increased turbidity in aquifers caused by piling works. A literature review was completed to inform this updated guidance. An industry consultation was also undertaken in order to inform this update.

The report covers the following piling and ground improvement methods:

- Bearing piles;
- Sheet piles; and
- Penetrative ground improvement.

A framework is provided that identifies various factors that affect the risk of adverse effects from piling and these are classified as low, medium and high risk. Seven possible pollution scenarios have been identified and described, representing situations where there is the potential for piling or penetrative ground improvement operations to cause pollution. However, whether that potential will be realised will depend on the site-specific conditions and in many cases there is no significant risk. The seven 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. The driving of solid contaminants down into an aquifer during pile driving;
3. Contamination of groundwater and, subsequently, surface waters by turbidity, support fluids, concrete, cement paste or grout;
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. Creation of preferential pathways, including through a low permeability layer, to allow upward migration of landfill gas, soil gas, mine gas or contaminant vapours (e.g. Volatile Organic Compounds (VOCs)) to the surface;
6. Causing off site migration of ground gas or increased vertical emissions as a result of vibration or other effects from the pile installation process; and
7. Direct contact of site workers and others with contaminated soil arisings which have been brought to the surface.

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

The report provides a framework to allow designers to select an appropriate piling or ground improvement method on a site affected by contamination. The first step in the process is to develop a robust scaled diagrammatic conceptual site model. This should be prepared at the preliminary risk assessment stage and developed as further information becomes available. Advice on conceptual site models is provided in British Standard (BS) 21365 (BSI, 2020).

The assessment and choice of piling method should be considered from the earliest point in the design of a development (Royal Institute of British Architects (RIBA) Stage 1, RIBA, 2020). It is often more cost effective to choose a method that avoids hazards than to implement mitigation measures. In some cases, mitigation will be required and several possible mitigation measures that may be applicable in particular circumstances are listed. Starting the assessment at an early stage during the preliminary risk assessment also allows site investigations to be designed to collect information relevant to the later stages of the foundation works risk assessment (FWRA).

Quality assurance and quality control (QA/QC) during construction are addressed. Advice on when groundwater or ground gas monitoring may be required during and/or after construction is provided together with suggested protocols.

The framework provided in this report will allow low risk sites to be screened out with minimum work and a simple one-page summary of the process to document the decision is all that is required. For medium and high risk sites a FWRA report will be required, which should present a thorough and auditable risk assessment, describing and fully justifying the decision-making process, including a description of any methods rejected after consideration. A suggested structure for the report is provided in Chapter 17.

Preparation of the FWRA report is intended to assist planning authorities to meet their objectives in granting permission or enforcing planning conditions. However, submission of a FWRA report will not absolve the developer and their 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. It is also recommended that reports are prepared by qualified professionals with experience and understanding of land affected by contamination and groundwater risk assessment as well as foundation construction.

This guidance is not applicable where a landfill operator, developer or landowner proposes to penetrate through the capping layer, base or sidewalls of a permitted landfill, where complex engineered lining systems are present including geomembranes and drainage layers. Where this is the case, please speak to the local Environment Agency, Natural Resources Wales, Scottish Environment Protection Agency or Northern Ireland Environment Agency office for advice and guidance.

Structure of the Report

Chapter	Details
1. Introduction	Provides an explanation of the scope and objectives of the report and the approach taken to achieve them. It highlights the benefits for all of using competent risk assessors to complete foundation works risk assessments.
2. Background	Explains in general terms the legislative and regulatory background around piling and groundwater improvement works in contaminated sites and/or where there may be a potential risk to groundwater.
3. Piling and ground improvement methods	Provides an explanation of all the different piling, sheet piling and ground improvement methods that could be used in the UK.
4. Choice of piling, sheet piling or ground improvement methods	Explains the factors that affect the choice of piling, sheet piling or ground improvement methods for a particular project. Explains how environmental impacts including risk to groundwater should be given equal weight as other considerations.
5. Hazard identification: potential adverse environmental impacts	Summarises the various environmental impacts that could potentially occur when piling or undertaking ground improvement in contaminated sites or into aquifers.
6. Hazard identification and risk assessment	Presents a risk assessment framework that fits in with the RIBA work stages and geotechnical and geoenvironmental work stages. It identifies that the foundation works risk assessment process should start at RIBA Stage 0 (strategic definition) and be developed as the development design progresses. Provides a framework for initial screening to determine the complexity of risk assessment that is likely to be required for a site. This should allow low risk sites to be screened out early in the process and allow resources to be focused on higher risk sites. For low risk sites a specific foundations works risk assessment report will not be necessary and can be included as a section in geoenvironmental reports. It also discusses the risk assessment process associated with ground gases.
7. Pollution Scenario 1	Discusses each piling or ground improvement method in relation to the creation of preferential pathways, through a low permeability layer, to cause contamination of groundwater in an aquifer.
8. Pollution Scenario 2	Discusses each piling or ground improvement method in relation to the driving of solid contaminants down into an aquifer during construction works.
9. Pollution Scenario 3	Discusses each piling or ground improvement method in relation to contamination of groundwater and, subsequently, surface waters by turbidity, support fluids, concrete, cement paste or grout.

Chapter	Details
10. Pollution Scenario 4	Discusses each piling or ground improvement method in relation to contact of the piles or materials with contaminated soil or leachate causing degradation of pile materials (where the secondary effects are to increase the potential for contaminant migration).
11. Pollution Scenario 5	Discusses each piling or ground improvement method in relation to the creation of preferential pathways for ground gas migration, including through a low permeability layer, to allow upward migration of landfill gas, soil gas, mine gas or contaminant vapours (e.g. VOCs) to the surface.
12. Pollution Scenario 6	Discusses each piling or ground improvement method in relation to causing off site migration of ground gas or increased vertical emissions as a result of vibration or other effects from the pile installation process.
13. Pollution Scenario 7	Discusses each piling or ground improvement method in relation to direct contact of site workers and others with contaminated soil arisings which have been brought to the surface.
14. Summary of pollution scenarios	Provides a summary of all the pollution scenarios and the indicative level of risk associated with displacement, replacement and penetrative ground improvement methods.
15. Mitigation measures	Where risk cannot be avoided or minimised sufficiently by the choice of an appropriate piling or ground improvement method, this chapter provides advice on when it is possible to remove a potentially adverse impact by the design and specification of mitigation measures.
16. Quality assurance and verification during construction	Provides advice on quality assurance of pile or ground improvement construction with respect to risk associated with groundwater or ground gas. It identifies when groundwater or gas monitoring may be required before, during and after construction and the need to set limits against which to compare results and the actions to be taken if the limits are exceeded (with timescales).
17. The Foundation Works Risk Assessment Report	Describes the suggested contents of a standalone FWRA report (where the assessment following the framework in Chapter 6 indicates that a standalone report is required). Standalone reports are not required on low risk sites.
References	A list of documents referred to in the report.
Appendix 1. Literature review	A summary of the key findings of the literature review completed as part of updating this report. The literature review discusses research that has been undertaken into the effect of contamination on piles; the risk posed by piling and the effects on migration of contamination and groundwater pollution; the risk posed by piling and ground improvement with respect to ground gas; leaching of support fluids or cement past into aquifers and the risk of turbidity in groundwater when piling into aquifers.
Appendix 2. Case study examples	Provides fifteen case study examples.

Contents

1 Introduction

1.1 Scope

This report reviews and provides guidance on preventing pollution from piling and penetrative ground improvement methods on land affected by contamination or where support fluids or turbidity may affect groundwater quality. It has been updated to reflect the research and practical experience gained on this subject since 2001 when the first version of this report was published.

1.1.1 Piling

A pile foundation is a type of deep foundation. It comprises a slender column or cylinder made of materials such as concrete, steel or, less common in the UK, wood which are used to support the structure and transfer the load to competent soils or rock at a desired depth (Figure 1.1). They may also be used to resist uplift or lateral loads. They are used where the shallow soils are weak and/or compressible and cannot support foundation loads. Piles can support loads by end bearing onto a competent stratum, skin friction between soil and pile shaft or a combination of both (Figure 1.1).

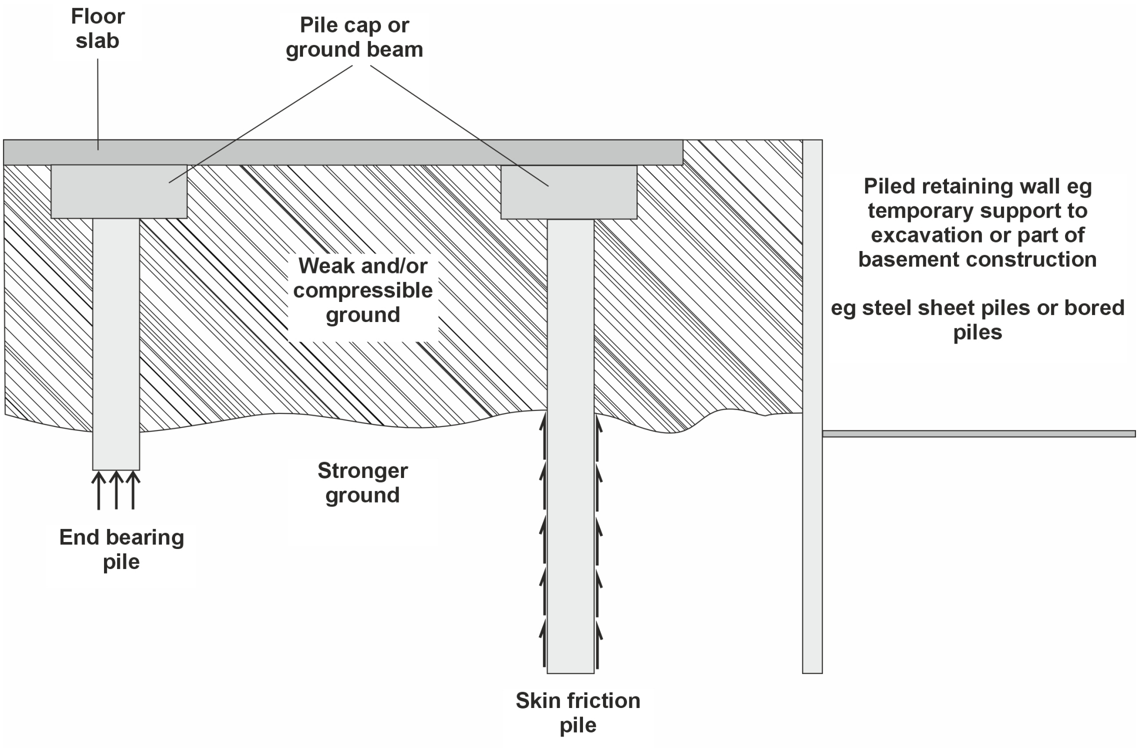


Figure 1.1: Piled foundation and piled retaining wall

1.1.2 Ground improvement

Ground improvement is the enhancement of the properties of weak and/or compressible strata in order to render them suitable to carry loads from structures. Penetrative ground improvement methods involve increasing the soil density locally by vibrating a poker down into the ground. Additional coarse gravel, concrete or soil binders may be introduced to form columns of stronger material in the ground (stone, concrete or soil mixed with binder) as shown in Figure 1.2.

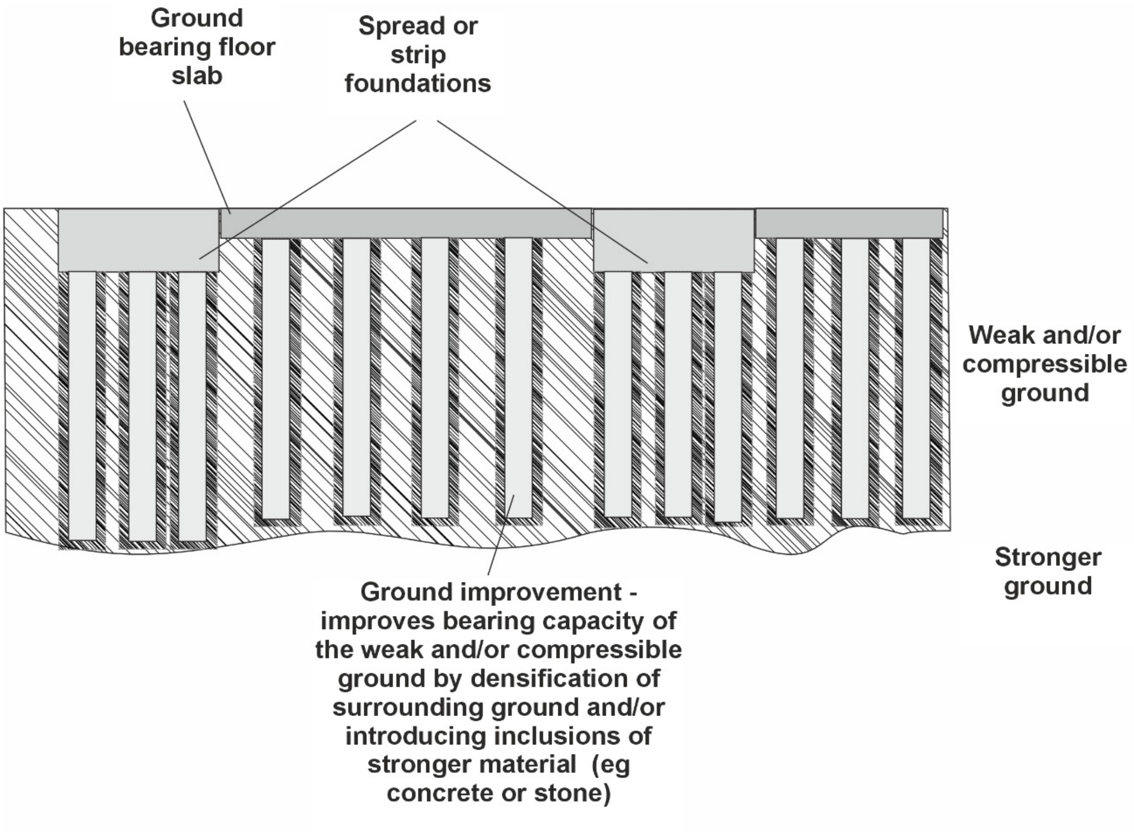


Figure 1.2: Ground improvement

The report also includes prefabricated vertical drains which are also known as band or wick drains (Figure 1.3) within the sections on ground improvement. Although not traditionally considered a ground improvement method they do have the potential to create pathways for groundwater or gas migration. They are used with a surcharge to speed up consolidation. They are also used together with rigid inclusions, again to increase the rate of consolidation of the surrounding ground.

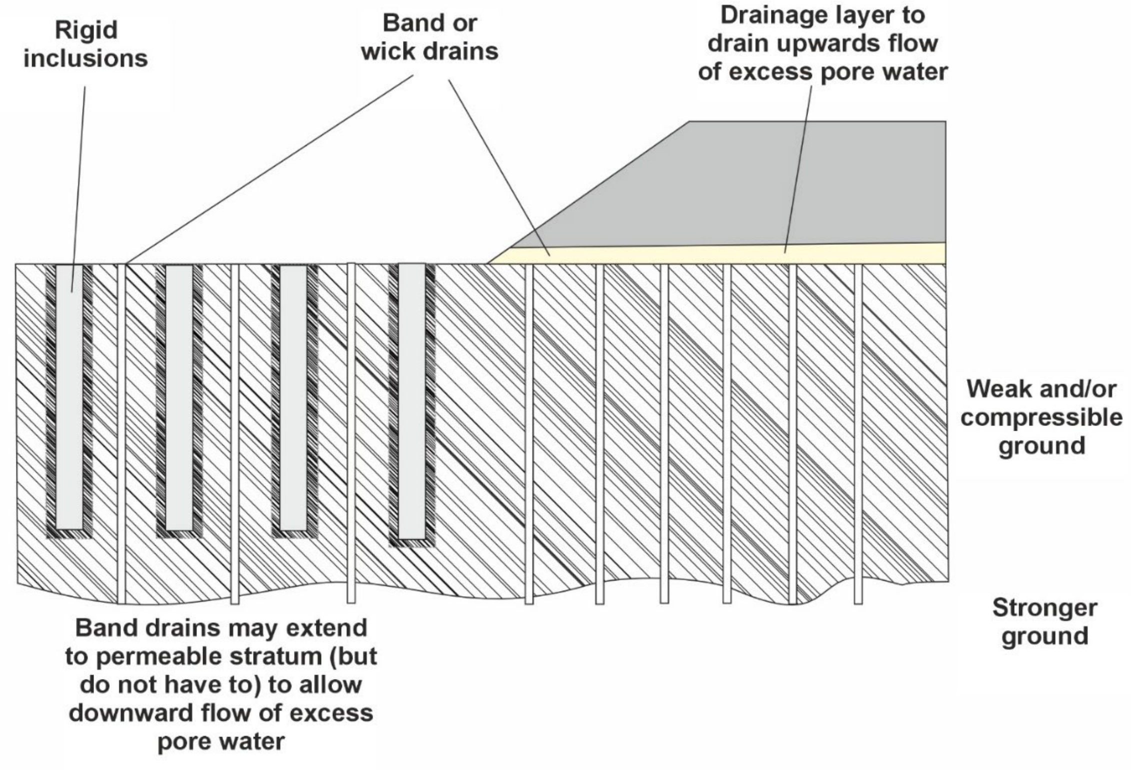


Figure 1.3: Prefabricated vertical drains

1.1.3 Application of piling and ground improvement on brownfield sites

Piling has been used in foundation engineering at least since Roman times and remains an important method of foundation engineering in soft ground. Penetrative ground improvement has become widely adopted for the support of lightly loaded structures including houses and warehouses. 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. Piling and ground improvement is also more widely used than previously because on many sites it is more cost effective than deeper excavations for spread foundations (because of the reduced cost of soil disposal compared to traditional spread, strip or deep trench fill foundations). There is also an increasing requirement for piled foundations for developments within source protection zones to water supply boreholes.

Some piling methods (bored piles and barrettes) are also used to construct retaining structures (Figure 1.1) or cut off walls in the ground to prevent contaminant or ground gas migration.

Sheet piles are used to construct permanent or temporary retaining walls, for example around basements. They have also been installed as cut off walls to prevent landfill gas or ground gas migration.

Piling, sheet piling and penetrative ground improvement methods have the potential, in certain circumstances, to create adverse environmental impacts when used on land affected by contamination or within source protection zones. There are also potential consequences to surface waters via groundwater (direct impact from surface flow into surface waters is beyond the scope of the report). However, it is increasingly being recognised that on many sites piling does not pose a risk of adverse effects to either groundwater or gas emissions because of site-specific factors. It is, however, extremely important that the potential risks from piling are considered from the very beginning of planning for a development and this requires the input of professionals with experience in land affected by contamination, groundwater risk assessment and foundation construction.

The consequences of causing groundwater pollution are often significant and also difficult to remediate once it has occurred. Therefore 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 what type of pile or ground improvement may be used. It is important therefore to consider this issue at the start of development planning.

In this report, where reference is made in general to the “regulator” this should be taken to include all of the following environmental regulators unless stated otherwise: Environment Agency, Natural Resources Wales, Scottish Environment Protection Agency and Northern Ireland Environment Agency. Liaison with local authority regulatory officers may also be required.

1.2 Objectives

This report addresses the following objectives with respect to the use of piles, sheet piles and ground improvement in land affected by contamination or within source protection zones:

- To promote early consideration of the potential for foundation solutions to pose a hazard to groundwater or for migration of ground gas and vapours;
- To improve the quality of risk assessment and 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 land contamination professionals;
- To provide a decision-making framework based on site-specific assessment of risk;
- To identify low risk sites that can be screened out early in the process; and
- To identify appropriate and cost-effective risk mitigation measures that minimise constraints on the construction industry, whilst ensuring adequate environmental protection.

1.3 Approach

The wide range of commercially available piling, sheet 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 covers all those used in civil engineering construction of foundations for built development, infrastructure projects, marine projects, wind turbines, etc. The report now includes non-foundation piling such as sheet piling, the construction of piles for deep basements and ground improvement methods such as deep soil mixing. It does not include surface-based ground improvement techniques such as dynamic compaction or preloading.

The experiences of industry were sought by means of an online questionnaire. There were 46 responses from a range of professionals including geoenvironmental consultants/hydrogeologists (31), remediation contractors (4), regulators (5), geotechnical engineers (2), piling contractors (2), main contractors (1) and water companies (1).

A literature review was undertaken to obtain up to date research and experience of piling in land affected by contamination and also on the effects of turbidity on groundwater abstraction wells. 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 to mitigate this during design and construction. The literature review is provided in Appendix 1.

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 methods may be more appropriate and pose a lower risk to the environment (including non-piling solutions such as raft foundations). The report does not set out to provide a prescriptive guide to the applicability or selection of individual piling, sheet 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 solutions 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.

The foundation works risk assessment (FWRA) process should be used to identify appropriate solutions that are reasonable to prevent the entry of hazardous substances and limit the entry of non-hazardous pollutants into groundwater. Where pollutants have already entered groundwater, the assessment should be used to design foundation solutions that minimise further entry of contaminants and limit the continued pollution of groundwater.

Guidance on determining remedial objectives to protect water resources is given in guidance from individual regulators (e.g. see the GOV.UK and SEPA.ORG.UK websites).

Regulators and local authority officers need to be able to satisfy themselves that foundation designers have fully considered the risk that the proposed works pose to 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 regulators and local authority officers will not absolve the developer and their 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.

1.4 Competence

The quality of a FWRA depends upon the competence of the individuals and the organisations undertaking the work. Demonstrating competence is important when reports are submitted to support or enable the discharge of planning conditions, when the regulators are encouraged by Government policy statements to ensure that any such work is carried out by appropriately competent persons.

It is recommended that anyone undertaking a FWRA has visited sites and has observed the installation of the various types of piles or ground improvement methods.

Competent persons are defined in the National Planning Policy Framework[1] – Annex 2 (NPPF) (MHCLG, 2024) as persons "*with a recognised relevant qualification, sufficient experience in dealing with the type(s) of pollution ….. and membership of a relevant professional organisation*". This definition is referred to in the Land Contamination: Risk Management (LCRM) guidance (Environment Agency, 2023) which also explains how practitioners should have appropriate knowledge, skills, experience and qualifications in the relevant aspect of land contamination/the type of contamination being addressed. In the case of the FWRA process discussed in this report an understanding and competence in land affected by contamination and a good understanding of the practical aspects of foundation engineering are likely to be required. Where professionals do not have combined experience across the geotechnical and geo-environmental fields then close collaboration between two separate specialists will be required.

LCRM provides examples of how competency may be demonstrated in relation to land contamination assessment. Reference is made to qualifications and experience in specific technical or scientific disciplines (including multidisciplinary) and to application. Examples cited are:

- A Suitable Qualified Person (SQP) under the National Quality Mark System (NQMS);
- The Society of Brownfield Risk Assessment (SoBRA) accreditation scheme;
- A Specialist in Land Condition (SiLC);
- Membership of a professional organisation relevant to land contamination; and
- A proven track record of dealing with land affected by contamination (with further detail provided in LCRM).

[1] NPPF only applicable in England.

Geotechnical competence can be demonstrated by membership of the Register of Ground Engineering Professionals (RoGEP).

Chartership with a relevant professional organisation (such as The Institution of Civil Engineers, The Geological Society, The Institution of Environmental Sciences, or The Chartered Institution of Water and Environmental Management) is important in demonstrating competence; not just because it demonstrates that individuals have reached a certain level of technical ability but also because they will be signed up to a code of conduct which should prevent them from providing advice outside of their area of expertise.

Geotechnical contractors and specialist companies (and teams) can also demonstrate success via a proven track record.

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 FWRA 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.

1.5 Communication

Communication between all interested parties during preparation and agreement of the FWRA (and during construction) is extremely important. The risk assessment will potentially be of interest to different stakeholders. For example, a local authority contaminated land officer or environmental health officer may be concerned primarily with the effects of piling or ground improvement on the risk posed by ground gas and the regulator is concerned primarily with risk to controlled waters, including groundwater. It is important that all interested parties are consulted during the risk assessment process.

It is also important that any requirements for design and construction of piled foundations or ground improvement are communicated to the designers and those doing the construction on site. Consideration for monitoring timescales during site investigation is important, and records for ground gas and groundwater levels should be as extensive as possible, with future investigations targeted in areas of known concern. The results should be provided to the foundation designer to allow for appropriate solutions to be chosen in order to minimise environmental issues.

Contractors should also be made aware of any monitoring requirements during construction, thresholds and the action plan if limits are exceeded. Contractors can often provide valuable input into minimising risks and may be consulted early in the FWRA process.

Where groundwater or gas monitoring is required as part of a mitigation plan the results should be provided to regulators in a timely manner. It is not acceptable to just provide a bulk set of results at the end of a project. Regulators need to monitor conditions throughout construction and be aware of early signs that problems may be developing that could require mitigation.

2 Background

2.1 Legislative and regulatory context

In England, redevelopment of land in general is controlled through the Town and Country Planning system. Wales, Scotland and Northern Ireland have similar planning systems. It is these systems that will normally be used to enforce any regulatory requirements or restrictions as sites are redeveloped.

Piling, sheet piling and penetrative ground improvement methods are generally used to provide foundations or retaining walls for new buildings or other engineering works. In England 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 section 106 agreements. Similar arrangements but under different legislation exist in the devolved regions. Certain activities may have to be regulated under environmental permitting legislation where the land contains waste or contaminated soil is excavated (see Section 2.3).

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 plans and when considering individual planning applications.

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 of the current site use and the proposed new use.

A planning permission may be granted with conditions supported by comments from statutory consultees and other interested parties (e.g. water companies – public water supplies; utilities and sewage undertakers – pipework and other infrastructure; and transport). 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 or retaining methods and in practice it is common for the inclusion of such conditions to be requested by the regulator where risks to the water environment are significant.

The regulator may place a standalone planning condition requiring piling details and a risk assessment to be completed (to demonstrate that there is no unacceptable risk to groundwater.

Where the work has the potential to impact groundwater, it may need to be regulated by a groundwater permit or authorisation from the regulator.

In addition to the planning system, the Building Regulations 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 or by private approved inspectors.

Reference should be made to the current planning legislation and guidance and the Building Regulations relevant to the site location.

2.2 Legal issues

The regulator has powers to remedy or forestall pollution of controlled waters, which includes powers to serve notices that require remediation of polluted groundwater. 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 regulator may serve notice on that person, which requires the remediation of polluted waters.

Under current legislation a successful prosecution may result in fines and/or imprisonment for those found guilty.

2.3 Waste management

Where arisings are generated as a result of piling or ground improvement works they should be disposed of or reused on or off site under the relevant waste management legislation. Section 34 of the Environmental Protection Act 1990 places a duty on any person who produces, carries, keeps, disposes of, treats, imports or has control of 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 on summary conviction or unlimited on indictment.

Excavated soils and rocks from piles may be considered waste unless managed appropriately, for example via a materials management plan (MMP), permit, etc. In any event arisings from piling works will have to be managed safely. This applies whether the arisings are removed from site or reused on site. Issues that the contractor and site engineer should consider include:

- Can the arisings be reused on site (or on other sites)?
- Does the waste need a special container to prevent its escape or protect it from the elements?
- Is it likely to change its physical state during transport?
- Can it be treated and where necessary disposed of safely in a landfill site with other waste?

It is recommended that waste management issues are addressed at an early stage in order to prevent contravention of the duty of care and any other waste management legislation.

2.4 Key technical issues

The key issues to be addressed when considering the use of piling or ground improvement in locations with the potential to cause, or allow the migration of, pollution into controlled waters (particularly groundwater) 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;
- Mobilising gas or contaminants during construction or installation and causing off site migration;
- The effects of aggressive ground conditions on materials used in piles;
- Driving contaminated materials downwards into an aquifer during construction/ installation;
- Increasing turbidity when piling or drilling into an aquifer; and
- Concrete, support fluid or grout contamination of groundwater and/or any nearby surface waters.

Throughout the discussions that follow, it is assumed that appropriate professional care, standards and workmanship will be applied to the design, method selection and construction of the foundation works considered. The proposed framework for FWRA 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, geotechnical 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 (see Section 1.4 on competence).

2.5 Case studies

There are few reported, and fewer still substantiated, incidents of the use of piling, sheet piling or ground improvement methods on contaminated and other 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 or ground improvement operations. A reasonable body of research is now available that has been used to inform this report. This should help ensure more robust FWRAs are prepared that identify high risk scenarios and specify the monitoring required to demonstrate piling or ground improvement has not adversely affected sensitive controlled water receptors.

One of the main problems is that 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 could probably be poorly decommissioned boreholes rather than piles and it could be very difficult to distinguish between aquifer contamination caused by piling or the boreholes. The same also applies to ground gas migration via unsealed boreholes. Site investigation works into aquifers should be undertaken in a manner that avoids creating pathways. Guidance provided by the Environment Agency and SEPA on clean drilling methods and decommissioning boreholes should be referred to (Environment Agency, 2006b and 2012; SEPA, 2014).

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.

The West Shell system was originally designed in the 1920s to form foundations for town gas works (West, 1972). West Shell Piles are precast, reinforced concrete tubes, about 1 m long, threaded on to a steel mandrel and driven into the ground after a concrete shoe has been placed at the front of the shells. Once the shells have been driven to the specified depth the mandrel is withdrawn and reinforced concrete inserted in the core. 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.

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 are insufficient data to show whether or not the piles contributed to contamination. However, there is now research available that indicates that there is likely to be a low risk from piling in many sites and with the most commonly used methods (including driven piles).

Case studies are provided in Appendix 2 from sites:

- Where assessment of the risk to groundwater has resulted in changes to the piling design or method selected, or where appropriate mitigation methods have been used;
- Where gas monitoring has been completed around the top of driven piles and stone columns installed in sites where ground gas or landfill gas is present; and
- Where groundwater monitoring has been completed during and after piling works.

3 Piling and Ground Improvement Methods

3.1 Introduction

There are numerous different piling, sheet piling and ground improvement methods and installation techniques. Anyone undertaking a piling or foundation risk assessment should have a good practical understanding of the different methods with respect to groundwater or ground gas risk.

The following review provides a basic overview of each method and focuses on the issues that may affect the potential risk in relation to groundwater or ground gas contamination. The references should be consulted for more detailed information on each method.

3.2 Differentiation between piling and ground improvement methods

Bearing piles are designed to transfer load to a competent bearing stratum, normally below a weaker layer of soil. Piles can also be used as retaining structures via contiguous pile walls, secant pile walls, or solider pile walls (less commonly in the UK diaphragm walls can be used as retaining structures). Diaphragm walls or secant pile walls are also used to provide a barrier to contaminant migration through the ground. Diaphragm wall methods can also be used to create rectangular bearing piles (known as barrettes). Piles are also used to resist uplift forces and these are known as tension piles. Sheet piles are installed to create either temporary or permanent retaining structures, but have also been used to create gas or groundwater barriers by welding the joints.

Penetrative ground improvement methodologies normally function in a different way to piles. Whilst piles are designed to transfer loads through poor ground to a competent founding level, ground improvement techniques normally aim to improve poor ground and to improve and control the anticipated settlement of the ground under load (by densification, or by a combination of densification and addition of stiffer granular, concrete or soil mixed material) so that it is made competent to support conventional foundations, floor slabs or other structures without excessive settlement. However, some ground improvement techniques such as vibro concrete columns are closer in form to piles than to ground improvement by densification although they are installed with equipment used for ground improvement.

Ground improvement methods can densify the soil by rearranging soil particles or improve its characteristics by addition of additives such as cement or by providing inclusions in it (e.g. stone columns).

There is a considerable variety in the materials, design and installation methods used in piling and penetrative ground improvement (Fleming *et al.,* 2009; Evans *et al.,* 2002). 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).

Table 3.1: Differentiation between methods of piling and ground improvement

Classification	Subdivisions
Function	Load support (bearing), retaining structure
Materials	Timber, concrete, steel, composite, plastic, stone, soil stabilised with binder
Load transfer	End bearing, friction, combination of friction and end bearing, ground improvement to support shallow foundations, earth pressure on retaining walls
Installation	Bored, drilled, driven, cast-in-place, precast, screw in (helical), pushed in (sheet piles) vibratory, soil mixing, water jetting
Effect of installation on soil mass	Displacement, replacement and subdivisions or combinations according to installation method, compaction, increased strength or stiffness

3.3 Bearing pile methods

It is most common to differentiate bearing piles based on whether they displace the soil around them (displacement) or the soil is removed and replaced with a structural material, typically concrete (replacement) (Tomlinson and Woodward, 2015). This is the approach used in this report. Piles are further subdivided according to the methods of construction and installation used. The literature review (see Appendix 1) identified that there is normally little, if any, difference in the environmental impact between displacement and replacement methods (with respect to contamination and ground gas migration pathways). The various types and methods of installation are well described in Fleming *et al*. (2009) as summarised in Figure 3.1.

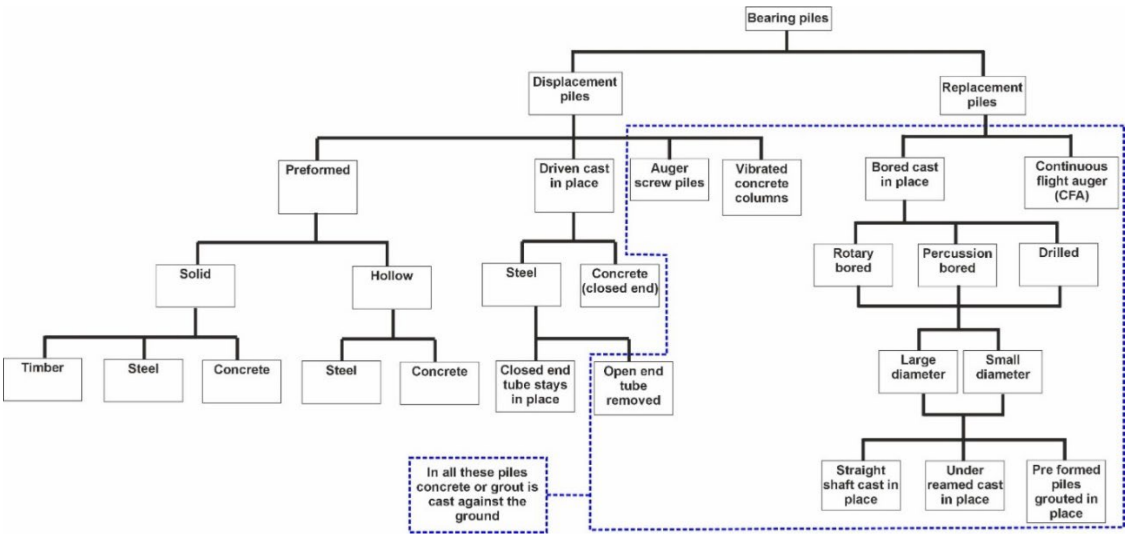


Figure 3.1: Types of bearing piles. Used with permission of Taylor & Francis Informa UK Ltd - Books from Fleming *et al*., 2009; permission conveyed through Copyright Clearance Center, Inc.

There are various different methods of installing both types of pile and new techniques may be developed. The following overview covers the most common methods currently used in the UK and concentrates on the specific aspects that will influence the risk of causing groundwater contamination or increase risk of gas migration from or through the ground. Specialist foundation contractor websites are a good source of further information on the different methods of installation and new and emerging techniques.

There are various British Standards that provide guidance on construction of piles or barrette foundations:

- *BS EN 1538:2010 + A1: 2015 Execution of Special Geotechnical Works – Diaphragm walls* (BSI, 2015a)[2];
- *BS EN 1536:2010 + A1: 2015 Execution of Special Geotechnical Works – Bored piles* (BSI, 2015b);
- *BS EN 14199: 2015 Execution of Special Geotechnical Works – Micropiles* (BSI, 2015c); and
- *BS EN 12699: 2015 Execution of Special Geotechnical Works – Displacement piles* (BSI, 2015d).

3.4 Displacement piling

3.4.1 General characteristics of displacement piling

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. The piles can be totally preformed with solid or hollow sections driven into the ground or a section is screwed into the ground. Piles can also be driven and cast in place where a tube is driven into the ground to create a void which is filled with concrete.

Small displacement piles comprise solid H, or I steel sections or hollow tube sections. Screw (helical) piles are also small displacement. They are called small displacement because the cross section area is small and the amount of soil displacement is small. Large displacement piles have larger cross section areas and may consist of precast concrete elements, closed-end steel tube or timber sections, or may be cast *in situ* inside a casing or in a preformed void. Auger displacement piles displace soil using an auger and the pile is cast *in situ*.

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 drag down can occur along the sides of the pile shaft but this is typically of a limited extent both horizontally and vertically.

[2] Barrettes are essentially rectangular piles installed using diaphragm wall methods

In general the mechanism of radial soil displacement causes densification of the soil surrounding the pile and generally this will lead to a reduction in permeability of the penetrated soil. 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.

This means that, with exception of steel H or I section and timber piles, driven piles will not generally create preferential pathways for contaminant or gas migration through clay layers, unless the clay layers are very thin and/or chlorinated solvents are present as Dense Non Aqueous Phase Liquid (DNAPL) over the top of the clay layer. Drag or push down of contaminants will be minimal, especially where pointed ends are used. There is no spoil from the construction which is particularly advantageous on contaminated sites.

There may be the potential for gas or contaminant migration up or down timber piles within the wood. In cohesive soils in particular, there may be voids formed in the corners of H and I section piles that can create routes for contaminant or gas migration.

3.4.2 Types of displacement piles

Displacement piles may be installed 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.

The following types of displacement pile are considered in this report:

- Driven piles (totally preformed);
- Driven cast-in-place piles (driven casing removed);
- Screw (helical) piles; and
- Augered displacement piles.

3.4.3 Driven piles (totally preformed)

Driven piles can use a variety of materials. These can be solid section precast concrete (normally square section), steel H or I section or timber. They can also comprise steel tube (open or closed end), a combination of steel tube and precast concrete, precast concrete shell or tube (normally in excess of 600 mm diameter, but not in common use in the UK, they are used in the Far East where they are favoured for heavy load applications (Fleming *et al.,* 2009)).

The piles can be installed as a single length or in sections that are jointed together as the pile is driven into the ground. Once installed and carrying their service load the compressive forces in the pile will ensure that the joints remain tight.

Concrete piles can also be prestressed. The pile installation process is shown in Figure 3.2. Driven piles normally derive most of their support from end bearing on a strong bearing stratum that is located below weaker ground. They are normally impact driven with a drop hammer although sometimes hydraulic or diesel hammers may be used. None of the different hammer methods will have any appreciable effect in relation to contaminant or gas migration around piles. Vibratory methods may also be used to install the piles. The potential implications of this are discussed in more detail in Section 3.11 on sheet piles.

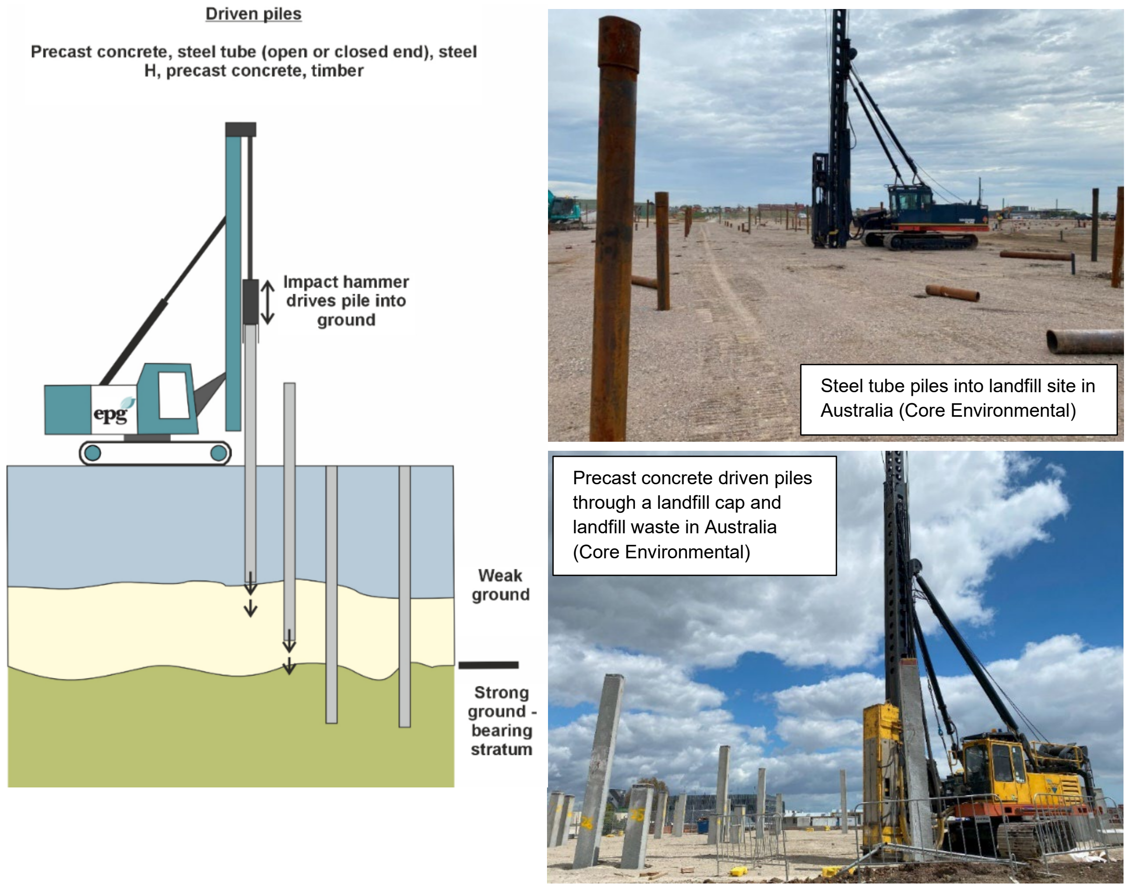


Figure 3.2: Driven piles (totally preformed)

Driven piles can also comprise cylindrical steel or concrete tubes that are driven into the ground to the required depth and may be left open or can be infilled with concrete (the driven tube is left in place – see Figure 3.3). Reinforcement may be installed before the concrete is poured. When filled with concrete the piles are technically a driven cast-in-place pile but because the hollow concrete or steel tube sections are left in place it is effectively the same as a driven precast pile in terms of its effect on groundwater and ground gas risk therefore they are included in this section. Often recycled steel casings from the oil and gas industry are used. They are an alternative to precast concrete piles where difficult driving conditions may be encountered.

The cylindrical elements may be a single length or a number of jointed elements. Some systems involve the driving loads being applied to the top of the pile, whilst others apply the driving force directly to a shoe at the base of the cylindrical column. The installation method makes no difference to the risk in respect of pathways for contaminant or gas migration. The tubes may be driven open ended, with soil entering the base of the pile forming a plug at the bottom, or with a closed end. 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. It also prevents gas migration up the piles.

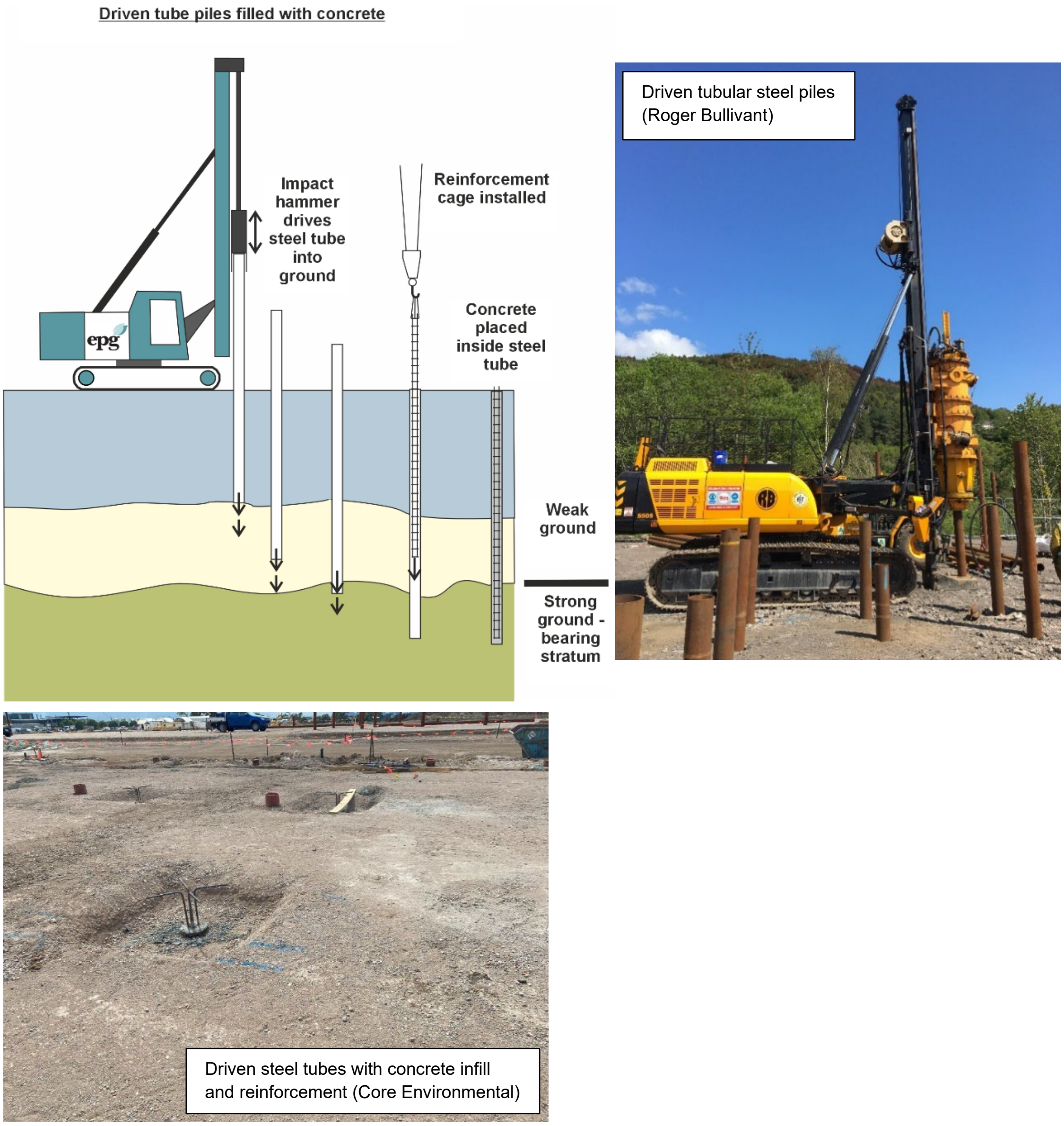


Figure 3.3: Driven steel or concrete tubes filled with concrete

Piles may be installed at sub vertical angles (known as raking piles). These are used to resist lateral loads and are common on bridge abutments (Figure 3.4). There may be an increased risk of migration pathways forming around raking piles. In the past, raking piles were normally driven precast concrete or steel tubes but they can be installed using rotary bored techniques (Figure 3.4).

Precasting 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 or vibration due to percussive driving. However, these effects are minimised by modern plant and methods.

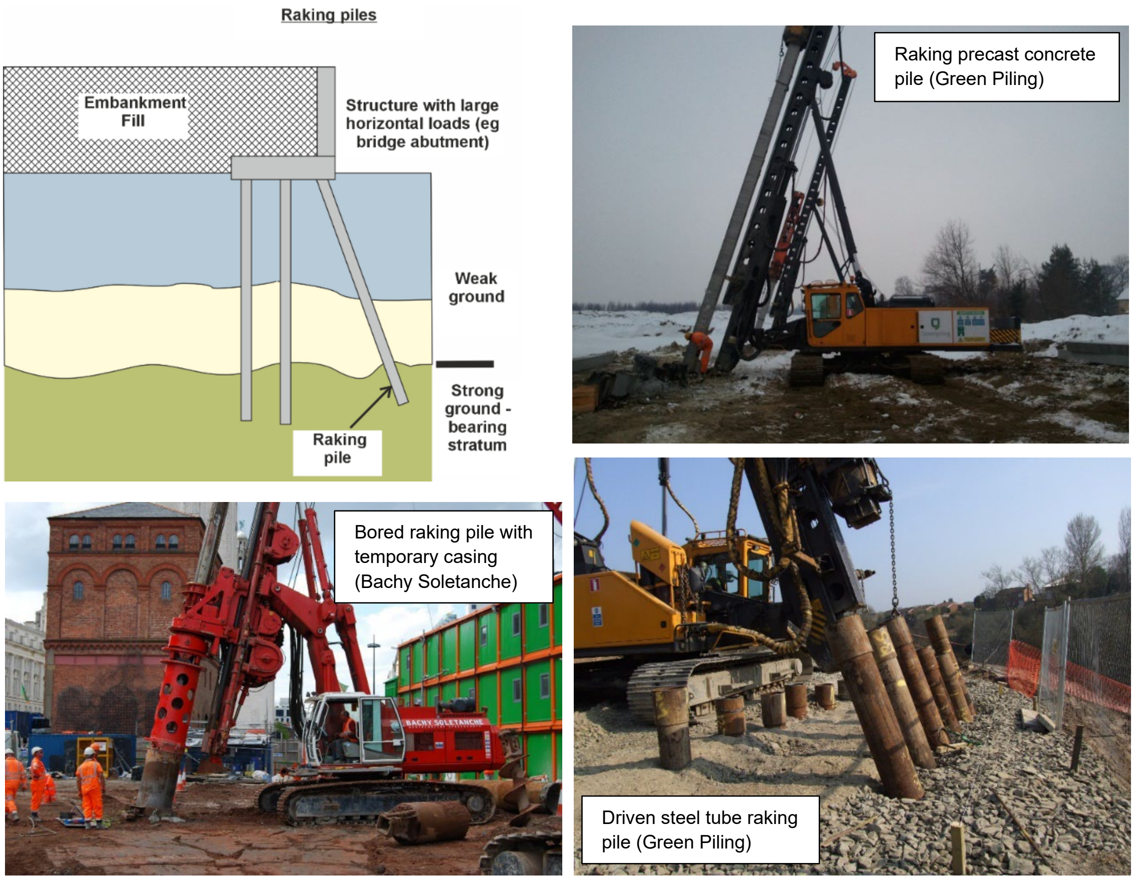


Figure 3.4: Raking piles

Preformed 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 in the past to use steel piles in land affected by contamination. However, research suggests that steel piles perform well in contaminated soils (SCI, 2001) although corrosion in some fill materials can be twice that in undisturbed natural soils (mainly due to the increased oxygen content or acidic conditions). Advice on corrosion of steel in contaminated ground is provided in Paul (1994) and Environment Agency R&D Technical Report P331 and P5-035/TR/01 (Environment Agency, 2000 and 2001). Allowing for corrosion in steel piles should follow guidance in Eurocode EN 1993 - Part 5: 2007 (BSI, 2007a). If this is followed it should minimise the risk of potential migration pathways forming (see Section A1.3).

The piles can withstand hard driving and penetrate hard strata or natural obstructions. It has been previously reported that very slender steel piles (such as H section piles) can have a tendency to wander off line and it is suspected that ‘whipping’ of 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. It is only likely to occur with poor installation and only affects a short length at the top of the pile (see Section A1.4). Discussions with UK piling contractors indicates that this whiplash effect is not a known issue with driven precast concrete or steel tube piles that are most commonly used for housing and commercial developments in the UK.

Timber piles are suitable for modest loads to depths of approximately 12 m (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*., 2009; CIRIA, 1988). Contamination or ground gas can potentially migrate within timber piles.

3.4.4 Displacement cast-in-place piles

Displacement (driven) cast-in-place piles in this report refers to those piles where the driven casing is removed from the ground as concrete is placed (Figure 3.5). The final pile concrete is therefore in intimate contact with the surrounding ground in the same way as a bored or continuous flight auger (CFA) pile. This minimises the potential for migration pathways to be formed.

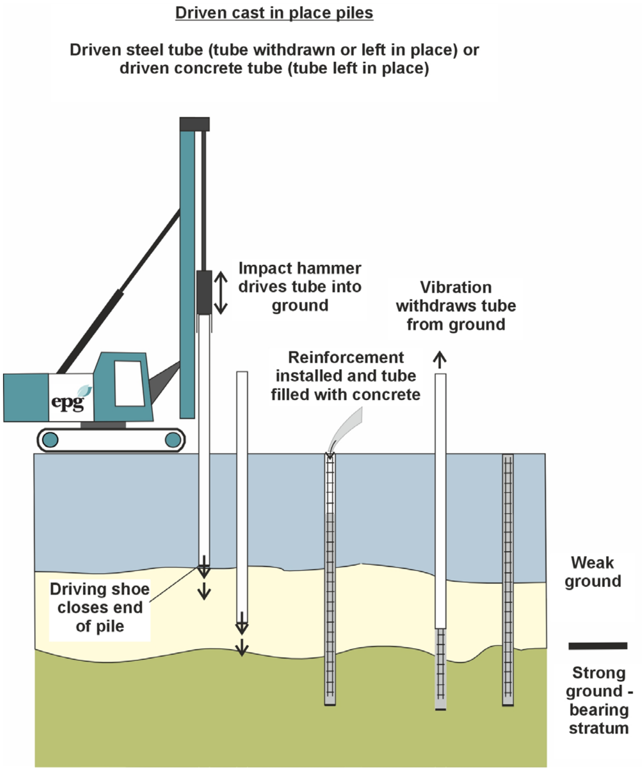


Figure 3.5: Displacement cast-in-place piles

Steel tubes may be closed or open-ended. A closed end eliminates the use of an enlarged base and is normally top driven. The steel tube may be of constant section or taper with depth (CIRIA, 1988).

The base of the pile may be enlarged to provide greater stability at the base of the pile Figure 3.6. If an enlarged base is required the 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 bottom 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 (Fleming *et al.,* 2009). This allows a thinner wall section in the steel tube, because it does not have to resist high driving forces.

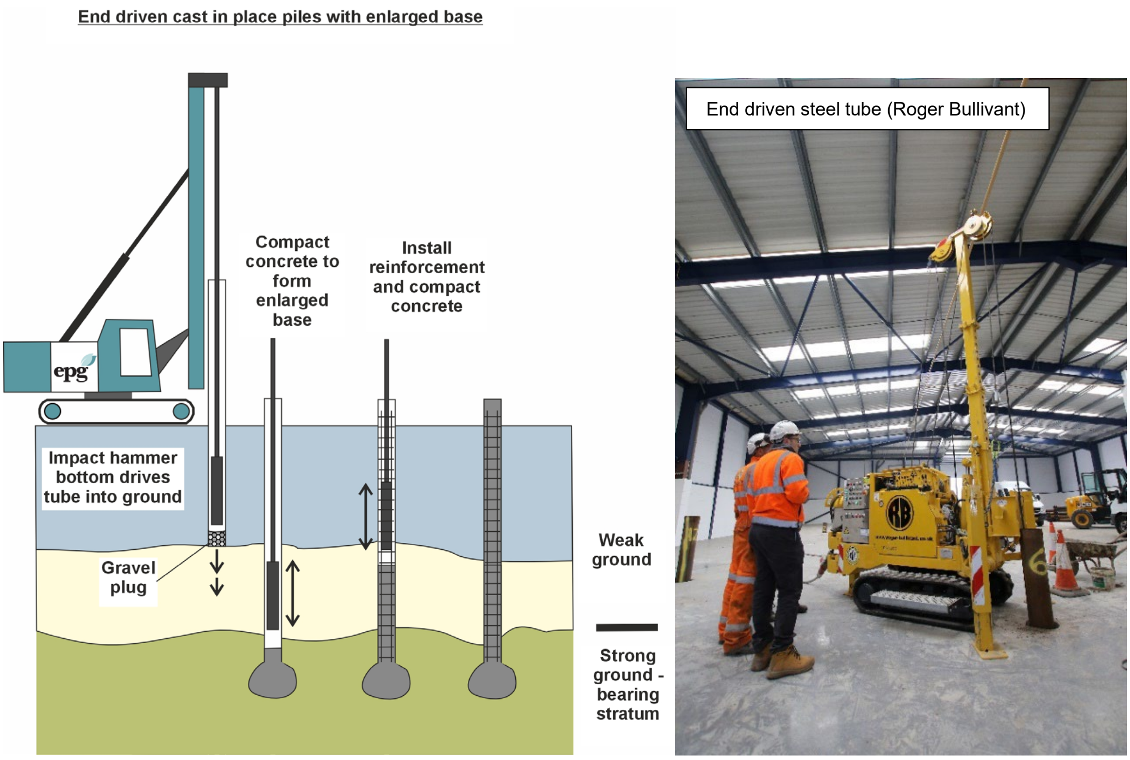


Figure 3.6: Driven cast-in-place pile with enlarged base

The finished pile is a continuous solid concrete column with or without reinforcement. The surface of the pile will vary in roughness depending on the nature of the surrounding material. However, it not likely to form a migration pathway.

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*., 2009). Once the mandrel is removed the remaining void is grouted. This type of pile is not commercially available at the time of writing this report.

3.4.5 Augered displacement piles

Augered displacement piles are full displacement piles formed using an auger that displaces soil as it is pushed/screwed into the ground (Figure 3.7). Several proprietary techniques exist for forming this type of pile, but all involve the use of an auger head, carried on a hollow stem, being screwed into the ground to the required depth. Unlike the CFA, 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, thus minimising the risk of migration pathways.

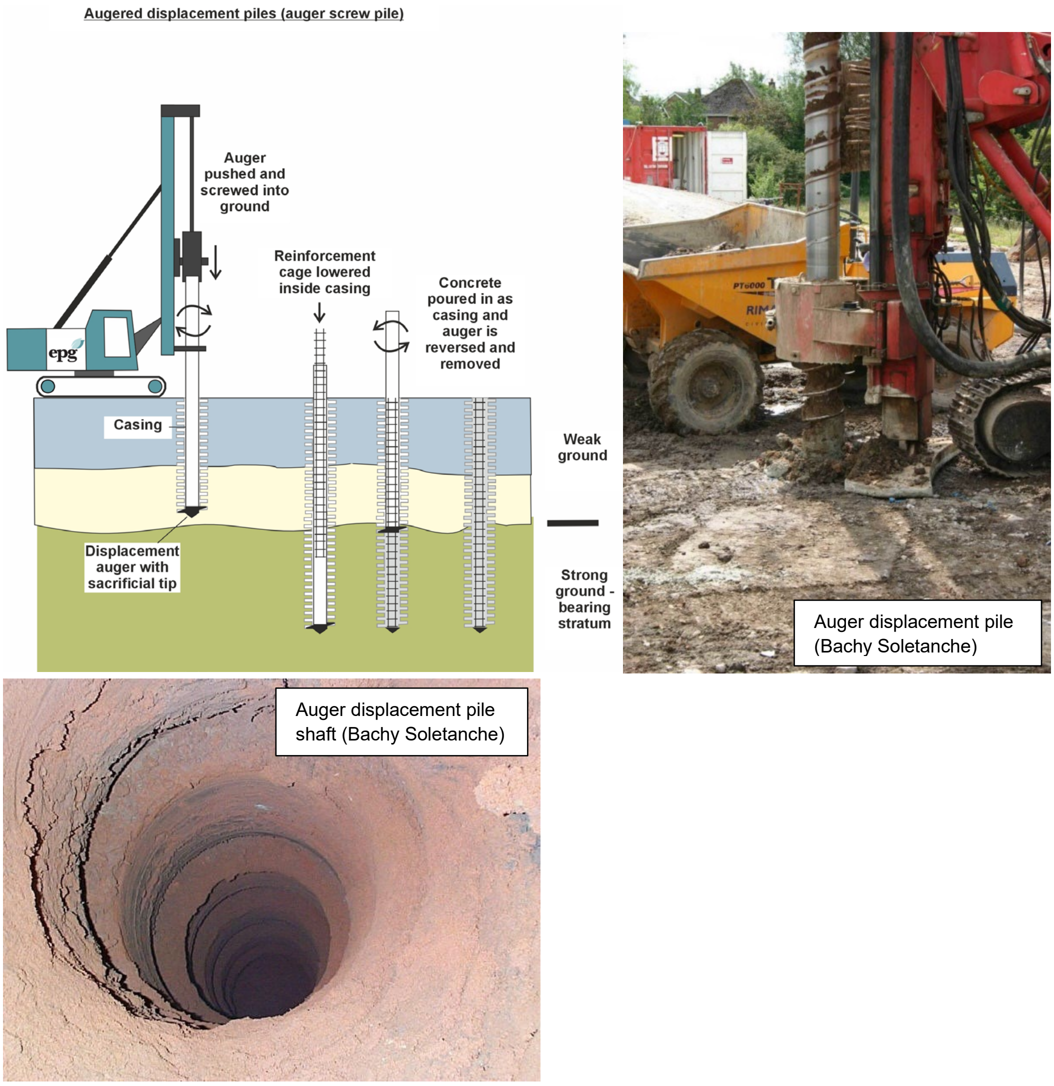


Figure 3.7: Augered displacement piles (auger screw pile)

The use of comprehensive instrumentation in the piling rig is essential for the successful installation of these types of piles. The concrete pumping rate is computer controlled or monitored along with the rate of extraction and auger rotation speed. A further development of this method of installation results in an augered displacement pile with a straight shaft.

3.4.6 Steel screw piles

Steel screw piles are screwed into the ground (Figure 3.8). They come in set lengths and as the pile is wound into the ground, additional sections are added. The soil is displaced and there are no arisings. This type of pile can be used on housing and commercial developments.

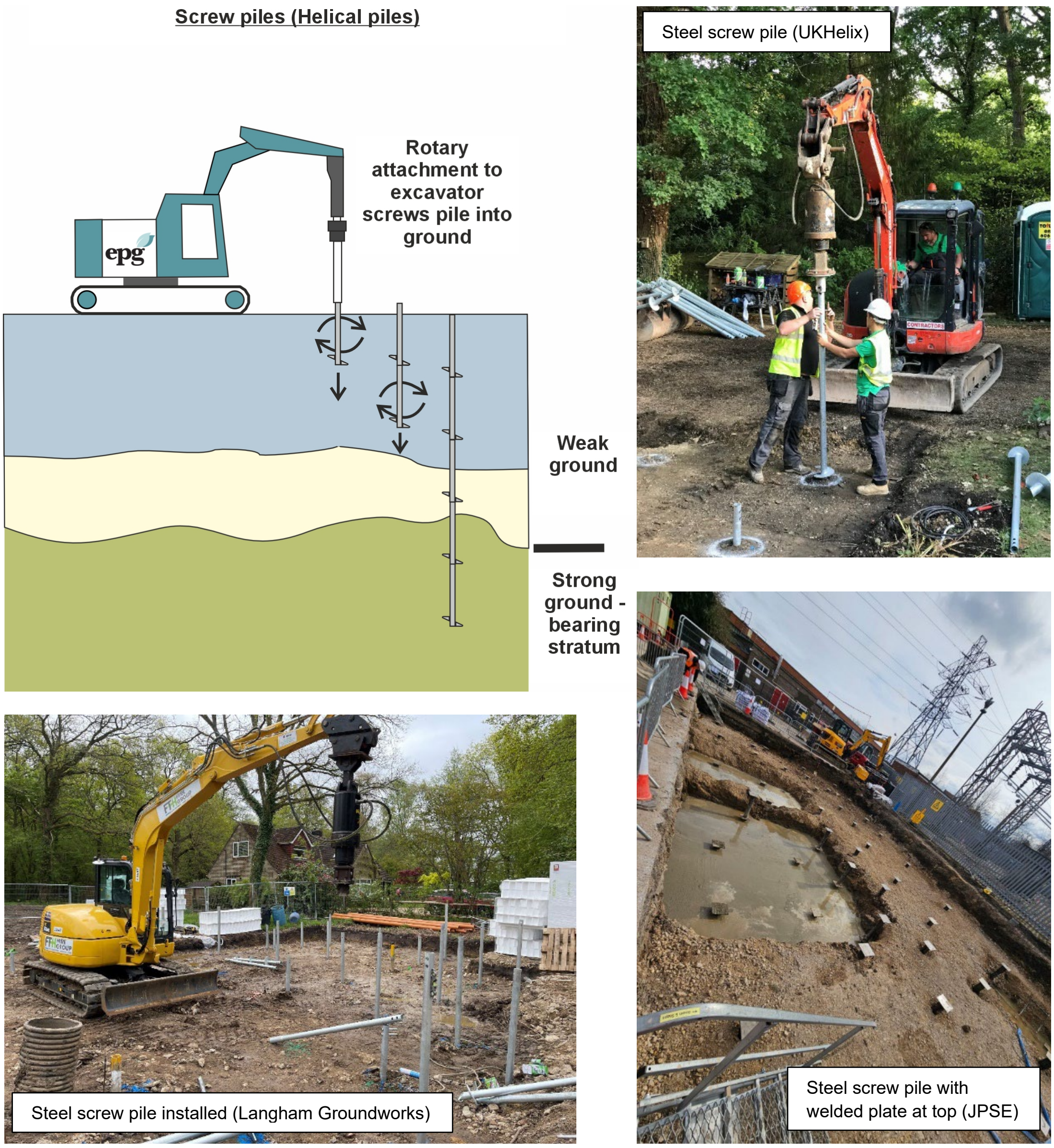


Figure 3.8: Steel screw piles

The steel shaft is hollow but will plug with soil at the bottom when installed. The risk of forming migration pathways or dragging down contamination is minimal. Gas migration up the piles will not occur if the top is sealed with concrete for ground beams or with welded plates (Figure 3.8).

3.4.7 Vibro concrete columns

This technique involves construction of concrete columns using a bottom-feed depth vibrator to transfer loads through weak strata to a firm underlying stratum (Figure 3.9).

Concrete is then pumped via a tremie pipe running through the hollow stem of the poker to the base of the column. The poker is raised and lowered into the concrete, displacing the concrete into a bulb at the base. 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.

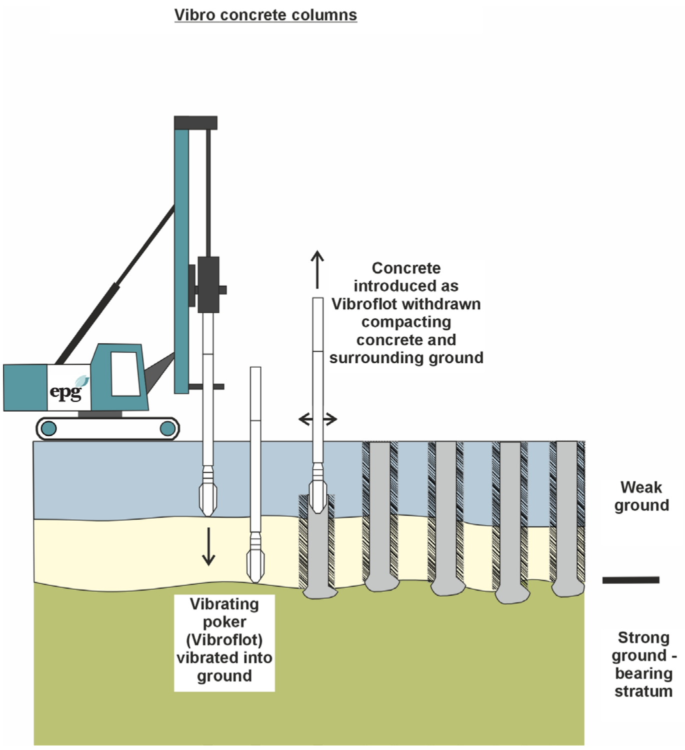


Figure 3.9: Vibro concrete columns

Vibro concrete columns are essentially unreinforced piles designed to transfer loads to depth. They behave differently to rigid inclusions that support load in conjunction with the surrounding ground (see Section 3.9.4). The risk of creating migration pathways is minimal.

3.5 Replacement piling

3.5.1 General characteristics of replacement piling

Replacement piles may be installed by various drilling or augering methods to form a void in the ground that is filled with concrete or grout. Diaphragm wall construction may also have implications for groundwater or ground gas risk and is also included in this section of the report. Diaphragm wall methods may also be used to construct barrette foundations which have been used in the UK for bridge foundations (Nichol and Wilson, 2002). Barrettes are in effect rectangular bored piles and can be constructed in various shapes including rectangular or multiple rectangular panels formed into I, X, T, L or H shapes.

3.5.2 Types of replacement piles

The following types of replacement piles are considered in this report:

- Bored piles
- CFA piles
- Barrettes/diaphragm walls

Replacement piling techniques involve the removal of soil and its subsequent replacement by the pile concrete. 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. It is possible, though undesirable, that granular deposits may be loosened which would increase permeability and the risk of contamination or ground gas migration. This can be avoided by good installation practice.

The concrete that is placed in the pile forms a close contact with the surrounding soil. The irregular interface between the pile and the soil improves load transfer and the difference in skin friction between the two types is small. It will also minimise the risk of contaminant or ground gas migration down or up the pile/soil interface.

Excavated soil is brought to the ground surface in the form of arisings, sometimes mixed with grout, concrete from the pile or support fluid (if used). These arisings need to be reused or disposed of in an appropriate manner if they are not suitable for reuse within the site earthworks. The appropriate waste legislation should be complied with.

Replacement piles are also used to provide retaining wall structures, especially in basement construction.

3.5.3 Bored piles

Bored rotary piling allows the construction of deep small and large diameter piles through almost any ground conditions. The rigs are generally track mounted augers that use various boring tools and equipment (augers and buckets or core barrels) to excavate the pile hole. These piles can be used for bearing and also where contiguous and secant pile retaining walls are proposed.

The auger is screwed into the ground using a telescoping Kelly bar. It is then removed and spun above ground to remove the soil. This process is repeated until the required depth is reached (Figure 3.10). Enlarged bases can be provided in suitable soil conditions by using an under reaming tool. The pile base is normally cleaned of debris using a cleaning bucket before inserting the reinforcement cage and concreting.

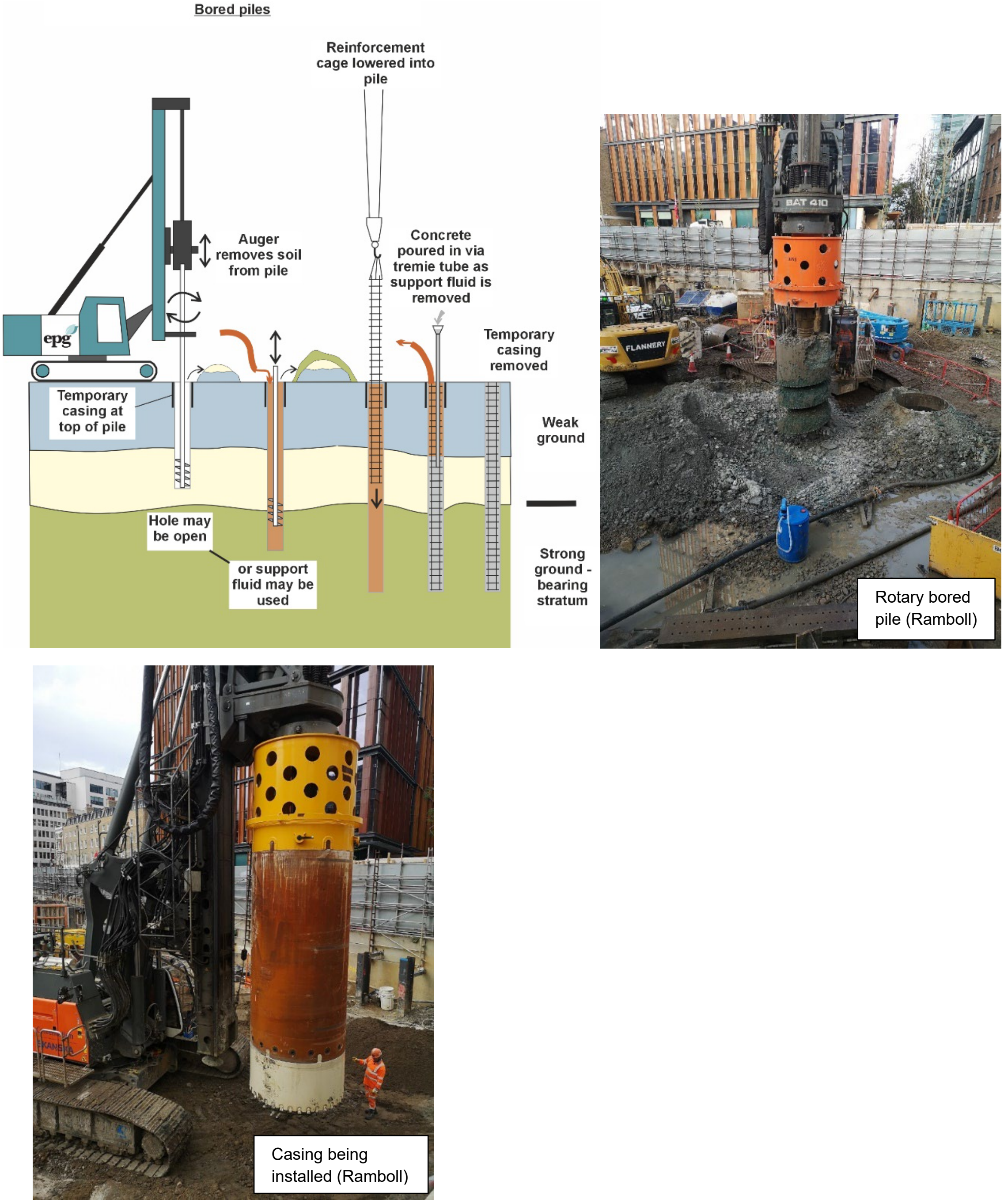


Figure 3.10: Bored piles

It is normal to provide a short length of temporary casing at the top of the pile to support unstable ground or cut off shallow groundwater inflows (Figure 3.10). This is removed by vibration once the pile is concreted. Thin walled casings are prebored and then rotated into a sealing depth. These are normally of limited depth and cannot be installed with oscillators (that rotate the casing backwards and forwards while gripping it and jacking it into the ground). If deeper casings are required for stability (or the installation of secant secondary piles into the primary (soft) piles) heavy segmental casings can be used. These can have cutting heads to core through obstructions or secant pile concrete (secant piles comprise soft piles which are installed first and then the hard piles are installed by cutting slightly into the soft pile concrete). They have additional torque resistance and can be installed using oscillators to reach greater depths. The casings can be removed by oscillating and heavy duty rams. Using casings seals off groundwater or NAPL and reduces the risk of it migrating downwards during construction.

If soils are self supporting, the rest of the pile can simply be drilled without any support. In unstable soils either deeper casing or a support fluid are used to prevent collapse of the pile bore (see Section 3.6 for information on support fluids).

Bored piles range in size from small diameters of less than 600 mm to large diameters of 3.0 m 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 is normally reinforced by the insertion of a prefabricated cage into the hole before placing the concrete.

Sockets into weak rock can be formed either with the auger or using percussion chiselling or rotary drilling bits.

The finished pile is a continuous concrete column with or without reinforcement. The completed pile is in direct contact with the surrounding material and the risk of preferential migration pathways is minimal.

Underpinning or installation of piles below existing buildings that are being refurbished may use small diameter percussion bored piles. These use the same percussive methods as used in site investigation in the UK. In clay soils drilling uses 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 3.11).

A shell is used in granular soils and if drilling below groundwater there is possibility of the loosening of granular soils due to 'piping' as groundwater flows into the hole. In granular soils below groundwater level the casing is driven into the ground in advance of the shelling and a positive water head is maintained inside the casing to prevent piping and minimise loosening of the surrounding soil. Care is needed to avoid disturbing soils and creating pathways.

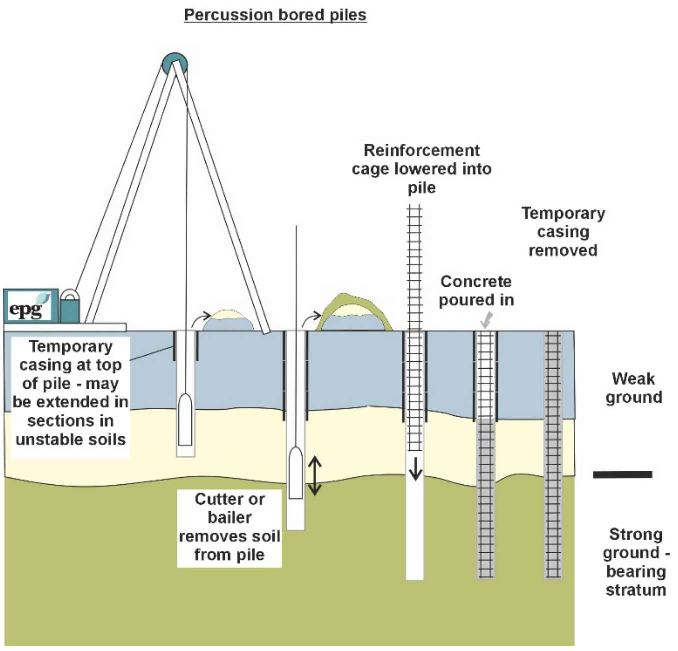


Figure 3.11: Small diameter percussion bored piles

A variation of bored piles is the drilled in tubular pile, where a permanent casing is rotated into the ground and the soil is removed from inside it as it penetrates deeper into the ground. There is minimal, if any displacement of the surrounding ground because the soil is removed as the tube is progressively inserted in to the ground. The tube may be left open or infilled with concrete. There may be an annulus between the casing and the ground, particularly where installed to weak rock. This may be grouted up, but if not it can potentially form a preferential pathway for contamination or gas migration.

Another variation of bored piling is the overburden drilling excentric Overburden Drilling Excentric (ODEX) system. A rotary percussive drill bit (also referred to as a down the hole hammer) on the end of a drill string is lowered inside a steel casing. The drill bit advances in front of the casing and wings open out to drill a hole that is slightly larger than the casing diameter. A shoulder on the drill bit impacts against a ledge inside the casing and drives it down. Arisings are removed by air flush. Once the required depth is reached the wings on the bit are retracted so it can be removed. Concrete is then placed and the steel casing can remain in place or be removed. If the casing is left in place it can be grouted in (which minimises the risk of a pathway for gas or pollution migration). ODEX drilling is used where obstructions are expected and need to be drilled through (e.g. boulders etc) and/or where the piles are required to be drilled through dense strata or to form rock sockets.

3.5.4 Continuous flight auger piles

This method uses a hollow stemmed CFA 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 pile shaft during drilling (Figure 3.12).

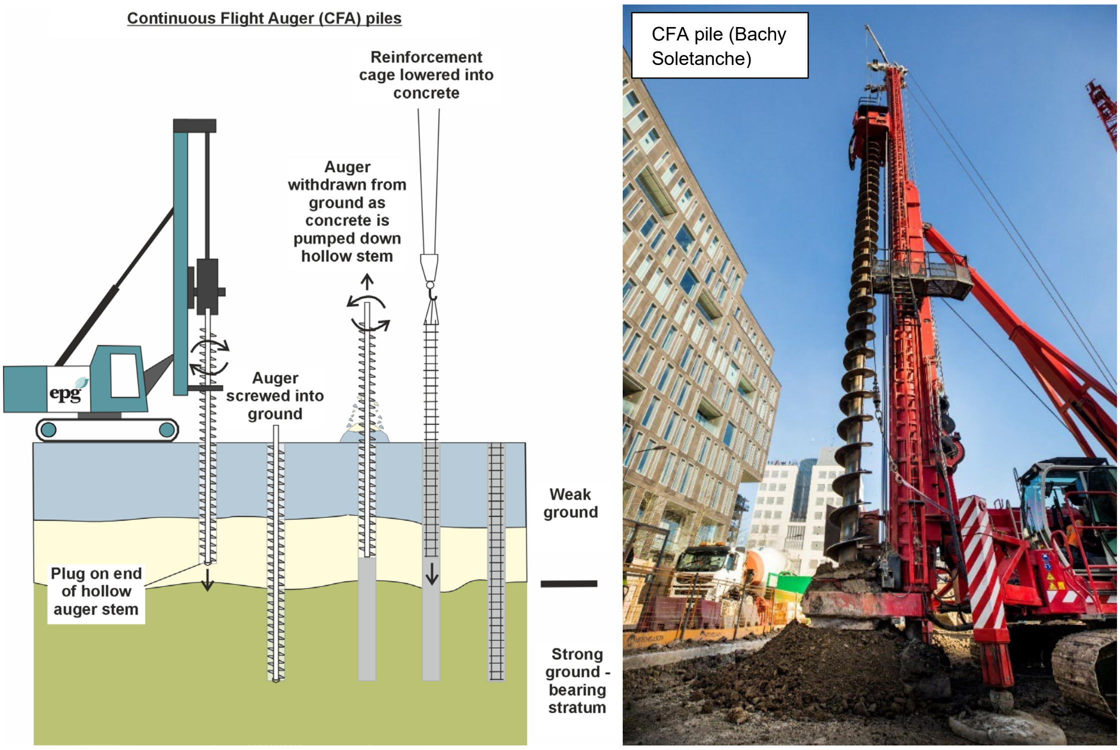


Figure 3.12: CFA Piles

On achieving the required depth, cementitious grout or 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.

Once the auger is fully withdrawn, the positive hydrostatic pressure from the concrete 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, a reinforcing cage can, if required, be introduced into the concrete in the pile, assisted by vibration.

CFA piles can also be cased during construction. This uses a specialist rig with double rotary drive units for the auger and casing. These rotate in opposite directions, simultaneously drilling the auger and casing into the ground.

3.5.5 Barrette foundations and diaphragm walls

Barrette foundations and diaphragm walls are essentially rectangular bored piles. Excavation in soil normally uses a grabbing method, and in rock rotating cutters are used (known as hydromills). A starter trench is excavated to 1 to 2 m depth and in this a concrete guide wall is constructed at the top of the barrette or diaphragm wall. Stability is normally maintained by using a support fluid. Once at the required depth a reinforcement cage is installed and the support fluid is removed as the concrete is introduced to the bottom of the foundation by a tremie pipe. The process is shown in Figure 3.13.

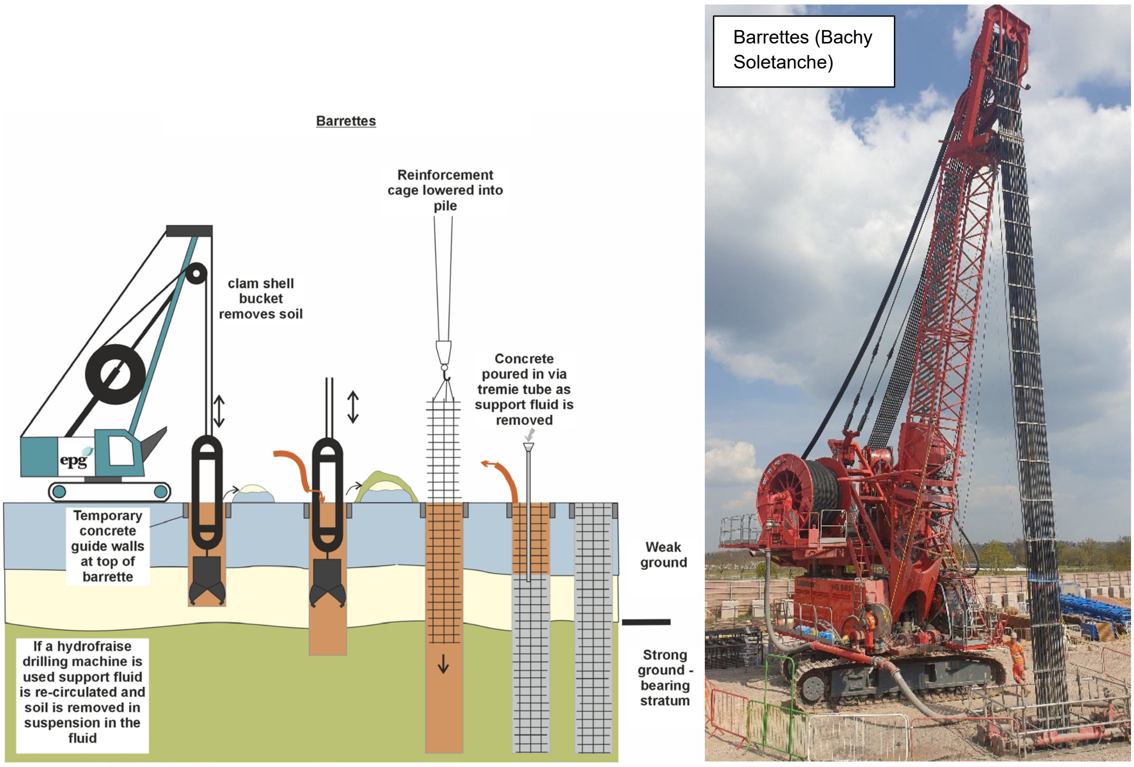


Figure 3.13: Barrette foundation

3.5.6 Minipiles and micropiles

Minipiles are small diameter bored cast-in-place piles (Figure 3.14). They are constructed using high-strength, small-diameter steel casing and/or threaded bars. The casing is advanced to the design depth using a rotary drilling technique. Reinforcing steel (typically an all threaded bar) is inserted into the minipile casing and high-strength cement grout pumped in around it. The casing may extend to the full depth or end above the bond zone (where friction is required between the grout/bar and the surrounding ground) with the reinforcing bar extending to the full depth. They generally have a diameter between 200 mm to 600 mm.

Different types of drilling may be used to install the pile including CFA, rotary bored or cable percussion. The same issues discussed for those techniques also apply to the minipiles.

Some common uses include underpinning foundations, enhancing the mass stability of the ground or as bearing piles in limited access locations. They have also been used to construct secant and contiguous pile retaining walls.

Micropiles are basically smaller diameter than minipiles. They are installed in the same manner but with smaller equipment. The diameter is normally between 65 mm and 300 mm and they are commonly used for extensions or small building projects. Micropiles may also be installed using rotary drilling methods that use a flushing fluid.

The installation process should be in accordance with the requirements of *BS EN 14199: 2015 Execution of Special Geotechnical Works – Micropiles* (BSI, 2015d).

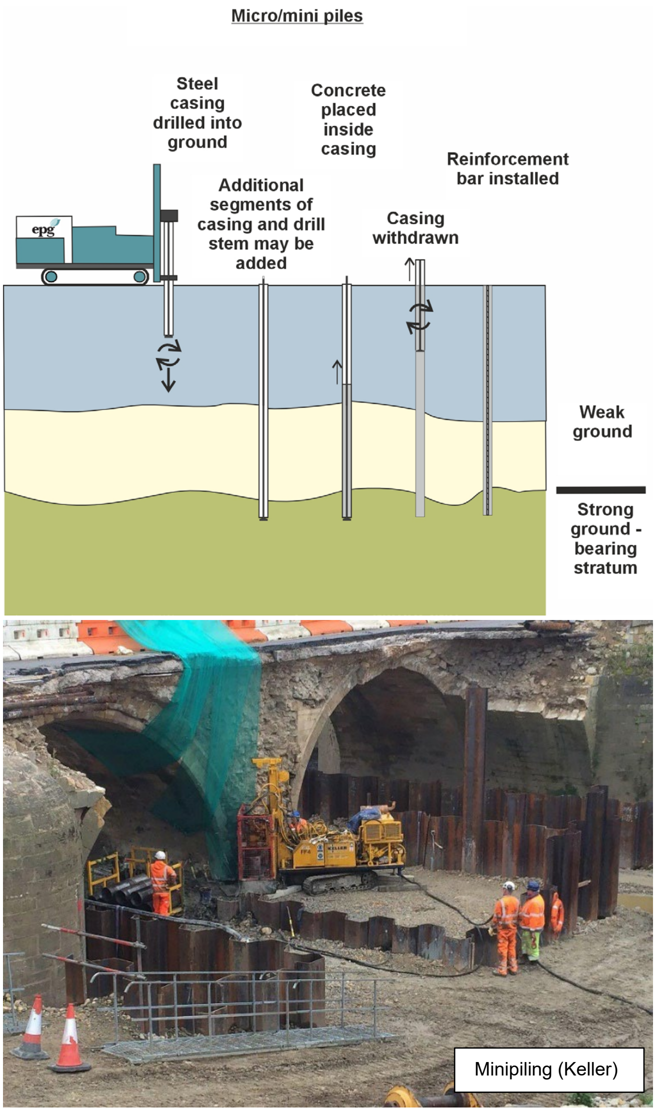


Figure 3.14: Minipiles drilled in steel casing method

3.6 Piling and diaphragm wall support fluids and water balance

Bored piles, diaphragm walls and barrette foundations may use support fluids where they are constructed through unstable ground. Another approach to limiting water inflow and maintaining stability is to use water balance.

3.7 Support fluids

Support fluid is a generic term used for materials that are manufactured and mixed with water to produce a compound that will support the sides of open and deep excavations for filling with tremie concrete (European Federation of Foundation Contractors/Deep Foundations Institute, 2019). Support fluids are sometimes referred to as muds or slurries.

The purpose of a support fluid is to maintain stability of the excavation throughout the excavation process and until the support fluid has been replaced by concrete. For some types of excavating equipment such as a hydromill (used to construct diaphragm walls or barrettes) the fluid has an additional role to carry the cuttings from the hydromill head, out of the excavation (where they are separated from the fluid).

The additives used in support fluids are there to help contain the fluids within the hole and minimise fluid loss through seepage out through the face of the excavation, thereby allowing the positive head pressure to be maintained inside the pile bore. This aim is also consistent with minimising the risk of pollution of groundwater by the fluids.

Support fluids can be made using bentonite, polymers or a combination of both. The effects of support fluids that may potentially be used is an important part of any FWRA and the potential for adverse effects on groundwater must be considered. In order to provide a robust assessment of the risk of pollution from support fluids, appropriate site investigation data should be collected. This will include the permeability and jointing/fissuring of the ground, groundwater levels and groundwater chemistry (see Section A1.6).

Commercial bentonite is a natural material comprising predominantly the mineral montmorillonite[3]. Bentonite fluids are denser than water and by maintaining the head of the fluid slightly above the groundwater level in the surrounding ground (typically 2 m to 3 m) water flow into the pile bore is prevented. A small amount of bentonite is added to water (typically 2% to 6%) and this increases the viscosity and density of the fluid. In permeable soils there is an initial flow of bentonite fluid into the surrounding ground for a very short distance and this results in the soil pores becoming clogged with a filter cake (Figure 3.15). This reduces the permeability of the excavation walls and prevents excess hydrostatic pressure and inflow affecting the excavation. The filter cake thickness is only a few millimetres. Filter cake formation can be expected to be effective in sealing fine to medium grained soils with relatively little penetration of bulk fluid into the soil.

[3] Montmorillonite is a specific type of clay mineral that is found within bentonite.

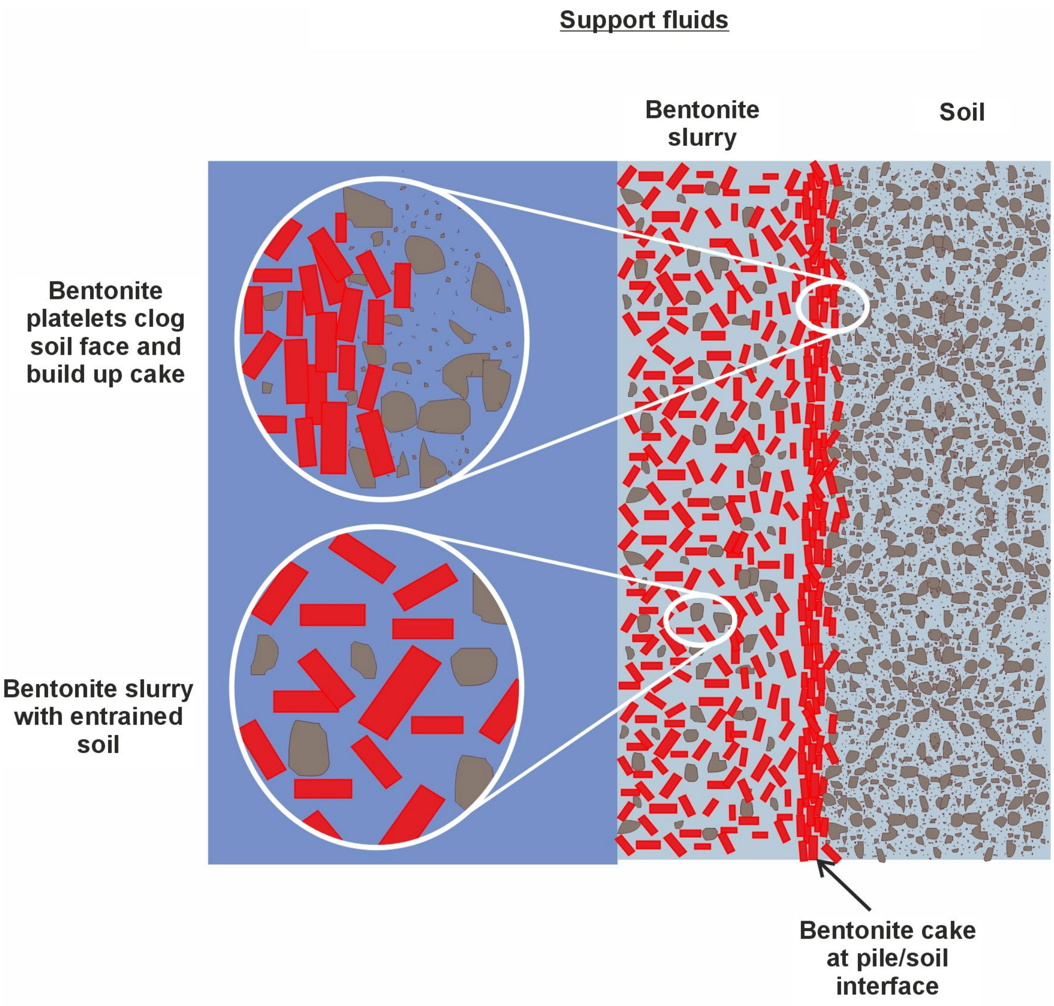


Figure 3.15: Bentonite filter cake (used with permission from the European Federation of Foundation Contractors/Deep Foundations Institute (2019)).

In more open soils such as coarse sands, gravels or fissured rock, the support fluid penetrates into the ground until clogging of the soil with solids in the support fluid (bentonite and excavated soil suspended in the fluid) and gelling of the support fluid prevent further movement. A filter cake then forms on the clogged soil to provide an interface between the fluid in the excavation and the surrounding soil. Sand may be added to the support fluid to promote clogging by deep filtration. Even in this case, in the absence of open voids or fractured rock, the penetration distance into the soil is small.

In addition to the filter cake formation, rheological blocking provides another mechanism to restrict fluid loss in more open soils and in rock with fissures, for example, in Chalk. Rheological blocking is a process whereby the support fluid continues to penetrate until its gel strength acting over the fluid wetted soil can restrain the differential pressure between support fluid and the external groundwater. In open soils or fissures, penetration distances can be substantial unless, as usually happens, sealing is helped by mechanical blocking by solids in the support fluid. With rheological blocking, the support pressure initially acts some distance into the soil, until over time a filter cake develops at the excavation face formed by the penetrated fluid. In heavily fractured rock, pregrouting may be necessary to prevent or minimise loss of support fluid and may be used as a precautionary measure to minimise risk to groundwater (recognising that risk from grouting also needs to be considered). Pregrouting was used to prevent support fluid loss from barrette foundations for a cable styed bridge across the River Dee in north Wales.

High molecular weight synthetic polymers are long chain-like hydrocarbon molecules, which interact with each other, with the soil and with the water to effectively increase the viscosity of the fluid. The polymer fluid is a slippery, slimy viscous liquid. Natural modified polymers such as modified celluloses (e.g. polyanionic cellulose (PAC)) have been successfully used in the reverse circulation process (e.g. hydromill), especially where challenging chemically aggressive ground conditions are encountered. In such systems, PAC is less sensitive to soil and water chemistry, and the resulting soil/polymer system allows a thin controlled filter cake to be formed which participates in the stabilisation process.

Polymer fluids provide support by helping maintain a pressure balance, restricting flow into the surrounding ground because of the high viscosity, forming a low permeability membrane at the face of the excavation and by pore blocking.

Further detailed information on support fluids is provided by the European Federation of Foundation Contractors/Deep Foundations Institute (2019).

The use of support fluid requires careful consideration of the environment in which it will be applied and should be a consideration in the FWRA at an early stage in the project. If support fluids are necessary, the site investigation should be designed to collect relevant information to select the most appropriate support fluid for the site-specific circumstances.

Support fluids can be adversely affected by chemicals in the ground or groundwater but in practice the effects are often not significant provided reasonable precautions and working practices are adopted. Compounds that can affect support fluids include:

- Cement from concreting or pregrouting of open formations;
- Sea water where effects of ionic strength and calcium and magnesium may be an issue;
- Gypsum and evaporites;
- VOCs, hydrocarbons and solvents;
- Heavy metals; and
- Acid or alkaline solutions.

Chemical adjusters may be added to the fluids to minimise the effects of contaminants in the ground. These include alkali hydroxides, sodium carbonate and sodium bicarbonate (European Federation of Foundation Contractors/Deep Foundations Institute, 2019).

The primary consideration when considering the risk to groundwater is to minimise loss of support fluids into the formation. Support fluids can contain additives that are classed as hazardous substances and non-hazardous pollutants. There is an obligation in the

Environmental Permitting Regulations to prevent the input of any hazardous substance to groundwater and limit the input of non-hazardous pollutants to groundwater so they do not cause pollution. One of the environmental objectives for groundwater bodies in the Water Framework Directive is also to prevent or limit the input of pollutants into groundwater.

Where there is the potential for inputs of pollutants in groundwater from the use of support fluids and additives in the support fluids, their use in piling construction works may need to be regulated through a groundwater permit or authorisation from the regulator. Each type of polymer has distinct chemical properties and specific compounds in a support fluid should be assessed and discussed with the regulator.

In some cases when using support fluids of some types in highly sensitive settings, it may be necessary to implement a programme of groundwater monitoring to demonstrate that there is no significant impact (for non-hazardous pollutants) or discernible release (hazardous substances).

Fluids should also be prevented from contaminating surface waters and be disposed of in accordance with waste management legislation once no longer required.

There may be environmental advantages to using polymer support fluids rather than bentonite. Fluids can be designed to be bio-stable and environmentally benign (Jefferis and Lam, 2013). They are preferred for projects near watercourses because they can be specified so as to not pose a danger to fish and, if they do inadvertently enter a watercourse, they do not build up on fish gills causing them to suffocate.

3.8 Water balance

Water balancing involves topping up the water level in a pile bore to maintain it at or slightly above the groundwater level in the surrounding ground. This stops groundwater inflow into the pile and any associated instability in the pile walls due to wash out of silt/sand from the ground.

The water used is either from the mains supply or extracted locally from groundwater, surface water, lagoons or ponds (subject to appropriate permits). The use of mains water should be the last resort on sustainability grounds, especially if it has to be delivered to site by tanker. The water should be of a quality that matches or is better than that of the groundwater in terms of pH and chemical composition. Regular testing should be undertaken on the water that is being added to confirm it is of acceptable quality.

The water in the pile will become contaminated with soil particles as the pile bore is progressed. If there is contamination in the surrounding groundwater this could also mix at the pile perimeter, although the risk of this should be low as the purpose of water balancing is to stop inflow and there should not be any net flow across the pile/ground interface in either direction. Water will also become contaminated as is displaced during concreting. Water should wherever possible be pumped to a holding tank, cleaned and recycled for adding back into the pile.

When water is no longer required it will need to be cleaned and put back in the ground or disposed of appropriately, depending on the results of chemical testing (subject to obtaining all necessary permits).

Although there should not be any net flow of water in or out of the pile, contractors will need to demonstrate to the regulator the method is suitable for a particular site and that:

- Water is injected back into the same stratum of water it was abstracted from and is at natural background quality and unaltered;
- It will not result in the mobilisation of existing pollution within groundwater; and
- It will not result in the release to ground of hazardous substances above discernible levels or non-hazardous pollutants at a concentration that may cause pollution.

3.9 Penetrative ground improvement methods

This report only considers penetrative methods of ground improvement. It does not consider shallow compaction, rapid impact compaction or deep dynamic compaction. There are three main types of penetrative ground improvement:

- Vibro compaction – compacts and densifies the ground;
- Vibro replacement – compacts and densifies the ground and introduces inclusions into the ground; and
- Soil mixing – soil is mixed with binder to provide a stronger and stiffer material in columns or as a mass.

Prefabricated vertical drains (also known as band or wick drains) are used to increase the rate of consolidation, typically with surcharge loads and rigid inclusions.

The methods are summarised in Figure 3.16.

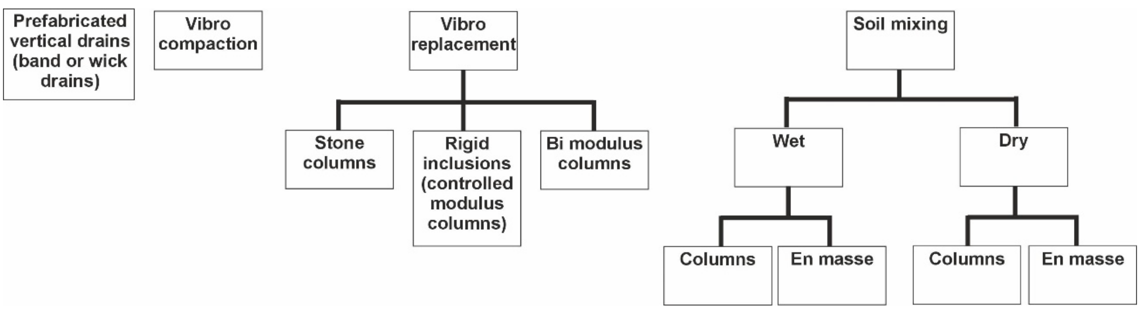


Figure 3.16: Penetrative ground improvement methods

Vibro concrete columns are a hybrid solution that are essentially a displacement pile foundation installed using vibro ground improvement equipment.

The are various British Standards that provide guidance on ground improvement methods:

- *BS EN 14679: 2005 Execution of Special Geotechnical Works – Deep mixing* (BSI, 2005a);
- *BS EN 14731: 2005 Execution of Special Geotechnical Works – Ground treatment by deep vibration* (BSI, 2005b); and
- *BS EN 15237: 2007 Execution of Special Geotechnical Works – Vertical drainage* (BSI, 2007b).

3.9.1 General characteristics of ground improvement methods

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 full or partial penetration of soil to be improved by a vibrating poker, by contrast with shallow compaction 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 or concrete which improves the overall stiffness of the ground. The existing soil can also be mixed with cementitious or pozzolanic materials to improve the strength of the soil in columns. This is undertaken using augers and the commonly used binders are cement, lime, ground granulated blast-furnace slag (GGBS) or pulverised fuel ash (PFA).

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.

Penetrative vibro ground improvement is carried out by the insertion of a vibrating sonde or poker, 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 widely used in the UK because subsoil conditions are not normally suitable.

The vibro compaction method has been amended to involve the filling of the hole created by the poker with stone or concrete. This approach is referred to as vibro replacement and it is suitable for a wider range of soils than vibro compaction.

Prefabricated vertical drains increase the rate of consolidation of compressible soils and are normally used in conjunction with rigid inclusions or surcharge loading.

One important aspect of all types of ground improvement is that the methods are normally used to improve weaker near surface deposits and do not extend into the underlying stronger strata. Therefore there is generally no requirement to penetrate aquicludes above deep aquifers.

3.9.2 Vibro compaction

Vibro compaction is executed using a vibrating probe supported by a crane, drill rig, or excavator (Figure 3.17). The vibratory probe is advanced to the target depth under its own weight with the assistance of vibration, and in some cases, water jetting and/or pull down of the supporting base machine.

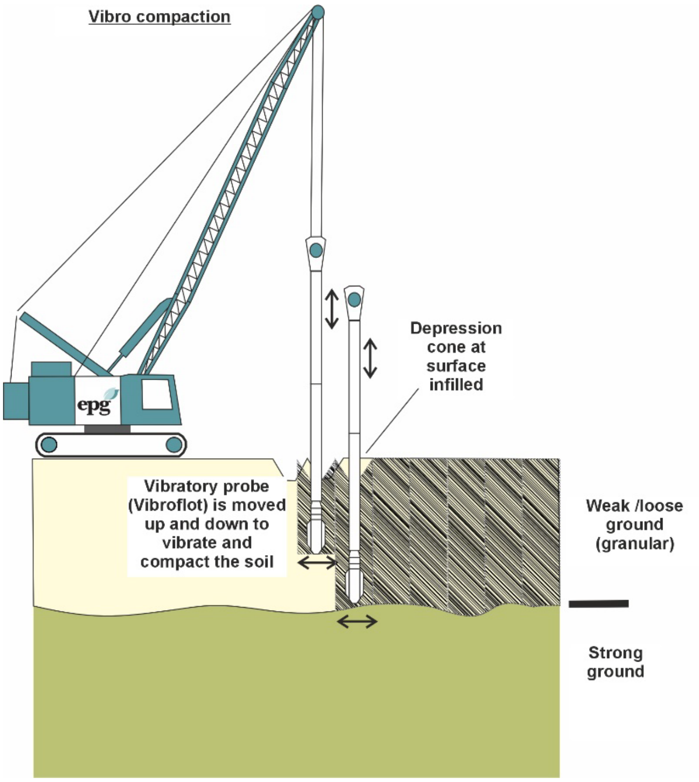
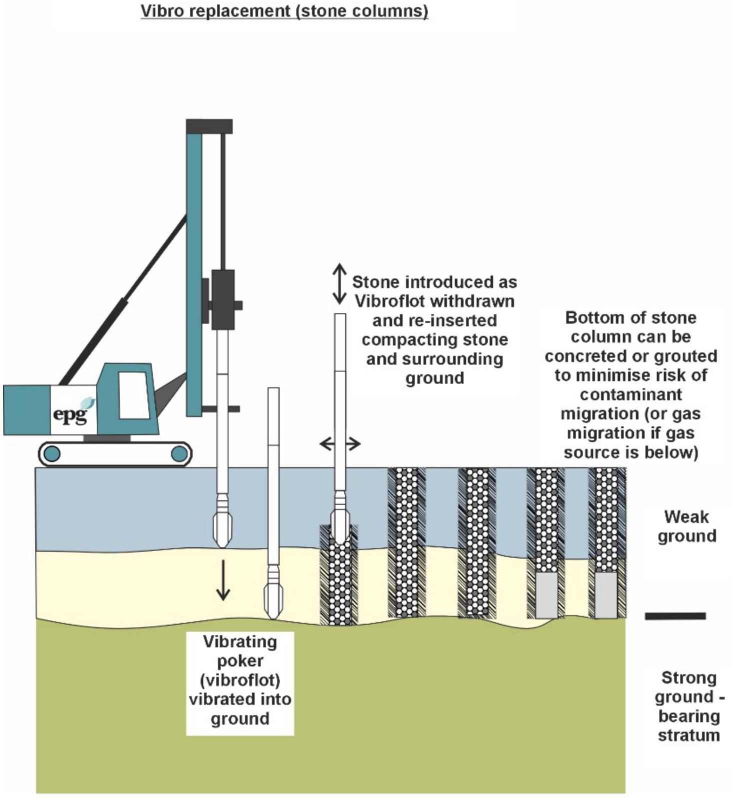


Figure 3.17: Vibro compaction

3.9.3 Vibro replacement stone columns

This technique involves the improvement of weak soils by the installation of densely compacted columns made from gravel or similar material with a vibrator (Figure 3.18).



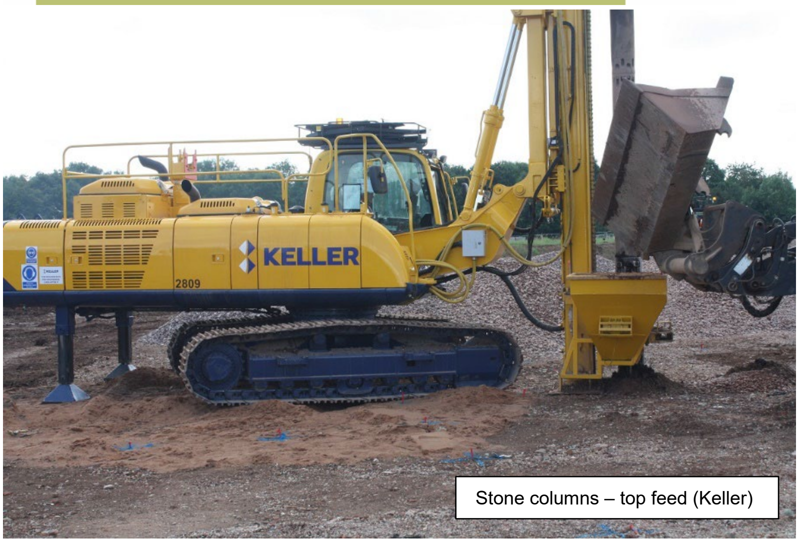


Figure 3.18: Vibro replacement stone columns

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 coarse and comparatively uniform grading. The surrounding soil will mix with the stone around the perimeter and the key factor whether these pose a risk of gas or contaminant migration is the spacing and the permeability of the surrounding ground.

Two main methods are used to construct stone columns. 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.

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.

When aquifers underlay made ground, a stone column is sometimes perceived as a potential pathway for contamination. In reality, vibro treatment reduces the mass permeability and so this is rarely an issue. However, in some cases it is necessary to seal the base of the columns. This is where a basal grout or concrete plug can minimise the risk. Typically a minimum 1 m thick lean mix concrete or grout plug is installed at the base with a modified bottom feed vibro rig. This technique prevents contact of the stone part of the column with any permeable stratum below.

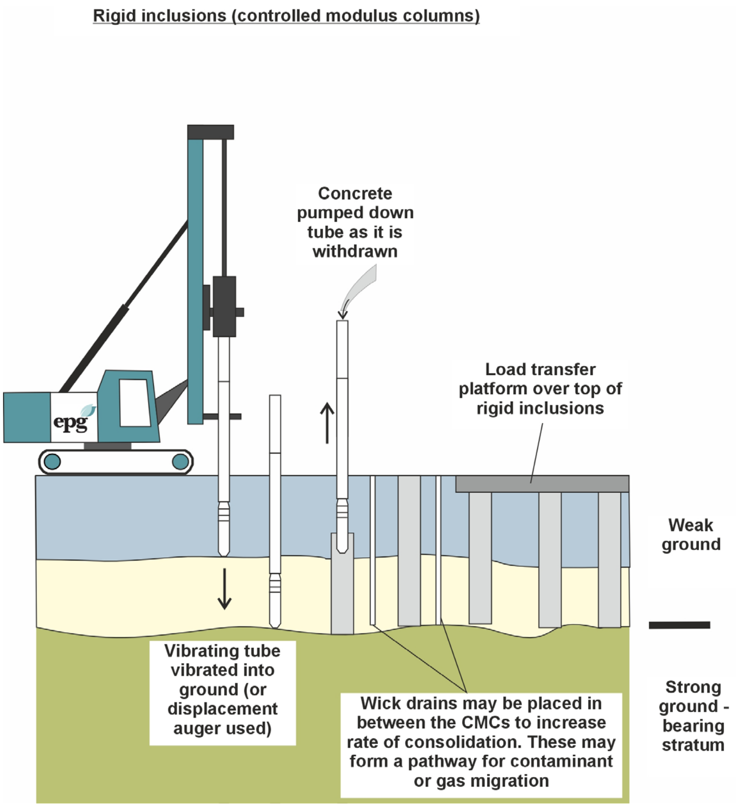
There may be an issue with preferential pathways in shallow layered alluvial soils if shallow contamination is isolated from deeper alluvial gravel by thin layers of clay.

Stone columns are also perceived to be preferential pathways for gas migration but this might not always have significant effect on the level of risk (see Section A1.4).

3.9.4 Rigid inclusions (controlled modulus columns)

Rigid inclusions are different to vibro concrete columns or piles. They are installed on a regular grid and do not transfer load to a deeper stratum but work in conjunction with the surrounding ground to reduce settlement and increase bearing capacity. A load transfer platform is then constructed over the top of the inclusions. This allows the use of spread foundations or ground bearing floor slabs. As with vibro replacement stone columns, a hollow stemmed poker penetrates the soil until the required depth is reached (Figure 3.19). Alternatively a displacement auger may be used.

The poker is then withdrawn at a set rate whilst concrete is pumped into the hole at a positive pressure.



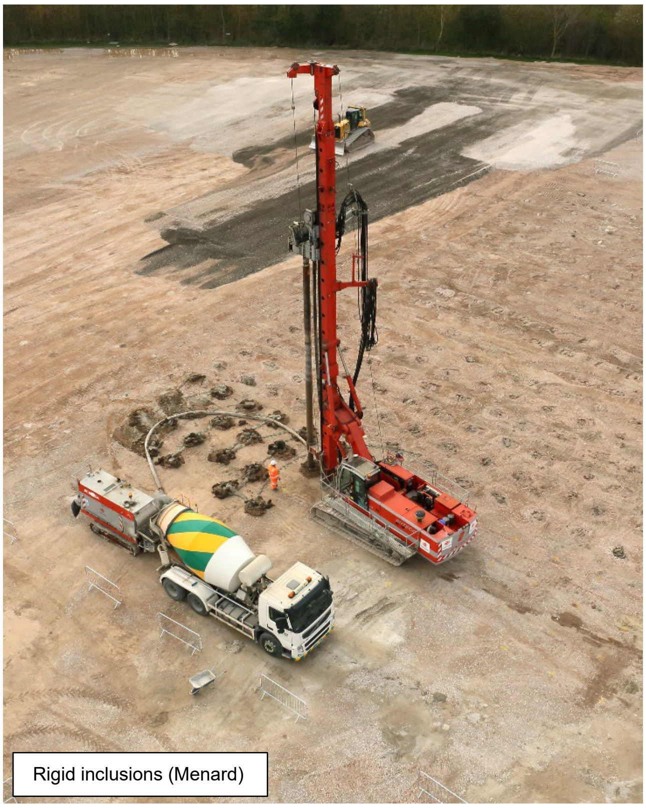

Rigid inclusions (Menard)

Figure 3.19: Rigid inclusions (controlled modulus columns - CMCs)

The low permeability of the concrete combined with the bulb end of the column and the tight interlock of concrete to soil minimises the potential for vertical migration of contamination to underlying aquifers, or upward migration of soil gas.

Prefabricated vertical drains (also known as band drains or wick drains) are sometimes installed in between the columns to allow consolidation of the ground to occur more quickly. These are typically a plastic core with a 3D profile providing a drainage channel that is wrapped in a filter geotextile. They are highly permeable and therefore can potentially create a pathway for gas flow upwards and contamination flow downwards. Contaminated pore water will also flow upwards during consolidation and should be collected and disposed of appropriately.

The drain is fed down through a hollow mandrel mounted on an excavator or crane mast, connected to an expendable anchor plate at the bottom. A vibratory hammer or static method inserts the mandrel to design depth. It is then removed, leaving the wick drain in place.

Bi modulus columns are a hybrid system that uses rigid inclusions for the lower part and a stone column for the upper part.

3.9.5 Soil mixing

Soil mixing uses modified augers to mix the soil with cementitious or pozzolanic binders (Figure 3.20) that increase the strength of the soil (a similar or in some cases the same process used for *in situ* soil stabilisation to reduce contaminant mobility). It can form columns of strengthened soil or can be undertaken to treat a mass of soil. Mixing can be either dry (using dry materials) or wet (using slurry).

Dry soil mixing improves soft, high moisture clays, peats, and other weak soils, by mechanically mixing them with dry binder. Wet soil mixing, also known as the deep mixing method, improves the characteristics of weak soils by mechanically mixing them with binder slurry.

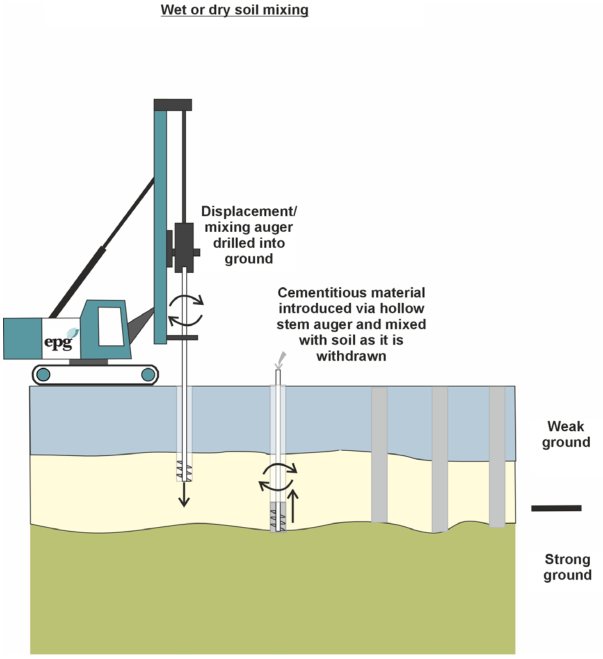


Figure 3.20: Soil mixing

3.10 Prefabricated vertical drains

Prefabricated vertical drains are also known as band drains or wick drains. They are plastic strips that have a 3D structure and are wrapped in geotextile. The geotextile allows water to flow into the drain but prevents soil particles entering. There have a high water transmission rate and act as a drainage path for pore water that is squeezed out of soft compressible soils as they consolidate. The drainage path through the soil is horizontal and shorter than the vertical path to the surface (it may also have a higher permeability because of anisotropy in the soil). This provides a short cut and allows the soil to consolidate faster than it would without the drains. The earliest vertical drains were actually sand filled auger holes and it is a well proven method to accelerate consolidation, but sand drains have largely been superseded by prefabricated vertical drains.

They are used below embankments or where temporary surcharge is placed to compress soils. They are also used in between rigid inclusions (see Section 3.9.4). If used below embankments or surcharge, a drainage layer is required at the bottom of the placed fill materials to allow water coming up the drains to drain away. If they extend to a permeable stratum below the compressible soil, water will also flow downwards. However, they do not have to extend to the full depth of the compressible stratum and sometimes this may not be desirable because it creates a pathway for gas or contaminated groundwater.

They are typically installed on a closely spaced square or triangular grid.

Prefabricated vertical drains are typically 100 mm wide and 3 mm to 6 mm thick. They are installed using a hollow mandrel mounted on a crane or excavator (Figure 3.21). The drain is fed inside the mandrel which is vibrated or pushed into the ground taking the drain with it (the drain is anchored to a plate at the bottom). The mandrel is then removed leaving the drain in place. If required, a drainage layer is placed over the vertical drains.

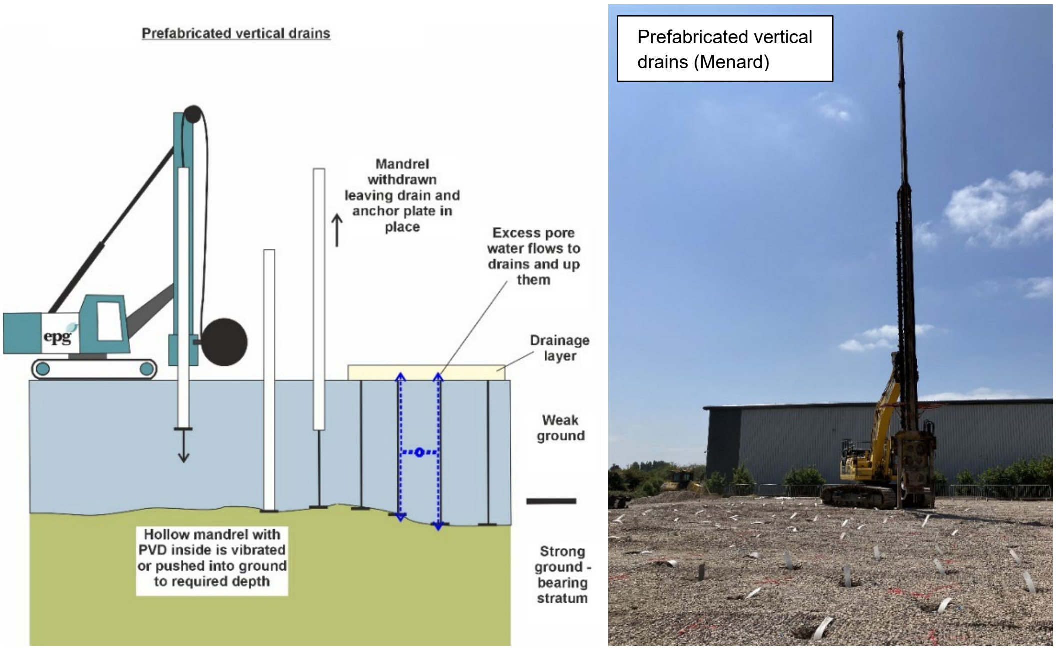


Figure 3.21: Prefabricated vertical drains (PVD)

3.11 Sheet piles

Sheet piles are a displacement method used to construct temporary or permanent retaining walls. When used as a temporary wall, once the structure or excavation is complete and the sheet piles are no longer required, they are removed. Steel and plastic sheet piles are small displacement and concrete and timber are larger displacement.

Sheet piles have also been used as in ground barriers to reduce or prevent contaminated groundwater or ground/landfill gas flow. In these cases the clutches (the joints between piles) need to be adequately sealed. They are also used as permanent basement walls and in this application, the clutches are sealed or welded to provide basement waterproofing. Unsealed clutches will not provide a fully watertight seal, and even when welded or if sealants are used, very careful installation is required to achieve watertightness.

BS EN 12063: 2022 Execution of Special Geotechnical Works – Sheet pile walls, combined pile walls, high modulus walls provides guidance on installation (BSI, 2022).

3.11.1 General characteristics of sheet piles

Sheet piles will normally extend below the base of an excavation that they are supporting. The piles are installed into the ground and then the soil inside the sheet pile box is removed (Figure 3.22). They may also be installed along rivers, docks, quays, etc to provide support. In this application the pile will extend below the bed of the water feature but there may not be any further excavation on the water side.

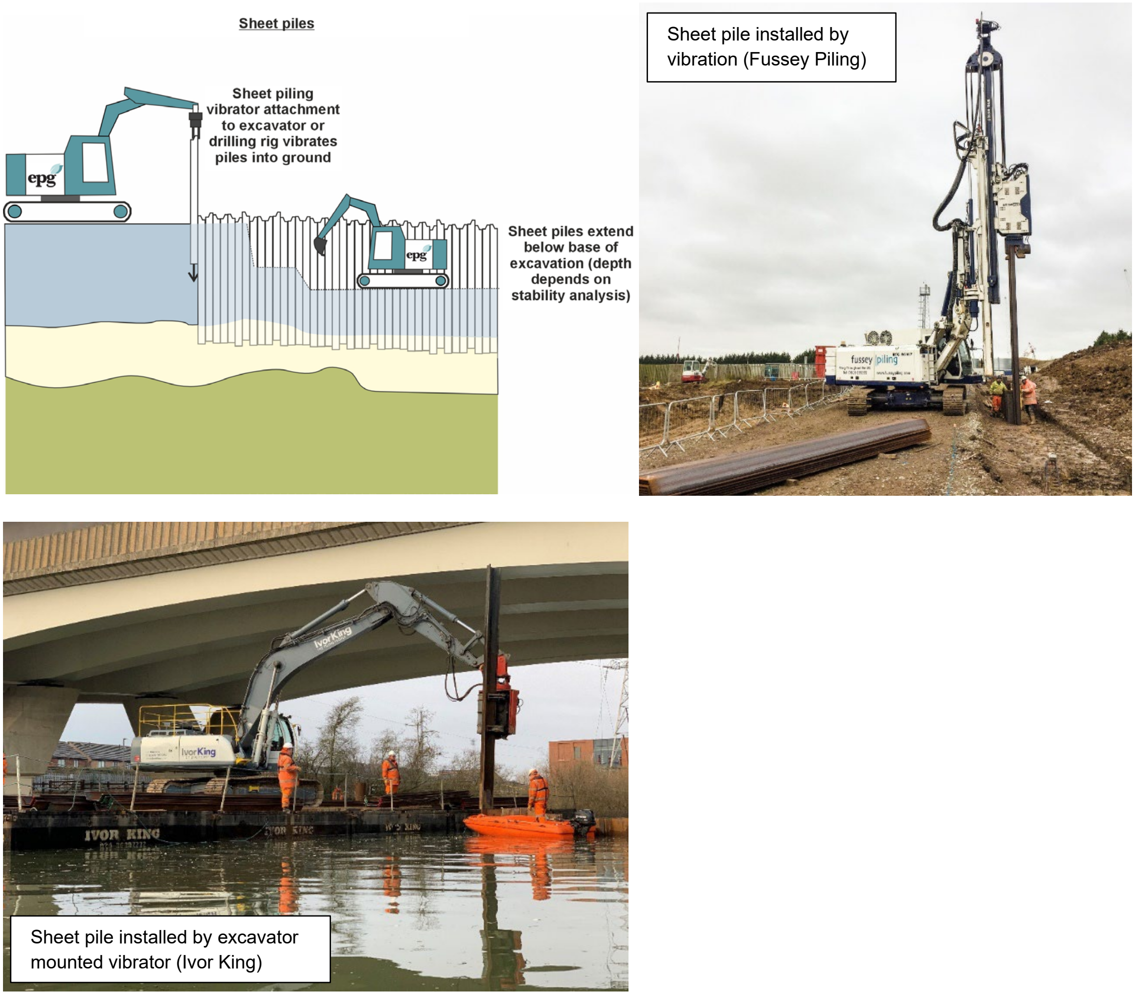


Figure 3.22: Sheet piles

The main variations of sheet piles relate to either the pile material or the method of installation as follows:

- Method of installation
    - Vibration driving - an oscillating driver is clamped to the top of the pile, to induce vibrations in the pile (and adjacent soil) and reduce friction along the sides of the pile, thus allowing the pile to fall under its own weight or with a small applied force
    - Impact driving - uses a falling weight to create the impact, spread to the top of the pile by a driving cap
    - Push (or press) driven - jacking the piles into the ground, using the adjacent piles for reaction

- Sheet pile materials
  - Steel (most common)
  - Timber
  - Plastic
  - Concrete

Sheet piles can be driven individually (known as pitch and drive) or connected together in pairs or as panels of several piles and installed together (known as panel driving).

The effect of impact driving or jacking piles into the ground will be similar to impact driving bearing piles with respect to forming pathways for contaminant or gas migration (i.e. the risk is normally low).

Vibration can cause liquification and/or settlement of loose sands.

Sometimes driving assistance methods are used to make construction of a sheet pile wall easier in hard ground. Jetting and pre-augering are the main methods. Jetting involves delivering a water jet to the soil at the toe of the sheet pile, reducing friction on it. There is the potential to mobilise contaminants in the ground and careful assessment is required.

Pre-augering uses a CFA to penetrate the ground along the pile line in advance of the sheet pile installation. This loosens but does not remove the soil. Again this has the potential to create preferential pathways for contaminant or gas migration and should be carefully assessed.

Potentially, migration of contaminants could occur down wooden sheet piles within the wood. Hydrocarbons could also permeate plastic sheet piles and migrate downwards, although the cross sectional area is small and the rate at which this could occur may be very low. A site-specific assessment should be made considering contaminant diffusion rates in the plastic material.

Push or press in piles (also known as silent piling) are used where noise and vibration is to be limited (Figure 3.23). This type of installation does not cause any vibration of the ground. These will not create pathways if the piles are left in place.

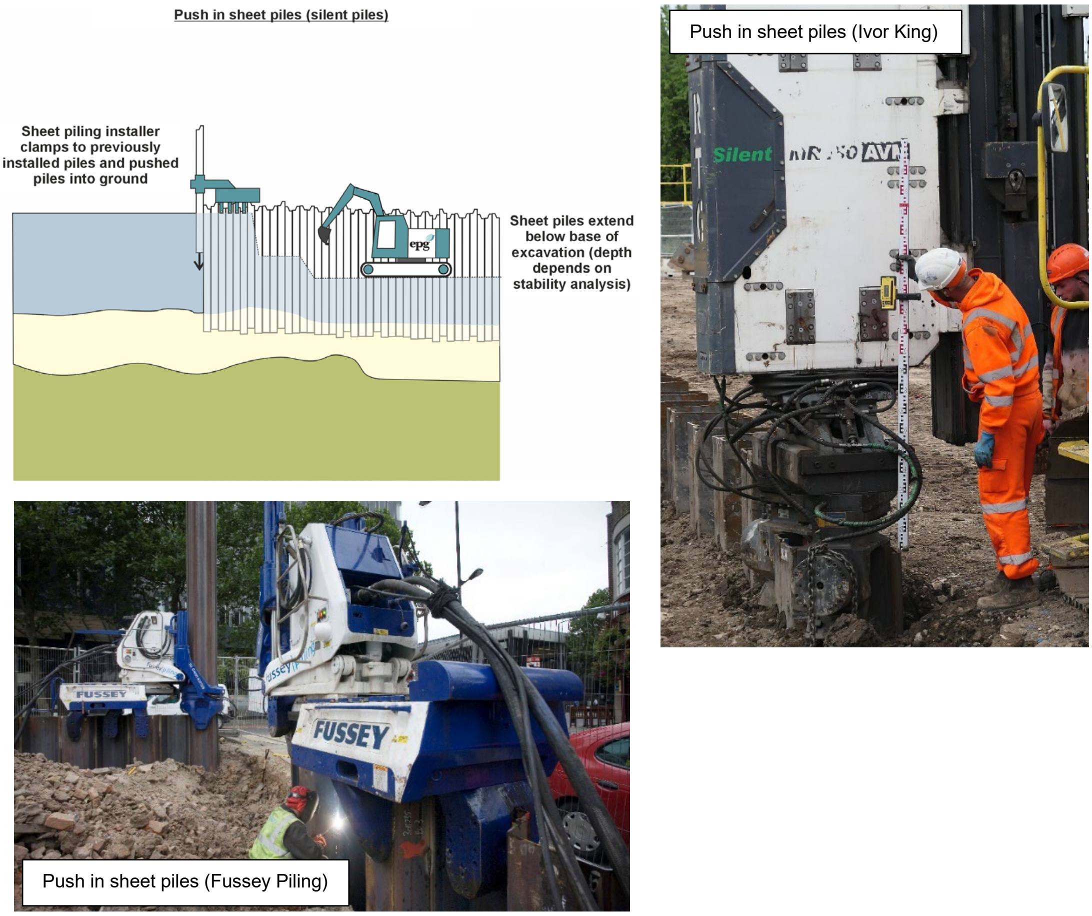


Figure 3.23: Push or press in sheet piles

When sheet piles are removed it will leave a small void in the ground that could be a pathway for gas or contaminant migration. This is likely to close up relatively quickly as the ground recovers, but the risk should be assessed if the piles penetrate an aquiclude or layer that is confining gas below it.

4 Choice of Piling, Sheet Piling or Ground Improvement Method

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 or ground improvement method preferred by a project's client and their professional advisers. However, this guidance recommends that potential environmental impacts should also be given equal weight.

There are several other factors that determine the choice of piling or ground improvement method for a particular project. These include (NHBC, 2010):

- Support requirements (both bearing capacity and settlement) for the structure;
- Ground conditions;
- Cost of materials, transport, installation and removal of waste;
- Plant access, working restrictions and storage area requirements;
- Temporary works requirements;
- Health and safety considerations;
- Environmental considerations (e.g. noise and vibration);
- Minimisation of waste and materials used; and
- Potential for exploitation as ground source heat.

Further information on the choice of piling systems is provided in NHBC Foundation Report NF21 (NHBC, 2010). The same considerations will also generally apply to the choice of ground improvement and sheet piling methods. It is important that the foundation designers have access to all relevant site investigation information (and that site investigations collect data that are relevant to both design and construction of the foundations). Consideration for monitoring timescales is important, and records for ground gas and groundwater levels should be as extensive as possible, to allow for a robust FWRA and choice of the most suitable foundation type.

The risk to groundwater and/or of gas emissions is an extremely important consideration in the decision on whether to use piling or ground improvement and which technique. The FWRA should be started early in the design process for a development to avoid unsuitable methods being chosen. A flow chart showing the different stages of the FWRA process and where it fits into the normal land contamination risk assessment and geotechnical design process is provided in Chapter 6 of this report.

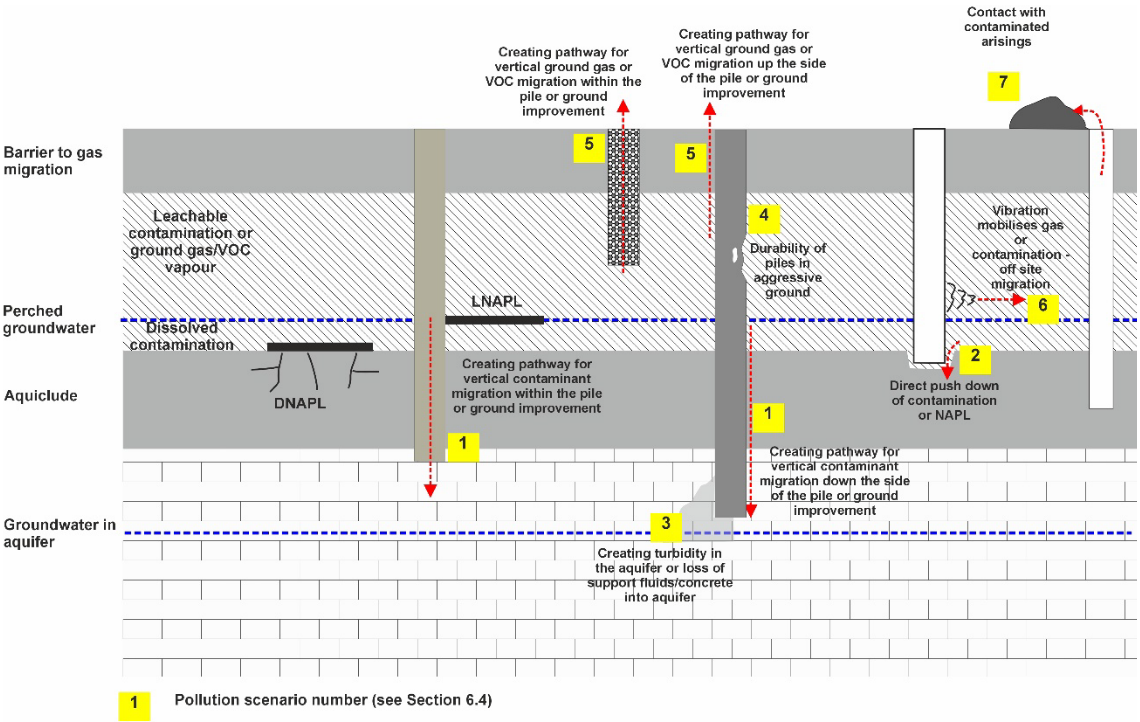
In urban areas the potential for noise and vibration created by the piling operations has often been a major concern to the local planning authority and local residents. However, modern plant and driving methods reduce this and driven piles are not the problem they once were and driven piles can be used in urban areas. In some very sensitive locations, however, noise and vibration constraints may limit the choice of piling or ground improvement method.

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. These should be assessed based on an understanding of their effect on the ground and groundwater or ground gas flow.

5 Hazard Identification: Potential Adverse Environmental Impacts

5.1 Introduction

There are several potential hazards to be considered when piling or carrying out ground improvement into contaminated ground or into aquifers. These are summarised in Figure 5.1.



LNAPL – light non aqueous phase liquid, DNAPL – dense non aqueous phase liquid, VOC – volatile organic compound

Figure 5.1: Potential hazards from piling and ground improvement

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 or gas migration, but an unacceptable risk of pollution or harm 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.

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 regulatory officers. For example, in England the Environment Agency adopts a risk-based approach which takes into account aquifer designations, groundwater vulnerability and sensitive groundwater locations such as Source Protection Zones (SPZs) and Drinking Water Protected Areas. These are generic indicators of risk. They are not site-specific risk assessments and developers may need to supply site-specific information to show the risks are acceptable and can be mitigated.

Current regulatory guidance on groundwater protection can be found on GOV.UK and SEPA.ORG.UK websites.

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 piling or ground improvement works could allow them to migrate into groundwater;
- Piling or ground improvement works would breach a low permeability layer or connect two previously discrete aquifers;
- Piling or ground improvement would increase the risk from ground gas or VOC vapour;
- The site overlies a Principal or Secondary Aquifer;
- The site is located within a SPZ;
- Groundwater is present and piles could be in contact with groundwater;
- The geological strata are fractured or fissured; and
- Works are close to a surface water course and uncontrolled run-off from arisings could pollute those waters.

The regulator’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 quality 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 unproductive strata and there is no groundwater present) and the regulator is satisfied that risks are low, then special precautions or design constraints are unlikely to be necessary. In sensitive situations the regulator may require a risk assessment to be undertaken and mitigation measures (including groundwater monitoring) to be incorporated. In the most sensitive situations, the regulator will object to proposals that it considers present an unacceptable risk of pollution.

Situations where piling may increase the risk from ground gas will normally be dealt with as part of the planning process by the local authority.

6 Hazard Identification and Risk Assessment

6.1 Approach

This chapter describes how the FWRA fits in with RIBA work stages and other geotechnical and geoenvironmental work. It goes on to explain the likely hazards associated with each generic piling and ground improvement method (discussed in Chapter 3). The critical issues relating to each method of piling or ground improvement are discussed and possible mitigation measures are described.

The limitations of any generic assessment of potential hazards 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 potential 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.

The objective of this chapter 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 or ground improvement method and mitigation measures, if required, when constructing on contaminated sites.

It is assumed that sufficient information (e.g. desk study information, site investigation data, contamination assessment, etc) is available to the designer in order to allow them 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 recommended that the impact of piling or ground improvement in relation to contamination is assessed from the earliest stage of the development and foundation design. The risk assessment for piling and ground improvement is a dynamic process that continues from the earliest stages of development design through detailed design, construction and longer term operation. From a geoenvironmental perspective the risk assessment process for piling and ground improvement should begin at the desk study/preliminary risk assessment stage.

Table 6.1 provides a framework for the risk assessment process that is linked to the RIBA project stages. This is based on the Association of Geotechnical and Geoenvironmental Specialists (AGS) guidance on geotechnical and geoenvironmental activities and the RIBA stages (Rolfe and Speed, 2023).

Currently most FWRAs are prepared at RIBA Stage 4 or even 5 (construction). This is too late and the process should start at Stage 1 and be developed as necessary through the subsequent RIBA stages.

Fundamentally, a good visual and scaled conceptual site model (CSM) is key to understanding the risks at any site and should form the basis for the FWRA. This should be prepared as part of the preliminary risk assessment and should be developed as further site investigation information becomes available and the foundation design progresses.

Table 6.1: Foundation risk assessment process and stages

RIBA Stage and description	Geotechnical and Geoenvironmental activities	Piling/Foundation risk assessment activities	Comment
0 - Strategic definition			
1 - Preparation and brief	Environmental Due Diligence	Preliminary assessment with interpretation of the desk study information and initial assessment of foundation geoenvironmental risks	Identify potential constraints with respect to piling and ground improvement and the presence of land affected by contamination and/or aquifers
	Geotechnical and Geoenvironmental Desk Study and Preliminary Risk Assessment	Preliminary options appraisal for foundations	Preliminary options appraisal for foundations should consider groundwater and ground gas risk
	Preparation of Ground Conditions chapter for Environmental Statement	Include preliminary FWRA as a paragraph or section in the environmental statement and/or preliminary risk assessment	
	Support for discharge of relevant planning condition (Desk Study)	Can any risk associated with piling or ground improvement be discounted at this stage?	Initial assessment of site using Table 6.2 For negligible and low risk sites include results in preliminary geoenvironmental risk assessment report For high risk sites start the FWRA report (a dynamic document to be updated as the design and site investigation progresses)

RIBA Stage and description	Geotechnical and Geoenvironmental activities	Piling/Foundation risk assessment activities	Comment
2 - Concept design	Exploratory level ground investigation	Site investigation designed to collect information relevant to the piling and foundation design and construction and the foundation risk assessment	e.g. If piling may penetrate an aquiclude collect information on the thickness, permeability, strength, over consolidation ratio e.g. If VOC contamination is present in perched groundwater and stone columns are to be used, collect soil vapour samples from the unsaturated zone above the groundwater and from wells that penetrate the VOC contaminated groundwater
	Ground Investigation Report (GIR)	Develop preliminary risk assessment and options appraisal for foundations using site investigation data	
	Preparation of Ground Conditions chapter for Environmental Statement	For simple low risk sites the assessment maybe part of the GIR and a specific FWRA may not be required	
	Generic Quantitative Risk Assessment (GQRA)		
	Outline Remediation Strategy	Outline remediation strategy to take account of foundation solution and risks	
	Support for discharge of planning condition (Risk assessment)		For high risk sites develop the FWRA report based on the additional site investigation data

RIBA Stage and description	Geotechnical and Geoenvironmental activities	Piling/Foundation risk assessment activities	Comment
3 - Developed design	Detailed level ground investigation	Design site investigation to collect information relevant to geoenvironmental assessment of foundation solutions	
	Geotechnical Design Development	Consider geoenvironmental risks and specify solutions that minimise the risk in preference to mitigation Design mitigation where necessary	
	Detailed Quantitative Risk Assessment (DQRA)	Development of site-specific assessment criteria (SSAC) taking account of foundation solution	
		Groundwater or gas modelling as part of the FWRA where necessary on higher risk sites	
	Outline Remediation Method Statement	Confirmation of choice of pile types and any mitigation requirements	
	Support for discharge of planning condition (Risk assessment)		Keep updating FWRA as design develops including mitigation options if necessary
4 - Technical design	Targeted ground investigation (if required)	Detailed specification of any pile parameters relevant to groundwater or ground gas risk (e.g. toe depth of piles)	
	Geotechnical Design Report (GDR)	FWRA report – final version	Once the development design is fixed finalise the FWRA report – highlight any mitigation, verification and monitoring requirements in the GDR

RIBA Stage and description	**Geotechnical and Geoenvironmental activities**	**Piling/Foundation risk assessment activities**	**Comment**
	Remediation Method Statement	Specification of monitoring requirements and action levels with specified actions and timescales Specification of mitigation measures if required	
	Verification Plan		
	Licensing	Materials Management Plan (MMP) and Qualified Person declaration where appropriate	
	Environmental Permit application		
	Support for discharge of planning condition (Remediation Strategy)		
5 - Construction	Temporary Works design	Take account of geoenvironmental risks (e.g. risk to groundwater from sheet piling)	
	On-site support Construction monitoring	Carry out groundwater monitoring if required	Ensure that staff working on site are aware of the requirements in the FWRA Provide test results in a timely and regular manner to regulators throughout the monitoring programme
	Verification	Verify compliance with design and any mitigation requirements	

RIBA Stage and description	Geotechnical and Geoenvironmental activities	Piling/Foundation risk assessment activities	Comment
6 - Handover and close out	Geotechnical Feedback Report	Ongoing monitoring if required	Complete foundation works verification report including monitoring data
	Verification Reports	Verification report confirming piles or ground improvement measures installed in accordance with design and assessment of any monitoring results	
	Support for discharge of planning condition (Verification)		
7 - In use			

6.2 Risk assessment – groundwater

The purpose of the FWRA is to achieve the following:

- Where pollutants are in the soil and have not entered groundwater, you must take all necessary and reasonable measures to:
    - prevent the input of hazardous substances into groundwater
    - limit the entry of non-hazardous pollutants into groundwater to avoid pollution
- Where pollutants have already entered groundwater your priority is to take all necessary and reasonable measures to:
    - minimise further entry of contaminants where there is a defined source
    - limit the pollution of groundwater or any effect on the status of the groundwater body from the future expansion of the plume, if necessary, by actively reducing its extent

The matrix in Table 6.2 can be used to assist in decision making and risk assessment. The matrix identifies several factors that will influence the level of risk of causing groundwater pollution at a site and the attributes that would define the site as low, moderate or high risk for each one. The table can be used for initial screening to determine the complexity of risk assessment that is likely to be required for a site. It is, however, not definitive and other site-specific factors may need to be considered.

In the early stages of a piling risk assessment (i.e. RIBA Stage 1 or preliminary risk assessment stage it may not be possible to tell whether the site is affected by dissolved phase contamination or NAPL. Therefore classification would have to be based on reasonable assumptions of their presence based on historical site usage and ground model.

Table 6.2: Foundation works risk assessment matrix for groundwater – initial screening

Factor	Negligible risk	Low risk	Moderate risk	High risk
Aquifer designation	Unproductive strata	Groundwater resource	Secondary	Principal
Receptor	No credible receptor	Groundwater outside SPZs (that contamination could credibly reach)	SPZ 3/total catchment zone Surface watercourse	SPZ 1 and 2 SSSI
Flow regime		Matrix intergranular flow		Fracture flow
Permeability	Very low permeability	Low permeability	High permeability	Very high permeability
Contamination	No significant contamination present	Low leachability (compare to suitable standards, EQS or DWS)	Dissolved phase in perched water	Dissolved phase in perched water NAPL
Piling/ground improvement depth	Pile toe >10 m above bottom of aquiclude[1]	Pile toe between 5 m and 10 m from bottom of aquiclude[1]	Pile toe <5 m above bottom of aquiclude[1]	Pile extends into aquifer

1. Based on research discussed in Appendix 1 and professional judgement
SPZ - Source Protection Zone; SSSI - Site of Special Scientific Interest; EQS - Environmental Quality Standard; DWS - Drinking Water Standard; NAPL - Non Aqueous Phase Liquid

Using the matrix in Table 6.2 the overall risk may be assessed. The outcomes are:

Negligible risk. No further action – no risk to groundwater because there is no source, pathway or receptor. No geoenvironmental limitations on choice of piling or ground improvement method. Include assessment as a section in geoenvironmental Phase 1 or Phase 2 reports.

Low risk. Simple FWRA required – risk needs to be considered in more detail using generic methods but specific report is not required. Include advice on any limitations on choice of piling or ground improvement method as part of geoenvironmental reports.

Moderate risk. FWRA required – risk needs to be considered in more detail using generic methods. This does not mean a site is high risk or that mitigation is required. This will be determined from the risk assessment. Specific FWRA report required. This should be started at the desk study stage (RIBA Stage 1) and should then be developed as further site investigation is completed and the design progressed.

High risk. FWRA required possibly with remedial targets assessment to determine if piling is acceptable at all and if so what mitigation and monitoring is required. Specific FWRA report required. This should be started at the desk study stage (RIBA Stage 1) and should then be developed as further site investigation is completed and the design progressed.

The results of the groundwater risk assessment can also be used in a similar way to the geotechnical risk classification. Geotechnical design standards (Eurocode 7) (BSI, 2013b) recommend the classification of geotechnical structures (which includes foundations and retaining walls) into three geotechnical categories. The classification is based on the complexity of the structure, the ground conditions, the loading and the level of risk that is acceptable. The geotechnical categories are used to establish the extent of site investigation required and the level of checking of the design that is required. The categories can be summarised as follows:

Category 1 – Small and simple structures where ground conditions are known from local experience to be straightforward and routine methods can be used in foundation design and construction. Excavation below the groundwater table is not required or if it is, local experience indicates it will be straightforward, with negligible risk. This could include the negligible risk category from Table 6.2.

Category 2 – Conventional types of structure and foundation with no exceptional risk, difficult soil or loading conditions. Examples include spread foundations, piled foundations, retaining walls, excavations, bridge piers and abutments. This could include the low and moderate risk categories from Table 6.2. In such a case more robust site investigation and analysis would be required along with checking of the assessment.

Category 3 – Structures that fall outside the limits of Categories 1 and 2. Examples include structures involving abnormal risk or unusual or exceptional ground or loading conditions. This could include the high risk category from Table 6.2.

The outcome of the FWRA should also be recorded in the geotechnical risk register (and updated as the design and construction progresses) as required by Eurocode 7 (BSI, 2013b). However, care is needed that the FWRA for groundwater does not result in excessive requirements for site investigation and checking of the geotechnical part of the design.

Examples of the initial screening of four sites are provided in Table 6.3.

Table 6.3: Examples of initial screening

Factor	Example site 1 No contamination present within SPZ 2	Example site 2 Low leachable contamination present within SPZ 1	Example site 3 Low leachable contamination present within SPZ 3	Example site 4 Perched groundwater in made ground with NAPL present
Aquifer designation	Principal (high risk)	Principal (high risk)	Principal (high risk)	Groundwater outside of SPZs (low risk)
Receptor	SPZ 2 (high risk)	SPZ 1 (high risk)	SPZ 3 (moderate risk)	Surface watercourse (moderate risk)
Flow regime	Fracture flow (high risk)	Fracture flow (high risk)	Matrix intergranular (moderate risk)	Matrix intergranular (moderate risk)
Permeability	High permeability (moderate risk)	High permeability (moderate risk)	High permeability (moderate risk)	High permeability (moderate risk)
Contamination	No significant contamination present (negligible risk)	Low leachability (compare to suitable standards, EQS or DWS) (low risk)	Low leachability (compare to suitable standards, EQS or DWS) (low risk)	NAPL (high risk)
Piling/ground improvement depth	Pile toe >10 m above bottom of aquiclude (negligible risk)	Pile toe between 5 m to 10 m above bottom of aquiclude (low risk)	Pile toe >10 m above bottom of aquiclude (negligible risk)	Pile extends into aquifer (high risk)
Piling/ground improvement method	Bored CFA piles	Bored CFA piles	Bored CFA piles	Driven pile
Overall risk	Negligible risk on the basis that no significant contamination is present and therefore there is no S-P-R linkage.	High risk specific FWRA is required possibly with DQRA	Moderate risk because although there is low leachable contamination present it is in a SPZ and specific FWRA is required	High risk specific FWRA is required possibly with DQRA

SPZ - Source Protection Zone; DQRA - Detailed Quantitative Risk Assessment; EQS - Environmental Quality Standard; DWS - Drinking Water Standard; NAPL - Non Aqueous Phase Liquid

The process of risk assessment for groundwater and its relationship with the RIBA stages is summarised in Figure 6.1.

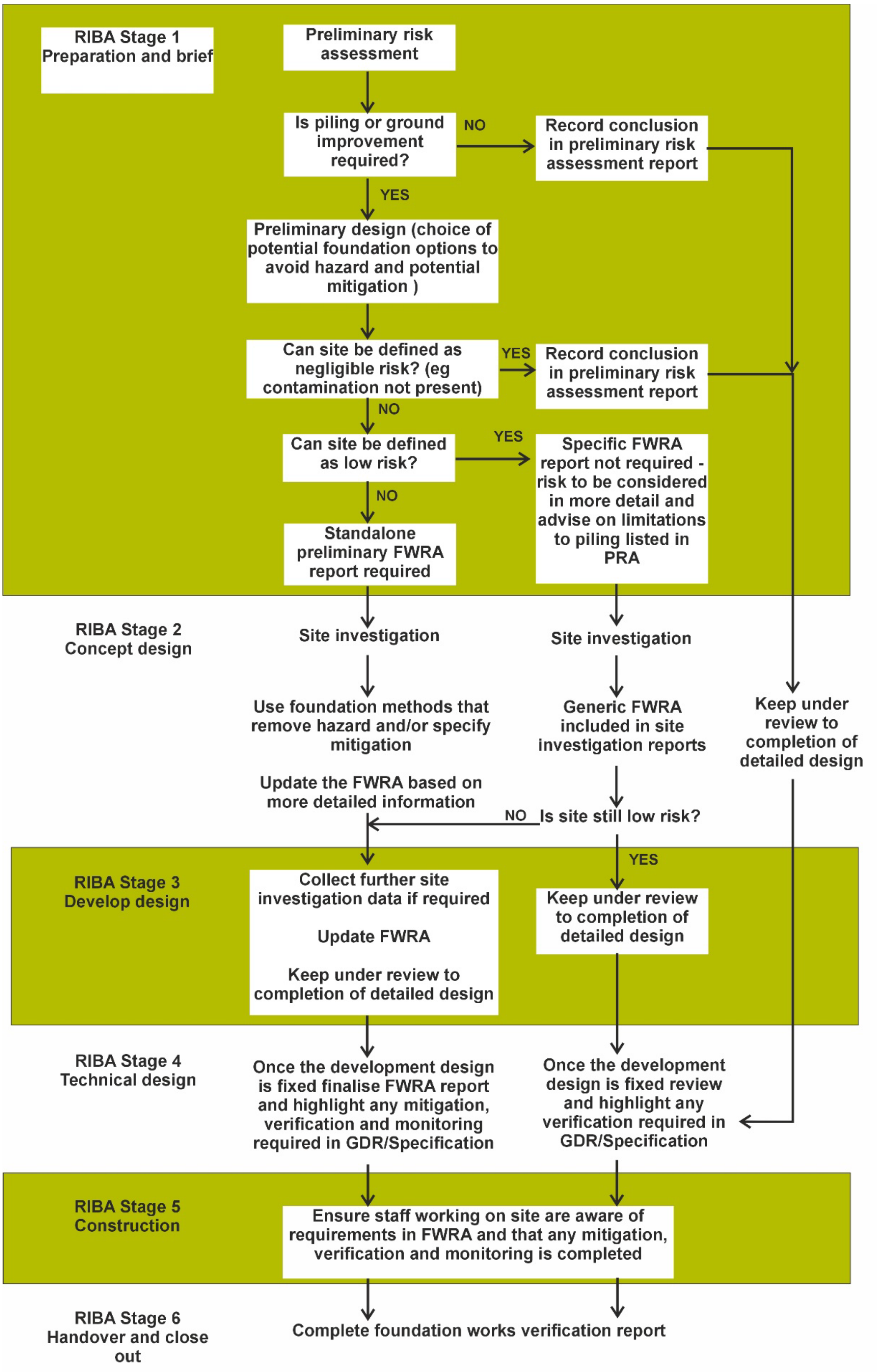


Figure 6.1: Flow chart for foundation works risk assessment - groundwater

It cannot be stressed highly enough that the FWRA is a dynamic process that is carried on through the design stages and should be reviewed and updated as necessary.

6.3 Risk assessment – ground gas/vapours

In most cases the use of piled foundations or ground improvement will not increase risk posed by ground gas and neither bored pile, driven precast concrete or open tube (with infill) piles or vibro concrete columns will form preferential pathways unless through a thin layer of stiff clay that is confining a gas source that is under pressure or of large volume in an open void (Wilson and Mortimer, 2017). Therefore most scenarios are low risk and do not need assessment. The process will be similar to that for groundwater as shown in Table 6.1 and Figure 6.1.

The only high risk scenarios are:

- Thin or engineered capping layer over high pressure source (e.g. recent landfill sites) or large volume gas source in an open void (mine workings); and
- Driven steel H or I section piles that are driven through a confining layer and link a gas source under pressure or of large volume to the surface.

Ground improvement using vibro compaction or rigid inclusions will not increase ground gas risk. Stone columns may increase risk where the columns penetrate a barrier and connect a source direct to a receptor (see Figure A1.9 in Appendix 1). Stone columns in made ground with isolated methane less than 30% concentration are low risk.

When assessing ground gas risk in relation to piles and ground improvement, it is not appropriate to simply increase the characteristic situation (CS) (as defined in BS 8485 [BSI, 2019]) because stone columns are present. A detailed risk assessment should be undertaken to determine whether or not the columns will increase risk. It is also not appropriate to use the BS 8485 points score system to design gas protection where stone columns are present. If the columns are acting as a preferential pathway for gas migration, modelling of gas flow up the columns is necessary.

In some cases prefabricated vertical drains are used in conjunction with continuous modulus columns. These form an open pathway in the ground and an assessment should be made to determine whether or not they will increase ground gas risk.

6.4 Source – pathway – receptor linkages

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

Groundwater

1. Creation of preferential pathways, through a low permeability layer (e.g. an aquitard that transmits water at slower rates than an aquifer), to allow potential contamination of an underlying aquifer;
2. The driving of solid contaminants down into an aquifer during pile driving or ground improvement;

3. Contamination of groundwater and, subsequently, surface waters by turbidity, support fluids, concrete, cement paste or grout;
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);

Ground gas

5. Creation of preferential pathways, including through a low permeability layer, to allow upward migration of landfill gas, soil gas, mine gas or contaminant vapours (e.g. VOCs) to the surface;
6. Causing off site migration of ground gas or increased vertical emissions as a result of vibration or other effects from the pile installation process;

Health and Safety

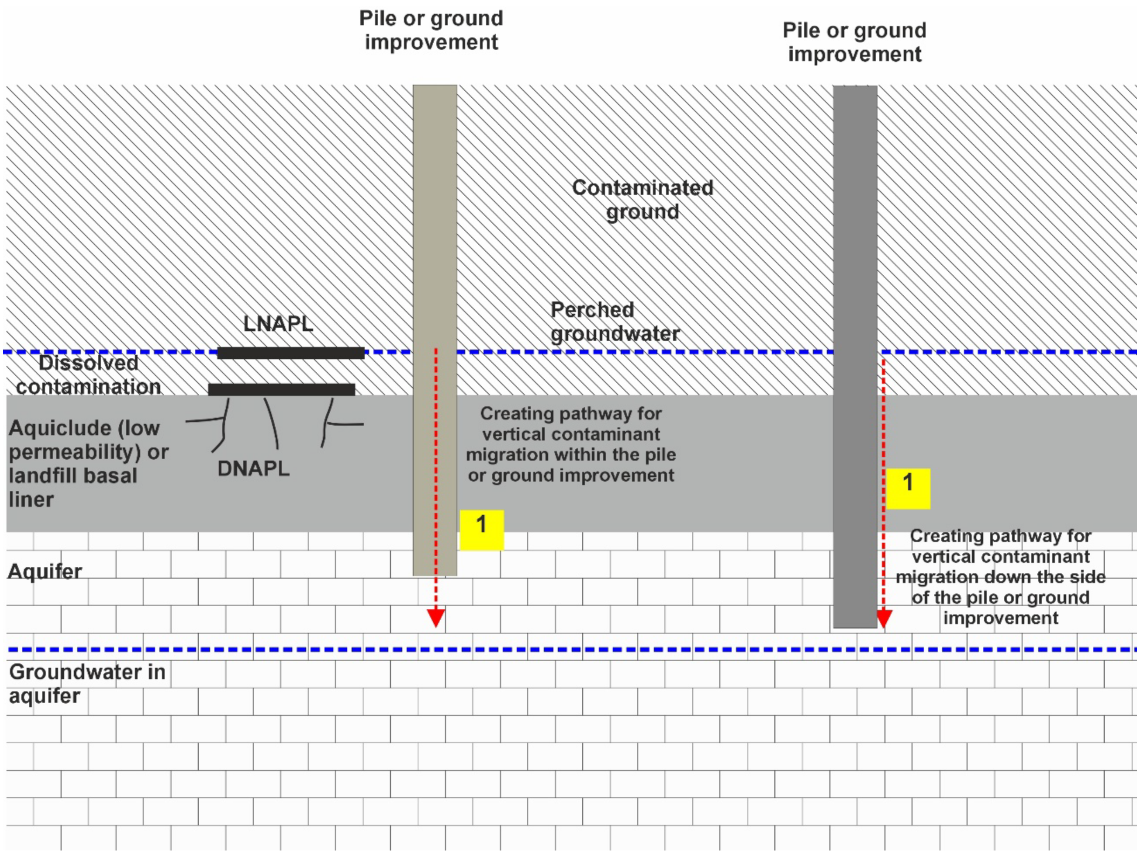
7. Direct contact of site workers and others with contaminated soil arisings which have been brought to the surface.

These scenarios are discussed in detail in Chapters 7-13.

7 Pollution Scenario 1 - Creation of preferential pathways, through a low permeability layer, to cause contamination of groundwater in an aquifer

7.1 Source – pathway - receptor

A diagram summarising Pollution Scenario 1 is provided in Figure 7.1.



LNAPL – light non aqueous phase liquid, DNAPL – dense non aqueous phase liquid

Figure 7.1: Pollution scenario 1: preferential pathways for groundwater or contaminant flow

Source/Contaminant

Contaminated made ground, contaminated perched groundwater or NAPL.

Pathway

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

Receptor

Groundwater in aquifer - typically in competent strata in which pile is founded (or at the base of ground improvement).

Description

A typical situation is where made ground with contamination in it is situated above clay drift deposits that in turn sits on solid strata such as the Chalk which is an aquifer. This situation is common in eastern and southern England. Frequently perched water or NAPL exists within 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. DNAPL could migrate without a hydraulic gradient being present by diffusion through the clay.

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

Cases of known/inferred pollution or research findings suggesting possibility of pollution

It has been reported (though there is no detailed information to substantiate the details) that installation of piles through 5 – 15 m 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 Principal Aquifer. Campbell *et al.* (1984) report a case of a site in the southern United States where vertical migration of contaminants around piles was implicated in groundwater pollution.

The literature (Section A1.3) has identified that, in general, driven piles and bored piles will not create preferential pathways. Driven piles have in the past been perceived as posing a greater risk but the literature review shows that is not the case unless the thickness of a clay layer is less than two pile diameters.

However, steel 'H' section piles could create migration pathways along the pile/soil interface if the thickness of the clay layer is less than eight pile diameters, and untreated timber piles and stone columns could allow transmission through the material of the pile or column itself if the clay barrier is thin (see Section A1.3).

Corrosion of steel piles may potentially increase interface permeability caused by changes in redox conditions in the soil around the pile. However, the research is not conclusive and if it does occur, the increase is one order of magnitude. This can be allowed for in a detailed risk assessment.

Although the research shows that corrosion in steel piles and its effect on permeability should be considered in a pile risk assessment the following should also be considered:

- The effects were found in montmorillonite rich clay (high plasticity). It is not clear if similar effect would be as significant with other clay mineralogy with a low plasticity;

- The effect is localised around the pile and reaches a 0.35 m radius from pile wall after 140 years; and
- The increase in permeability is less than one of order of magnitude around the pile.

For detailed risk assessment of contaminant migration in very sensitive locations or where a clay layer is thin the approach described by Katsumi *et al*. (2010) in Section A1.3 can be used to estimate the impact of a virtual clay column that has a permeability determined by taking account of interface leakage.

There may be a higher risk of groundwater migration down the pile/soil interface where chlorinated solvents are present especially where DNAPLs are present over the top of a low permeability clay layer. Chlorinated solvents can cause cracking in clays (Çinar, 2015) which may be exacerbated by driven piling or it could open up a pathway at the side of the pile.

Raking piles may also increase the risk of a preferential pathway forming. However, lateral movement of vertical piles under lateral loading is not likely to cause a preferential pathway.

7.2 Specific issues - displacement piling methods

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. This has been confirmed by research. 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. A layer of sand above a clay layer can be dragged down to a depth of 5 m and can increase permeability down the side of the pile.

The thicker the low permeability layer the less likely it is that a preferential pathway will form.

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. This will only be of significance if the clay layer is thin. Research by the University of Sheffield found that if a clay layer is greater than two pile diameters thick, driven circular piles are sealed (and this should also apply to square section piles) and do not form a migration pathway for contaminants.

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

Where a pile is installed through a body of contaminated groundwater or leachate it is important that free water cannot flow to the aquifer during pile construction or afterwards. The risk of this occurring is minimised with displacement piles.

Driven displacement cast-in-place piles where the concrete ‘shell’ or casing is left in place, behave as a displacement pile. 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.

To minimise the torque required to screw displacement auger 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.

Screw piles should not cause preferential pathways for contaminant migration.

7.3 Specific issues - replacement piling methods

Replacement 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.

Avoidance of disturbance to the surrounding soil requires a high standard of workmanship in the construction process. Reduced 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. This could create 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 pile is installed through a body of contaminated groundwater or leachate, it is important that free water cannot flow to the aquifer during pile construction. When using bored piles in this situation the method of installation should prevent vertical water flow (e.g. using casing or support fluids to keep groundwater out of the pile bore). The action of the auger in CFA piles should maintain support of the soil. The short construction period for the piles means the risk is normally low, unless the auger is bored in and left stationary whilst large volumes of contaminated water flow down it.

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.

CFAs 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. Modern rigs are computer controlled so the risk of defects is reduced.

7.4 Specific issues - sheet piles

The same considerations relating to displacement bearing piles apply to sheet piles. The only additional consideration is where sheet piles are temporary and are withdrawn after construction. This could create a pathway for contaminant migration if an aquiclude has been penetrated.

7.5 Specific issues - ground improvement methods

As ground improvement methods commonly involve a shallower depth of penetration than piling (the maximum penetration is normally less than 10 m) 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 especially in shallow layered alluvial soils.

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. If the top feed process is used, water jetting may be used. In the absence of open voids in the ground where fines can migrate to, this is unlikely to flush fines from the surrounding soil as previously believed. This is because without a void to move into, the fines will be locked in place.

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 higher than the surrounding ground, 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. Rigid inclusions and soil mixing will also be formed from material that has a lower permeability than the surrounding ground and will not create pathways.

Prefabricated vertical drains will create highly permeable pathways for both gas and contaminant migration. This can be prevented by terminating the drains above the base of the low permeability compressible soils into which they are installed. This should not significantly affect the performance of the drains.

8 Pollution Scenario 2 - The driving of solid contaminants down into an aquifer during pile driving

8.1 Source – pathway – receptor

A diagram summarising Pollution Scenario 2 is provided in Figure 8.1.

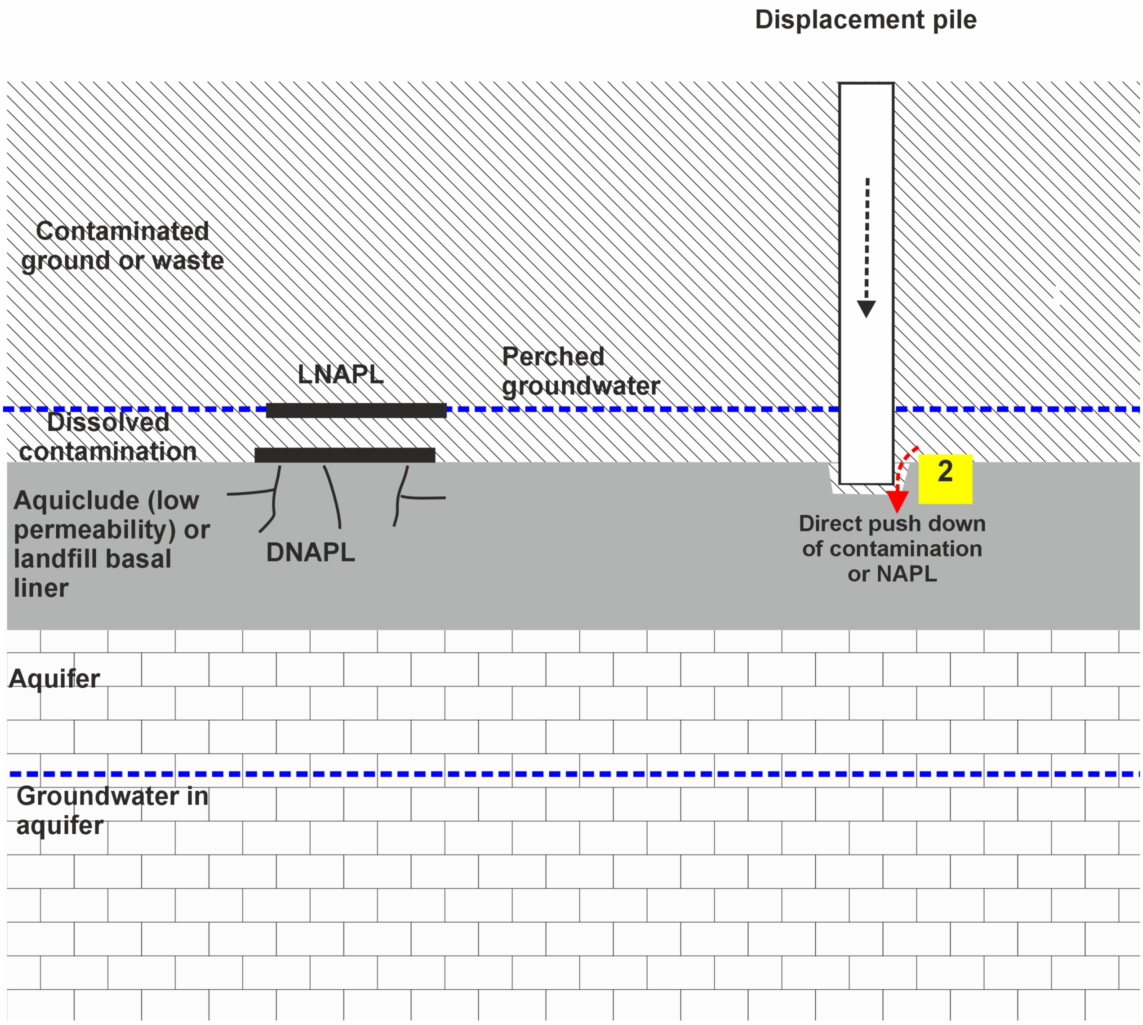


Figure 8.1: Pollution scenario 2: Driving contaminated material into aquifer

Source/Contaminant

Contaminated soil or NAPL.

Pathway

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

Receptor

Groundwater in aquifer, typically in competent 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. 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. However, other research discussed in Section A1.3 indicates that the use of conical tips has no significant benefit.

8.2 Specific issues - displacement piling methods

Driven displacement piles may potentially 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, researchers at the University of Sheffield and others have shown that the risk of this is low, especially with conical tips. 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 down with the pile until it achieves set and would bring the load-bearing capacity of the pile into doubt. It is therefore considered unlikely that, in practice, this occurs.

This potential problem will also be minimised by using small displacement piles because small sections tend to cut through or push material aside. It is not a problem with screw piles. Thus unless a low permeability layer is very thin drag down is not likely to be a significant issue.

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. The volumes of soil are small and unless very heavily contaminated are not likely to pose a risk. The use of conical tips is therefore not required, again unless there is a very thin low permeability layer.

8.3 Specific issues - replacement piling methods

Replacement methods, which involve the extraction of the soil prior to placing the pile, will not in normal circumstances lead to soil being dragged downwards. With CFA piling techniques drag down cannot occur as the soil is constantly moved up the auger flights.

8.4 Specific issues - sheet piles

Sheet piles are small displacement and drag down of contaminants is not likely to be a significant risk.

8.5 Specific issues - penetrative ground improvement methods

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.

9 Pollution Scenario 3 - Contamination of groundwater and subsequently surface waters by turbidity, support fluids, concrete, cement paste or grout

9.1 Source – pathway – receptor

A diagram summarising Pollution Scenario 3 is provided in Figure 9.1.

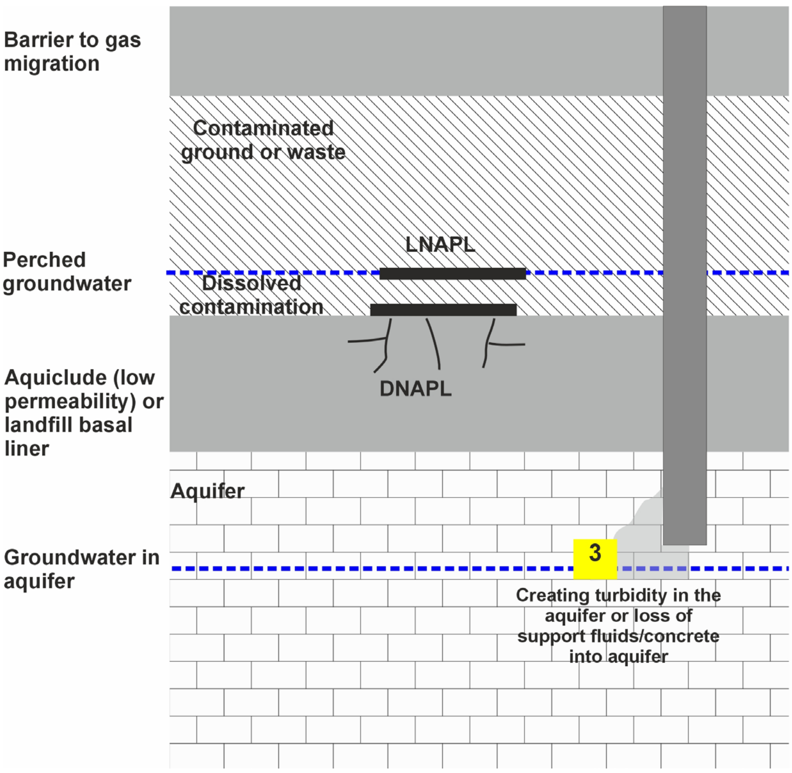


Figure 9.1: Pollution scenario 3: loss of concrete or support fluids into groundwater

Source/Contaminant

Concrete, cement paste or grout introduced to the ground during piling/penetrative ground improvement operations. Support fluids used to support pile bores. Turbidity caused by pile construction.

Pathway

Flow within highly permeable or fractured strata or voids.

Receptor

Groundwater and surface water. Ultimate receptor may be surface water or water abstraction well. Turbidity is a particular issue for water abstraction wells.

Description

Loss of wet concrete, cement paste or grout may occur, but only in fast-flowing groundwater (see Section A1.6), probably associated with fractured or jointed rocks such as limestones and the Chalk or permeable gravel formations. Migration of cement or grout may occur until initial or final setting of the concrete, cement paste or grout occurs; this would generally occur on a timescale of a few hours to a few days. Whilst the effect may be localised, if close to a water supply abstraction, it may be significant enough to cause a Category 1 or 2 pollution event. The research discussed in Section A1.6 indicates that the risk of leaching of metals and other contaminants from pile concrete is low. The use of cement replacements such as fly ash and ground slag increases total metal concentrations but the porosity of the concrete is reduced and thus the leachable concentration of contaminants is a small proportion of the total content.

Loss of support fluids may occur if there are voids in the ground or it is highly permeable. If this is considered a risk, it can be prevented by use of casing or pregrouting the ground. In one case study of bored pile construction discussed in Section A1.6 there was little loss of bentonite during pile construction on a site and a filter cake from the bentonite developed rapidly (within seconds). However, loss did occur in a test pile on the same site in an area of Chalk affected by faulting, demonstrating how difficult it can be to predict where losses will occur. If there is a risk to an aquifer adequate site investigation is required to allow robust assessment of the risk of bentonite loss and its consequences.

Turbidity can be caused by replacement (bored) piles and probably to a lesser extent by displacement (driven) piles. This is a particular issue of concern in Chalk aquifers (see Section A1.7).

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.

For geotechnical, economic as well as environmental reasons, a piling method which avoids the risk of loss (e.g. use of permanent casing or preformed piles) would generally be chosen when piling through highly fissured or permeable strata. Good QA/QC and computer monitoring of concrete pumping rates and pressures will also minimise this risk.

Drilling of site investigation boreholes has caused an increase in turbidity at water abstraction wells (see Section A1.7). There are no cases where piling has been conclusively proven to have caused turbidity at abstraction wells.

Leaching of the concrete from piles has occurred in a project due to high groundwater flow velocities in Chalk layers beneath a substantial thickness of alluvium. Pumping for dewatering of a wetland area resulted in groundwater flow translating to a substantial depth which caused inclusions in a significant number of piles. There are also several instances of large-scale loss of concrete into solution features in Chalk.

9.2 Specific issues - displacement piling methods

Where displacement piling methods involve the driving of steel piles, precast 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.

Turbidity risk is lower with driven piles although they do cause remoulding of the Chalk which could pose a risk of creating turbidity.

9.2.1 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.

These types of pile will also increase the risk of causing turbidity if installed into aquifers.

9.3 Specific issues - replacement piling methods

Where replacement piling involves the casting of concrete directly against soil, 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. There is minimal risk above groundwater or in slowly moving groundwater. In order to minimise the risk where groundwater flow rate is high, temporary or permanent casing may be used to prevent wash out. This should be considered in the risk assessment.

Support fluids are designed to prevent water flow into an excavation and support the sides, and normally the risk of these migrating into the ground is low. However, if groundwater flow is high or there are voids, the fluid may be lost into the ground. See Section 3.7 for information on support fluids and the risk to groundwater.

Piling into Chalk requires careful consideration. There are several examples where the presence of solution features has led to large-scale loss of concrete into the ground and failure of piles. The site investigation should be thorough and a method that minimises the risk of this occurring should be used. Advice on piling in Chalk is provided by CIRIA (2002).

Boring piles can cause turbidity (see Section A1.7).

9.4 Specific issues - sheet piles

Sheet piles do not use support fluids and there is no risk to groundwater. Sheet piles are similar to driven piles but with less disturbance, and are not likely to penetrate significant depths into Chalk. The risk of causing turbidity is low.

9.5 Specific issues - ground improvement methods

Vibro replacement concrete columns, rigid inclusions and soil mixed columns are placed in direct contact with the surrounding ground and leaching of wet concrete, cement paste, grout or binders into fast moving groundwater is theoretically possible. However, for groundwater to be sufficiently fast, the stone columns would need to be installed into fractured rock or very open gravel. It is not possible or likely that they would be installed in such conditions. Thus leaching is not considered to be an issue.

It is unlikely that ground improvement methods would be used below groundwater level in a deep aquifer where an abstraction well is present in the proximity, and therefore turbidity is not considered to be a significant issue. However, turbidity could be caused when ground improvement methods are undertaken within shallow aquifers (not perched water), and below the groundwater table when sensitive shallow water features exist in the proximity, and are in hydraulic continuity with the site under consideration.

10 Pollution Scenario 4 - Direct contact with contaminated soil or leachate causing degradation of pile materials

10.1 Source – pathway – receptor

This pollution scenario is summarised in Figure 10.1.

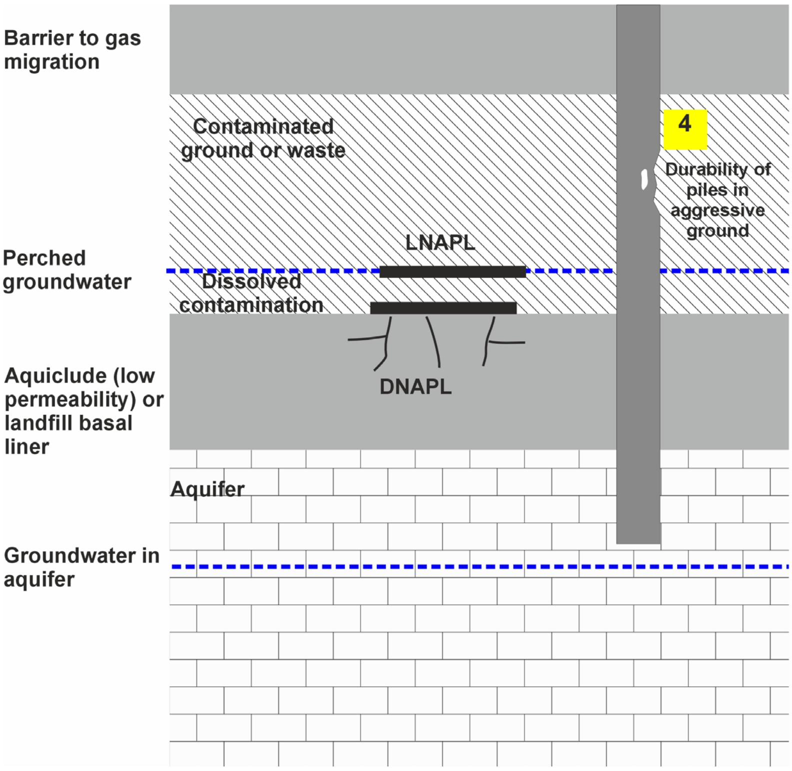


Figure 10.1: Pollution scenario 4: corrosion of pile leading to creation of flow paths

Source/Contaminant

Contaminated soil, waste, groundwater/leachate or NAPL.

Pathway

Direct contact with pile.

Receptor

Built development (and users).

Description

Some contaminants or constituents of contaminated soil, groundwater or leachate may be aggressive to materials used in piles or ground improvement. This has the potential to cause degradation to the piles, reducing their load carrying capacity, and possibly creating migration pathways. Free hydrocarbon product (NAPL) could also be present. 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).

The foundation designer should consider aggressive properties of the ground in preparing and approving their designs. However, 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.

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 issues or research findings suggesting possibility of issues

Research on this subject is discussed in Section A1.2 of this report. Buried concrete in the ground should be designed to take account of sulfate and pH conditions in accordance with current Building Research Establishment (BRE) guidance (BRE, 2017).

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 (e.g. special coatings on piles).

The regulator's interest in this issue is primarily where corrosion of steel piles would subsequently lead to opportunity for pollution migration. Responsibility for assessing the risks to buildings normally lies with the Building Control organisation. The research indicates that unless the soils are strongly acidic (pH <4), the underground corrosion of steel piles driven into undisturbed soils is negligible. The design of steel piles should make a suitable allowance for corrosion following the guidance in Eurocode 3 (EN 1993 – 5: BSI, 2007) depending on how the ground is classified in terms of aggressiveness.

There are examples where aggressive ground conditions have caused structural issues in below ground concrete, predominantly associated with high sulfates and acidity, but no known examples where this has caused contaminant migration. Research has shown that crude-oil-contaminated soil can adversely affect the geotechnical behaviour of the soil supporting piles. It can also reduce the hydraulic permeability. The former can be managed by pile load tests that are normally carried out during construction to confirm the actual load capacity achieved on site.

Research has shown that hydrocarbons could reduce the strength gain in fresh concrete placed in contact with the contamination, if present in sufficient concentrations (more likely with NAPL). This can be allowed for in design, thus avoiding the need for expensive sleeving or surface protection systems. The effect of petroleum hydrocarbons on hardened concrete, which has achieved its design strength, is of limited concern. Creosote, however, can affect hardened concrete that has achieved its design strength. Where hardened concrete is likely to come into contact with creosote-derived contamination a reduction in the assumed long term strength of concrete should be considered in the design.

Aggressive ground conditions can particularly affect deep soil mixed columns where, for example, high ammonia concentrations in the soil can slow the hydration of the cement mixed with it.

10.2 Discussion

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, as can support fluids. Information is provided in Section A1.2 of this report.

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 preformed concrete piles). The use of partially preformed replacement 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.

Ground improvement methods 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. Similarly concrete and binders used in rigid inclusions and soil mixing can be affected by aggressive ground.

11 Pollution Scenario 5 - Creation of preferential pathways to allow migration of landfill gas or contaminant vapours to surface

11.1 Source – pathway – receptor

This pollution scenario is summarised in Figure 11.1.

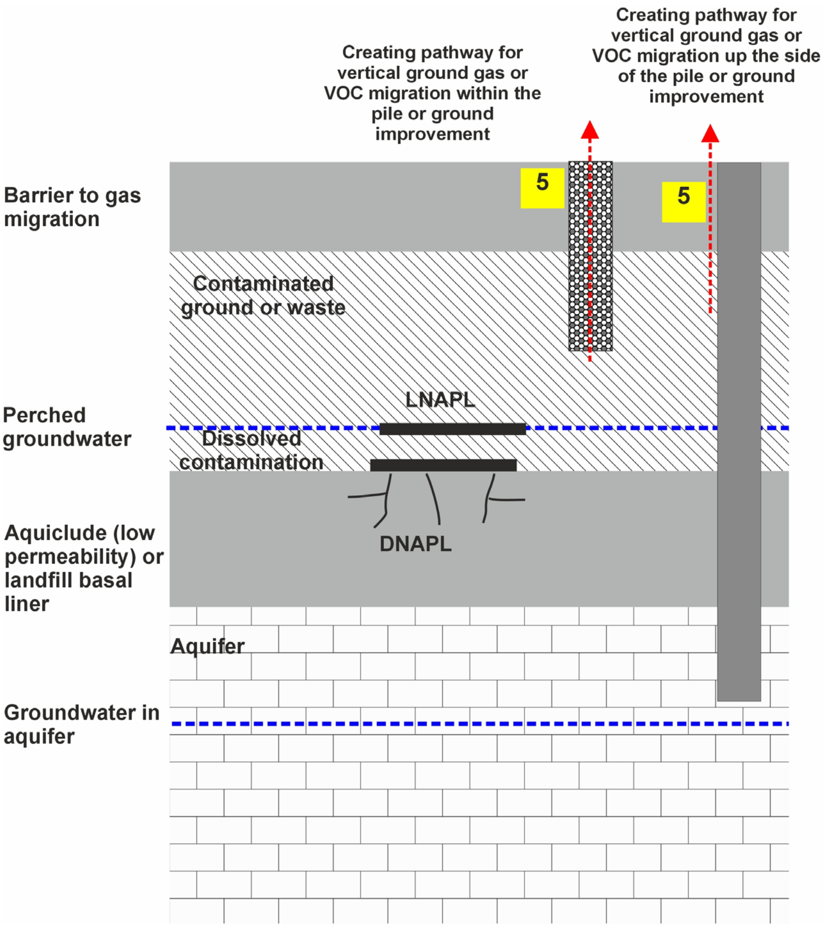


Figure 11.1: Pollution scenario 5: vapour migration to surface

Source/Contaminant

Gassing (e.g. methanogenic) landfilled waste or contaminated ground. Ground with VOC contamination or contaminated groundwater.

Pathway

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

Receptor

Users of built development; structures.

Description

Piles or ground improvement may be installed into strata that contain ground gas or where there is gas in the ground below a low permeability layer that is partially penetrated. On old landfill sites there may be an impermeable cap present to minimise gas emissions to atmosphere. There may be a low permeability layer of soil above old shallow mine workings that minimise gas emissions to the surface. If VOCs have migrated downwards they may be present in groundwater below a low permeability layer. This can occur for example in the River Thames Terrace Gravel Deposits in London where VOC contamination may be present below a cohesive alluvium layer.

Disturbance of capping layers or low permeability cover has the potential to create a migration pathway for landfill gas or VOCs. Where an active gas extraction system is present, the pathways could allow oxygen ingress that could impair the performance of flares or engines.

However, as discussed in Section A1.4, in most cases there is no risk of any type of piling or ground improvement system increasing gas risk to developments (Wilson and Mortimer, 2017). There are some specific circumstances where the design of the gas protection system should take account of the increased risk of gas migration via the piles or ground improvement. Piling or ground improvement will not increase the CS, it just needs the increased gas flow to be allowed for in the design of the protection system (normally it will only affect the sub slab ventilation rates).

Cases of known/inferred pollution or research findings suggesting possibility of pollution

A case of mine gas migration into houses occurred at a site in Gorebridge in Scotland where the presence of stone column foundations may have contributed to the problem (CL:AIRE, 2021 and case study 15 in Appendix 2). Two potential mechanisms may have occurred:

1. Direct connection of open shallow mine workings to the underside of the building via stone columns, although given the depth of the columns and superficial soils this seems unlikely.
2. Indirect connection with a thin granular layer separating the stone columns from the workings. Gas slowly diffused into the columns to create a reservoir that intermittently becomes large enough to cause migration into the building during falls in atmospheric pressure.

11.2 Specific issues - displacement piling methods

In general the normal displacement or replacement piles used for UK built developments will not pose a significant risk of increased gas emissions through a low permeability layer. The presence of ground gas or vapours should not be used as a blanket reason to not use displacement piling methods, especially precast concrete driven piles. They have significant advantages on sites where contamination is present because they avoid arisings.

There are circumstances where driven piles may increase gas emissions which are discussed below.

11.2.1 Specific problems and uncertainties

In most scenarios displacement piles will not cause a preferential pathway for upward gas or vapour. In heavily compacted or stiff clay cover, pile driving may cause cracking in the upper levels due to upwards expansion, although this is less likely where the stiff clay is confined by overlying soil.

Based on the available research, it can be concluded that in most sites in the UK where diffusive flow of gas through the ground will be dominant, large displacement-driven piles or replacement piles will not cause preferential pathways for ground gas migration. This assumes the piles are constructed with reasonable standards of workmanship and quality assurance in appropriate ground conditions (e.g. obstructions will not damage driven tube piles).

The only situation where gas migration may potentially be enhanced by piles other than H or I piles is where driven or bored piles penetrate a clay layer that is very thin (thickness less than two pile diameters), very heavily over consolidated (or stiff) and at shallow depth and that covers a gas source that is under pressure (see Section A1.4).

Other issues such as “pile whip” referred to in the previous version of this report are now known to not be an issue with respect to ground gas.

Soil may not close up around piles with re-entrant angles in cross section (e.g. cruciform or H or I section piles) and this can cause a preferential pathway. The risk reduces with increasing thickness of clay. Whether the pathway has any practical impact on the scope of gas protection measures required will depend on the generation rate of the gas source and the number of piles below the building. Sealing of piles into a concrete pile cap will also effectively cut off the pathway.

The implications of displacement piling through a low gas permeability cover layer might have on rates of gas flow can be determined by gas flow modelling. In critical cases gas monitoring can be undertaken around the top of piles after installation, using an instrument with a suitably low limit of detection (a few ppm level) to confirm emission rates (see case studies in Appendix 2 for sites where this has been carried out).

11.2.2 Piling method variations

Open tube piles should be plugged to prevent gas migration up them.

11.3 Specific issues - replacement piling methods

Replacement piles installed to reasonable standards of workmanship should not cause 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, except where the clay layer is less than two pile diameters in thickness and the gas below is under pressure.

11.3.1 Specific problems and uncertainties

None.

11.3.2 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.

CFAs 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. Modern rigs are instrumented to minimise the risk of such issues occurring.

11.4 Specific issues – sheet piles

If sheet piles are withdrawn after construction they could leave a small void in the ground. However, this is likely to close up quickly, and unless it is below a proposed building and there is a gas source such as a recent landfill immediately below the building, it is not likely to pose a significant risk for gas migration.

11.5 Specific issues - ground improvement methods

Penetrative ground improvement methods are shallow methods and would not normally penetrate a deeper aquiclude. In shallow layered alluvial soils they may penetrate clay layers that are preventing deeper migration of contaminants into granular alluvial layers below. In this situation stone columns can potentially provide a preferential pathway for contamination migration.

All the 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.

The relatively high permeability of the granular stone columns may make them a preferential migration route for ground gas or VOCs or a place where gas can accumulate in a reservoir. Indeed stone columns have been used specifically for purposes of gas venting.

If the gas flow is particularly high, the gas protection measures may need to be specially designed and enhanced. Where stone columns are installed in a low generation source such as made ground there is most likely minimal increased gas risk. This will depend on the rate at which gas can migrate to the columns and up the columns compared to the general gas emissions from the surrounding ground.

Where stone columns are present it is not appropriate to just increase the site CS. The BS 8485 (BSI, 2019) points system is also not appropriate to design the system where stone columns are present. The gas protection system and the sub slab venting should be designed based on modelling of gas generation, flow towards and accumulation in the stone columns followed by gas migration up the columns. The use of gas screening values or hazardous gas flow rates is not appropriate in this instance and the models should be based on diffusive and/or advective flow.

As described in Section A1.4 where columns are only located below foundations and are covered by the foundation concrete it is likely that the columns will not increase gas risk. Where columns are present below floor slabs and connected to sub-base then, if there are a sufficient number, they can potentially increase gas risk. Surface gas monitoring can be undertaken over the top of stone columns to confirm if emissions are significant.

If an active gas extraction system is already installed in the gas source, the provision of stone columns may allow ingress of air into the ground, with deleterious effects (in terms of gas generation and/or operation of flares or engines). However, on most development sites without in ground extraction this is not an issue. Active sub slab pressurisation systems can also force air into the ground via stone columns and effects should be carefully considered as this can increase the risk of spontaneous combustion where the source of gas is former mine workings, colliery spoil fill or a recent actively gassing landfill site.

Stone columns may also allow increased infiltration of surface water, increasing the possibility of contaminant leaching, though the built development cover will most likely limit this. A possible mitigation measure applicable to stone columns constructed by the bottom feed process is the use of cement fill at the base of the columns (see Section 3.9.3).

With vibro concrete columns the infill concrete is relatively impermeable and cast in contact with the surrounding soil. These will not form preferential pathways for gas migration.

12 Pollution Scenario 6 - Causing off site migration of ground gas or increased vertical emissions as a result of vibration or other effects from the pile installation process

12.1 Source – pathway – receptor

The pollution scenario is summarised in Figure 12.1.

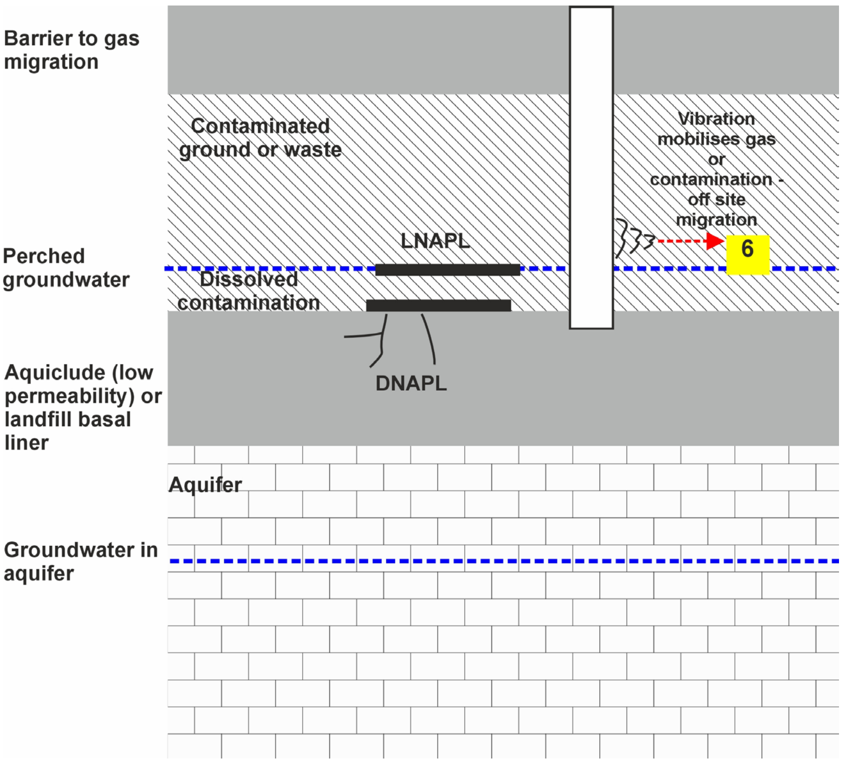


Figure 12.1: Pollution scenario 6: off site gas or vapour migration during installation

Source/Contaminant

Gassing (e.g. methanogenic) landfilled waste or contaminated ground. Ground with VOC contamination or contaminated groundwater.

Pathway

Through the surrounding ground.

Receptor

Users of built development; structures both on and off site.

Description

The installation of the pile or ground improvement can mobilise ground gas or vapours and potentially cause off site lateral migration. Vibration of the ground can cause it to densify, resulting in reduced volume for gas. This can cause displacement of gas, if there is a sufficiently large reservoir across the whole site and to the full depth of the stratum. This effect will not be significant if there are only isolated pockets of gas at elevated concentrations in a mass of ground that has generally low gas concentrations.

Cases of known/inferred pollution or research findings suggesting possibility of pollution

There are cases where vibration may have increased gas concentrations in gas monitoring wells. The main perceived risk is with vibratory methods of pile installation or ground improvement. However, there are no known sites where the installation of piles or ground improvement has resulted in an incident with increased gas or vapour concentrations inside buildings or other structures off site. On sites with low gas generation potential, the main limitation is the source itself in that it is not likely to be able to generate sufficient gas to sustain the rate of gas migration required to pose a risk to off site receptors (gas has to be continuously replenished to support off site migration).

12.2 Specific issues - displacement piling methods

If displacement piles are installed into ground with a large reservoir of gas that could also reduce in volume due to vibrations, there may be a risk of gas migration off site. This will be a short term effect. In high risk cases (where there is a large volume of gas and there are receptors within influencing distance and a migration pathway) perimeter gas monitoring and/or mitigation measures such as a vent trench may be appropriate. The number of piles to be installed will also influence risk. The more piles there are, the greater the risk of a large area being densified.

12.2.1 Specific problems and uncertainties

None.

12.2.2 Piling method variations

None that will significantly influence this scenario.

12.3 Specific issues - replacement piling methods

Replacement piling methods will not cause disturbance of the ground sufficient to cause off site migration of gas.

12.3.1 Specific problems and uncertainties

None.

12.3.2 Piling method variations

None that will significantly influence this scenario.

12.4 Specific issues – sheet piles

The vibration caused by sheet piling should not be sufficient or prolonged enough to cause significant volumes of gas to migrate off a site.

12.5 Specific issues - ground improvement methods

Ground improvement is designed to densify the ground and therefore there is the risk of reduced volume of space for gas. The gas is far more likely to migrate up the stone columns than any distance horizontally. Therefore gas migration off site is not considered to be a significant risk when installing stone columns. For other types of improvement, the vibration is not sufficient or prolonged enough to cause significant volumes of gas to migrate off site.

12.5.1 Ground improvement method variations

None that will significantly influence this scenario.

13 Pollution Scenario 7 - Direct contact with contaminated soil arisings that have been brought to the surface

13.1 Source – pathway – receptor

The pollution scenario is summarised in Figure 13.1.

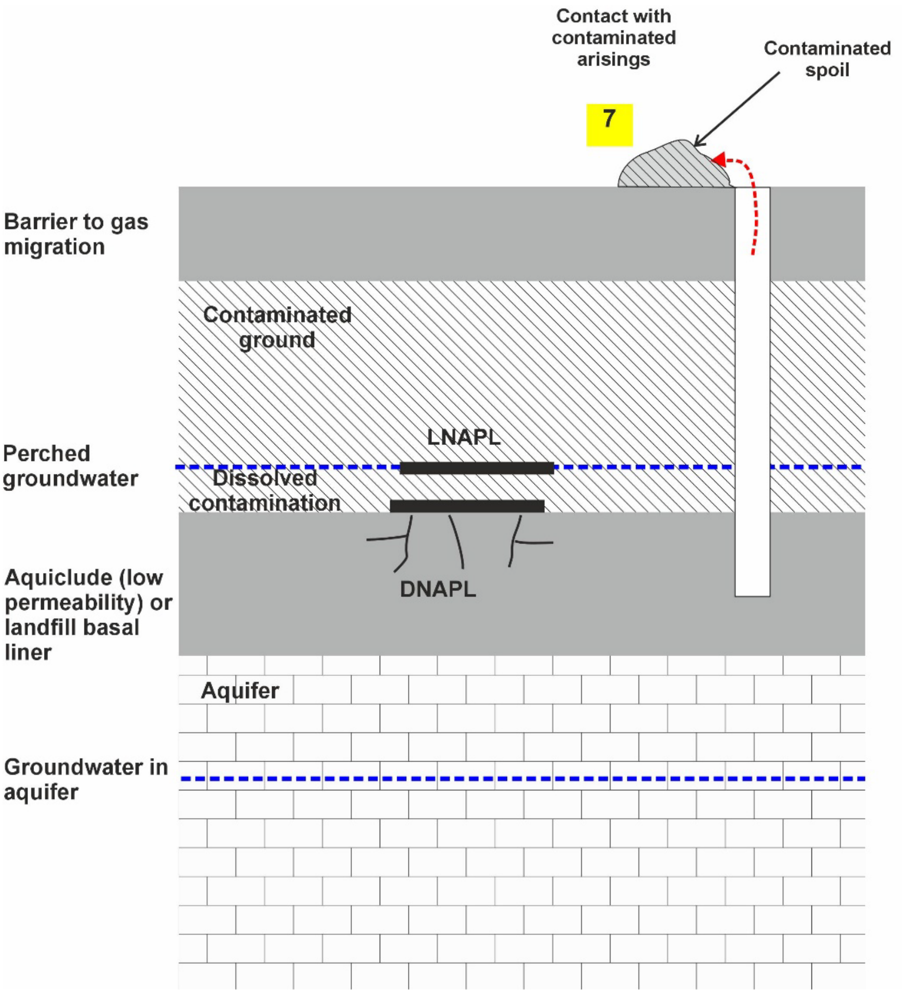


Figure 13.1: Pollution scenario 7: contaminated arisings exposed as surface

Source/Contaminant

Contaminated soil.

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 use of displacement piles (including sheet piles) eliminates arisings and avoids this risk (and the associated cost of disposal of the arisings). 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 vibro replacement and vibro concrete columns is in general considered to be negligible.

The bored 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.

There is an example where 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 acceptable limits and were not causing an airborne hazard.

13.2 Specific issues

Displacement piling, ground improvement and sheet piling will not generally create arisings that need to be managed. Replacement piling does create arisings which will have to be dealt with in accordance with Waste Management Legislation. This issue should be identified within the FWRA report and works verification. Since piling is a development, not a remediation activity, there is no exemption from landfill tax for these contaminated materials.

Disposal or reuse 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, include possible impacts on development construction workers and the public in the site surroundings.

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

14 Summary of Pollution Scenarios

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 1 to 7 is provided in Table 14.1. It is not based on site-specific considerations which are assessed in Table 6.2. This table should be used with care and not in a prescriptive manner. For a particular site, circumstances may be such that the generic level of risk indicated in this table is not appropriate to conditions at the site. This table does not consider structural or geotechnical issues. The risk has been classified into four bands from A to D as follows:

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

B: Low risk - Subject to appropriate workmanship, mitigation and QA/QC measures, to be outlined in the FWRA (as a section in the geoenvironmental report - see Chapter 17) and incorporated in the design and contract specification, this method is likely to be acceptable.

C: Moderate risk - 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 FWRA report. However, a more suitable piling or ground improvement method may be available.

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

Table 14.1: Indicative hazards associated with piling and penetrative ground improvement methods

Pollution scenario	Displacement piles	Replacement piles	Sheet piles	Penetrative ground improvement	Prefabricated vertical drains
1: Creation of preferential pathways, through a low permeability layer, to cause contamination of groundwater in an aquifer.	**A-D** (dependent on details of method)	**A-C** (dependent on details of method)	**A-B**	**D** (stone columns) **A** (vibro concrete columns)	**D**
2: The driving of solid contaminants down into an aquifer during pile driving.	**A-B**	**A**	**A**	**A**	**A**
3: Contamination of groundwater and, subsequently, surface waters by concrete, cement paste or grout.	**A**	**C-D** (dependent on details of method)	**A**	**A** (stone columns) **D** (vibro concrete columns)	**A**
4: Direct contact with contaminated soil or leachate causing degradation of pile materials.	**A-C** (dependent on pile materials and contaminants)	**A-C** (dependent on pile materials and contaminants)	**A-C**	**A-B** (dependent on pile materials and contaminants)	**A**
5: Creation of preferential pathways to allow migration of landfill gas or contaminant vapours to surface.	**A**	**A**	**A**	**C** (stone columns) **A** (vibro concrete columns)	**D**
6: Causing off site migration of ground gas or increased vertical emissions as a result of vibration or other effects from the pile installation process.	**A-B**	**A**	**A**	**A-B**	**A**
7: Direct contact with contaminated soil arisings which have been brought to the surface.	**A**	**B-C** (dependent on contaminants)	**A**	**A**	**A**

15 Mitigation Measures

The primary aim should be to avoid or minimise risk by the choice of appropriate piling or ground improvement method early in the design process. This will most likely give the most cost-effective solution. If this is not possible then in many cases it will be possible to remove a potentially adverse impact by the design and specification of mitigation measures. Mitigation measures can however be expensive compared to choosing a foundation solution that avoided the hazard in the first place.

Mitigation 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?

Potential mitigation measures that could be used to address some of the issues described in the preceding sections are noted in Table 15.1. 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 15.1: Potential mitigation measures

Mitigation measure	Relevant pollution scenarios (PS)
Use alternative piling/ground improvement method or variant	PS1, PS2, PS3, PS4, PS5, PS7
Design shorter piles to avoid reaching aquifer or penetrating aquiclude (found at shallower level)	PS1, PS2, PS3
Remediate shallow groundwater or NAPL prior to piling	PS1
Permanently lower shallow groundwater prior to piling (to remove positive hydraulic gradient)	PS1

Mitigation measure	Relevant pollution scenarios (PS)
Remove, immobilise or remediate contaminants in soil through which piles pass	PS1, PS2, PS4, PS7
Isolate contamination around piles from groundwater flow and infiltration (e.g. casings, surface cover, in ground barriers)	PS1
Use of bentonite during boring or driving	PS1, PS2
Grout pile or stone column after installation	PS1, PS5
Provide gas protection measure to building designed to deal with increased gas flow	PS5
Establishment of appropriate health and safety and waste management procedures for working with contaminated soil and disposal of arisings	PS7
Use alternative piling/column material or improved material specification (e.g. sulfate-resisting cement)	PS4
Coating of pile/column with protective product	PS4
Use of a permanent or temporary casing	PS4
Use pile with pointed or convex butt end or driving shoe	PS2

An important consideration when specifying mitigation measures is whether they could be adversely affected by subsequent building works and, if so, how this will be prevented.

Groundwater monitoring is not considered to be a mitigation measure. Monitoring is used to verify that the piling and any mitigation measures are working as expected. Monitoring is discussed in the following chapter.

Examples of how risk assessment has informed the choice of foundation type and mitigation measures are provided in the following three examples:

- At a site in the north of England, the National Rivers Authority (one of the Environment 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 was 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 its concern, and the solution features were treated by compaction grouting prior to piling.

- 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.

16 Quality Assurance and Verification During Construction

16.1 Quality assurance of pile or ground improvement installation

In general, all site works should be carried out under an appropriate 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 QA/QC 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 that 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 predate 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, hydraulic and contaminant flow rates, engineering techniques applied and environmental setting. Groundwater monitoring will generally only be required on areas of Principal Aquifer, or within SPZs, unless there are specific issues of local concern that justify monitoring in other locations.

The regulator 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. Consideration of contaminant flow rates is important when considering how long after works to monitor and the suitable location of monitoring wells to give early warning of issues. Flow rates in unfractured aquifers may only be a few hundred mm per day, and thus any contaminants released by piling may not reach a monitoring well located 15 m away until several weeks after piling has finished.

16.2 Groundwater monitoring

Groundwater monitoring should be undertaken in accordance with ISO 5667-11 (ISO, 2009) and other relevant guidance.

In high risk scenarios it may be appropriate to undertake groundwater monitoring to manage the risk to groundwater. Groundwater monitoring will generally only be required on areas of Principal Aquifer. It is beyond the scope of the report to advise on specific requirements but the following should be considered:

- Monitoring boreholes should be located in a suitably close downgradient position so that they can observe any effect of the piling in a reasonable time frame. All such monitoring wells must be protected during the placement of the working platform and throughout the piling works and for a suitable period thereafter;
- The groundwater monitoring response zones should be designed so they are at appropriate depths and have acceptable lengths;
- The monitoring wells should be installed to a high standard (following guidance provided by the Environment Agency, 2006b) and all wells should have a borehole record with soil and rock descriptions to BS EN ISO 14688-1 (2018a) and 14688-2 (2018b) by qualified and experienced ground engineering professionals;
- The sampling should use appropriate pumping methods and containers to obtain representative samples;
- A suitable period of baseline monitoring should be completed prior to piling works starting. The longer the baseline period the more likely it is that the full range of natural (before piling) variations in parameters will be detected, thus reducing risk for the contractor that mitigation measures may be required;
- The frequency of monitoring should be appropriate to the operations on site and the level of risk to the aquifer; and
- An action plan should be prepared after the baseline monitoring has been completed and prior to piling works starting with agreed limits, action levels and details of the actions to be undertaken and the timescales for those to occur. For example, actions may include initially taking additional samples or alternative monitoring test/test methods to confirm adverse results. In the worst cases piling may have to be stopped and an alternative method of working used or contaminant levels in the ground being piled through may need to be reduced.

Threshold limits will be site-specific and will need to be agreed with stakeholders. The targets are often a defined increase relative to baseline conditions. When setting targets it is important to recognise the detection limits of the proposed monitoring instruments to ensure that the target can be detected. There also need to be defined actions and timescales when threshold limits are exceeded. This should be a progressive escalation of actions depending on the exceedance of the thresholds. It is also important that monitoring data are shared with regulators as they are collected and not simply compiled into a report at the end of a project. This allows regulators to look for early warning signs that limits may be exceeded and allow preventative action to be taken.

16.3 Gas monitoring

On the majority of development sites gas monitoring is not normally required during or after pile construction. In some high risk scenarios it may be prudent to undertake gas monitoring around the top of piles (e.g. where piles penetrate through a thin confining layer into a gas source that is under pressure and generating large volumes of gas, such as recent domestic landfill or where mine gas could be present in open voids close to the underside of the piles or ground improvement).

It is not normally necessary to undertake perimeter gas monitoring for off site migration during piling or ground improvement works, unless there is a large reservoir of gas across the whole site that could be displaced. In that case the installation and monitoring should follow the guidance in BS 8576 (BSI, 2013a).

16.4 Reporting

All QA/QC information and groundwater or gas monitoring data should be collated into a verification report that can be included in the geotechnical feedback report.

17 The Foundation Works Risk Assessment Report

The piling and/or ground improvement risk assessment should be summarised in a Foundation Works Risk Assessment (FWRA) report. Submission of a FWRA report will not absolve the developer and their 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.

The report should be a dynamic document that is updated as site investigation data are collected and the foundation developed. It may well be that as it progresses responsibility for design changes to different organisations.

It is envisaged that the issues outlined in Box 17.1 should be addressed in the FWRA 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 17.1: Suggested contents of FWRA 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. A scaled diagrammatic CSM showing geological strata, proposed piling or ground improvement and receptors.
3. Initial selection of piling method. Justification, on the basis of geotechnical, structural, noise/vibration and groundwater or ground gas risk of the initially preferred method.
4. Identification of potential adverse environmental impacts that may be caused by the proposed works.
5. 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.
6. Identification of any changes to preferred method. Consideration of mitigation measures that may be required to prevent pollution, harm or nuisance occurring.
7. Identification of QA/QC methods and measures.

17.1 Examples of issues to be addressed in report

Reference is made to the potential environmental problems considered in Chapters 7 to 13 of this report for examples of issues to be addressed in the FWRA report:

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 Principal or Secondary 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 flow path for the migration of contaminated perched water or leachate into an aquifer or surface water body?

Pollutant scenario 2: 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 Principal or Secondary 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?

Pollutant scenario 3: Contamination of groundwater and, subsequently, surface waters or abstraction wells by concrete, cement paste, grout, support fluids or turbidity

- Does the chosen piling or penetrative ground improvement method involve the introduction of support fluid, wet concrete, cement paste or grout into the ground?
- Are there additives/pollutants present in the support fluid and is there a risk of these entering groundwater during the piling construction works? Where pollutants could enter groundwater from the use of support fluids in highly fractured settings, a groundwater permit or authorisation from the regulator may be required.

- Is the groundwater directly underneath the site, or in strata penetrated by engineered structures, considered to be in a Principal or Secondary 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?

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?

Pollution scenario 5: 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 (e.g. waste materials giving rise to methane, sulfur dioxide and carbon dioxide) or VOCs (e.g. BTEX volatilising from hydrocarbon contaminated soils)?
- Will the piling or ground improvement method of choice have the potential to create a preferential flow path 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?

Pollution scenario 6: Causing off site migration of ground gas or increased vertical emissions as a result of vibration or other effects from the pile installation process

- Will the ground be densified significantly by vibration?
- Is there a sufficiently large reservoir of gas to support off site migration?
- What is the likely duration of any potential off site migration?

Pollution scenario 7: 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?

17.2 Procedure for presentation of report

It is envisaged that any requirement for a FWRA will normally be enforced through the planning system. In England, the Environment Agency, as a consultee on planning application matters with respect to land affected by contamination would normally, by means of its consultation response, seeks 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 FWRA 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 planning process may be slightly different in Wales, Scotland and Northern Ireland, so it is important to check with the local planning authority and regulator for the details.

The procedure for the consideration of the FWRA 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 their professional advisers, the regulator 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.

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Appendix 1: Literature review

A1.1 General research (not related to land affected by contamination)

The majority of research carried out into the performance of piling and penetrative ground improvement methods has focused 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. Sulfate minerals are common in many soils (natural as well as from man-made sources) and concrete has a particular susceptibility to attack from sulfates. Other sources of aggressive chemical attack have also been studied, for example acids, alkalis, organic solvents and inorganic salts (CIRIA, 1983; Paul, 1994; Environment Agency, 2000).

A study in the late 1960s (Farmer, 1969) described how occasionally leaching of cement by groundwater flow was observed to cause honeycombing in the concrete of piles. Laboratory experiments were carried out to determine the effect of groundwater flow at various velocities on leaching of cement from a concrete pile.

It considered the critical particle size diameter for leaching of solid cement particles from the concrete through the soil. Freshly placed concrete would be expected to have a critical erosion velocity similar to soft earth and water flow above this would cause collapse of the wet concrete. However, the erosive effects are limited by the ability of water to transport the eroded particles through the surrounding soil, which acts as a filter. The research concluded that the most severe groundwater velocities likely to be encountered will be insufficient to cause leaching of cement from well graded, correctly placed concrete in a fluid state. Surface leaching to a limited depth could occur at velocities in excess of 0.05 m/s.

A1.2 Effect of contamination on piles

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 CIRIA into material durability in aggressive ground (CIRIA, 1983) identified the contaminants of concern and outlined the mechanisms of attack on structural materials in the ground. BRE carried out a major study which considered aggressive contaminants in land affected by contamination, the mechanisms of corrosion and degradation and acceptance criteria for use of structural materials in these situations (Paul, 1994). BRE completed further work investigating the corrosion behaviour of steel piles in the presence of various contaminants. A report on contaminated land risk assessment for building materials was published by the Environment Agency (2001). This describes the risk assessment process for assessing the effects of land contamination on the physical buildings, etc as opposed to human health. It considers the effects of aggressive substances, combustible material, expansive slags and unstable fills.

Research into corrosion attack on steel piles was carried out by the Steel Construction Institute (Corus, 2005). This included a review of published data and concluded that unless the soils are strongly acidic (pH <4), the underground corrosion of steel piles driven into undisturbed soils is negligible. This was irrespective of the soil type and characteristics. Evaluation of piles extracted from UK sites also confirmed that losses due to corrosion were negligible. In sites where sulfate-reducing bacteria are present (possible for example in landfill sites or alluvium), microbial corrosion of steel can occur. However, this has only been observed on shallow pipelines and not deep steel piles. The design of steel piles should make a suitable allowance for corrosion following the guidance in Eurocode 3 (BSI, 2007a) depending on how the ground is classified in terms of aggressiveness. Corus (2005) discusses several methods of reducing corrosion of steel piles including:

- Use of a heavier section;
- Use of a high yield steel at mild steel stress levels;
- Apply a protective organic coating;
- Apply cathodic protection; and
- Use concrete encasement where practicable.

Quantitative data are available regarding the effects of a range of contaminants on concrete, the most well-known being BRE SD1 (BRE, 2017). 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 land affected by contamination for an extended period. For example, Matheson and 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 sulfate concentrations and acidic conditions recorded at a site in Camberley and high sulfate, 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 1 mm 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 and it is limited to wet concrete.

Wilson *et al*. (2001) conducted tests to investigate the effect of hydrocarbon contamination on foundation concrete. The results indicate that petroleum hydrocarbons reduce the long term strength gain of concrete by up to 25%. This can be allowed for in design, thus avoiding the need for expensive sleeving or surface protection systems. Available evidence suggests that the effects of petroleum hydrocarbons on hardened concrete, which has achieved its design strength, are of limited concern. Creosote, however, can affect hardened concrete that has achieved its design strength. Where hardened concrete is likely to come into contact with creosote-derived contamination, a reduction in the assumed long term strength of concrete should be considered in the design. The use of dense concrete with a low water-cement ratio is also beneficial.

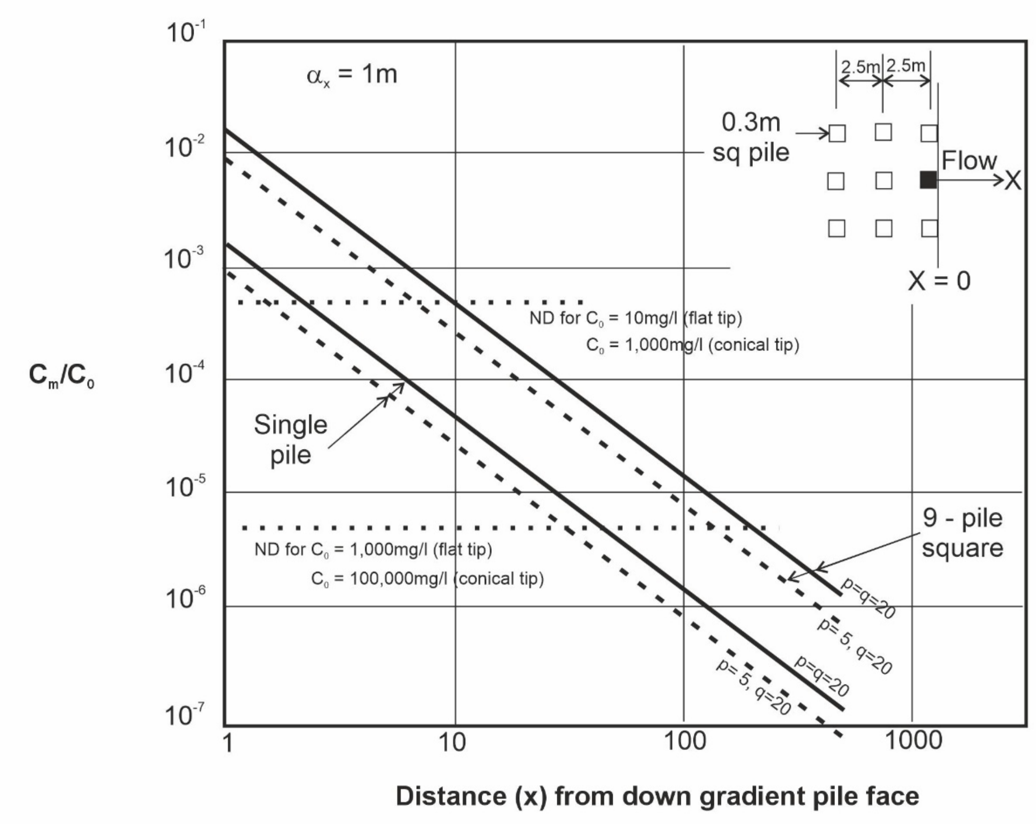
Alfach and Wilkinson (2020) looked at the effect of crude-oil-contaminated soil on the geotechnical behaviour of piled foundations. This was a parametric study conducted using numerical analyses (finite element). The research concluded that oil contamination of soils adversely affected the geotechnical behaviour of the soil supporting piles. It also reported that as the oil content of soil increases the hydraulic permeability reduces. The former can be managed by pile load tests that are normally carried out during construction to confirm the actually load capacity achieved on site.

A1.3 Migration of contaminants and groundwater pollution

There is now a substantial body of research into the environmental impacts of piling systems in contaminated sites from the UK, USA and Japan.

The earliest research was in the United States where Hayman *et al.* (1993) considered direct transfer of contaminants into groundwater below the tip of a driven pile. They provided analytical solutions to assess the volume of the soil plug pushed down below a driven pile and the resulting dilution of the direct transfer contaminants in static groundwater below the pile. The paper concluded that the potential for drag down of contaminants during pile driving is finite, in most cases insignificant, and can be mitigated effectively by the use of a conical pile shoe. They also conducted tests to assess migration of tetrachloroethene (PCE) and trichloroethene (TCE) down the pile-soil interface and concluded the risk of migration via this pathway was not significant.

Boutwell *et al.* (2000) and Boutwell et *al.* (2004) report on research carried out at the University of New Orleans, funded by the United States Environmental Protection Agency. It looked at different mechanisms for contaminant transfer by piles. They extended the analysis of Hayman *et al*. (1993) to consider dilution as the contaminant plume moved away from the tip of the pile (Figure A1.1). They concluded that direct transfer by driven piles does not pose a significant risk of contaminant migration. They repeated the mitigation measures from Hayman *et al*. (1993) regarding the use of conical tips to minimise drag down.

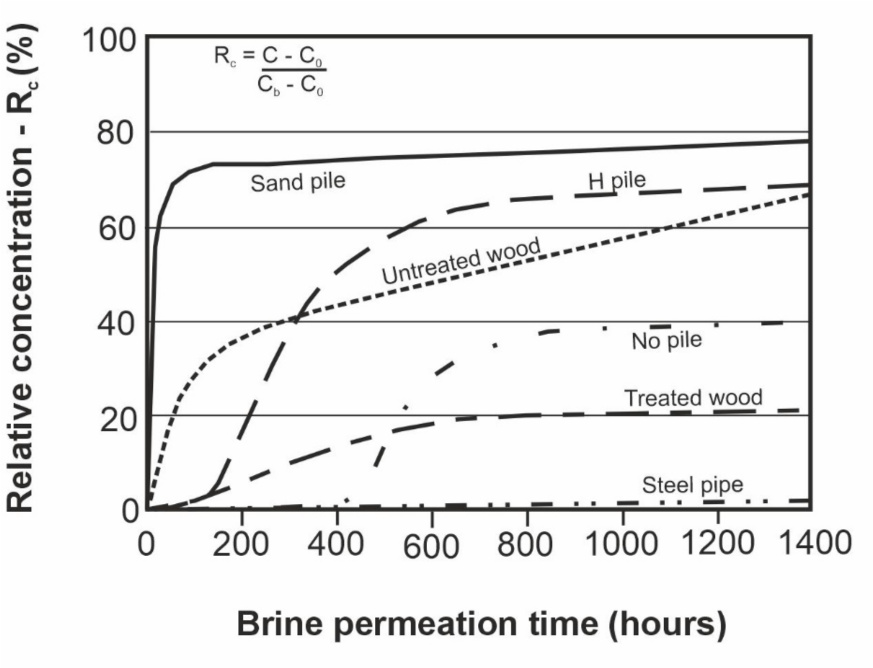


C_m = maximum concentration in the plume at a distance x from the pile group centre, C_0 =concentration of contaminant in upper stratum, α_x = Characteristic length in x-direction

Figure A1.1: Dilution of direct transfer contaminants (Boutwell *et al.*, 2004)

The results also included bench-scale laboratory tests to examine the possible impact of vertical contaminant migration along the pile-soil interface and, for timber piles, contaminant migration through the material of the pile itself. The tests modelled steel tube piles, steel H piles and timber piles driven through a clay layer into sand below.

Their research indicates that the potential for vertical contaminant migration down the pile-soil interface of steel tube piles is negligible. The piles densify the surrounding soil and reduce the permeability to the extent that brine permeation was greater in the no pile test than with the tube pile (Figure A1.2). They concluded that the same effects would occur with driven concrete piles. Steel H piles caused an increase in effective hydraulic permeability because of gaps that occur internally between the flange and web.



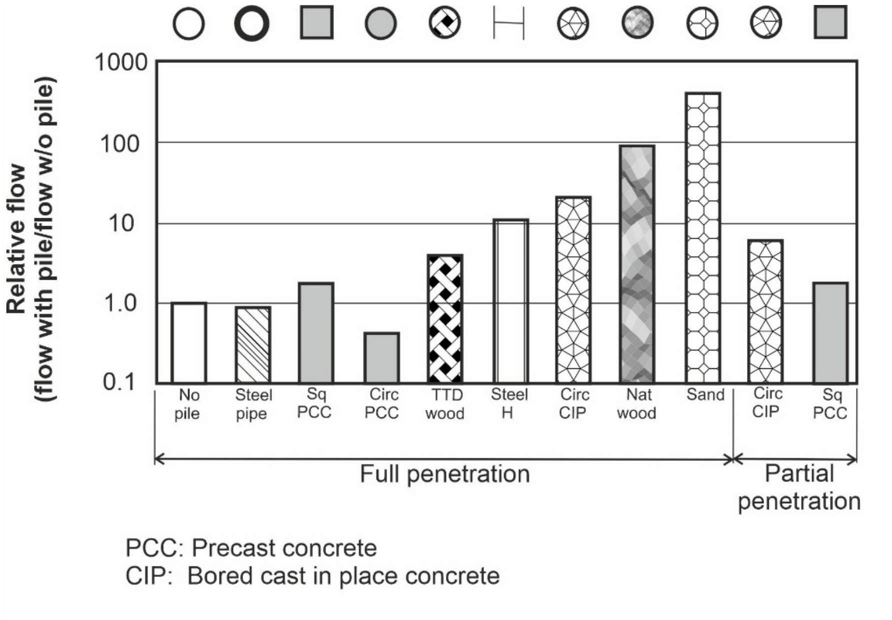
C = measured conductivity, C_0 =background conductivity, C_b = brine conductivity

Figure A1.2: Brine concentration over time (Boutwell *et al.,* 2004)

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.

The University of New Orleans work referenced in Boutwell *et al*. (2000) and Boutwell *et al.* (2004) was reported comprehensively by Satyamurthy (2005). The report discusses the same tests as Boutwell plus additional tests and research on driven and bored concrete piles. The author found that there is a higher relative flow of contaminants down the pile-soil interface of bored cast-in-place piles compared to driven piles. However, it was considered possible that this was caused by a lower concrete pressure in the model piles compared to full size piles. Concrete pressure in full size piles is sufficient to give intimate contact with soils (it has to develop skin friction). It concluded that driven steel tube and precast concrete piles with a conical tip minimise the risk of contamination migration.

The study also looked at the effects of full and partial penetration of an aquiclude (Figure A1.3). This concluded that depth of penetration of the aquiclude plays a significant role in contaminant migration down permeable piles (timber). There is low potential for contamination migration for relative penetration (length of pile/thickness of clay aquitard) less than 0.95. This information could be useful when considering the impact of ground improvement that might partially penetrate an aquiclude, for example in shallow layered alluvial soils.



Key:

Sq PCC – square precast concrete

Circ PCC – Circular precast concrete

TTD wood – Treated wood

STL H – Steel H pile

Circ CIP – Circular cast in place

Nat wood – Natural (untreated) wood)

Sand – sand pile (to represent worst possible case for flow)

Figure A1.3: Relative flow via piles (after Boutwell *et al.*, 2005)

The Environment Agency undertook a comprehensive research project to study the effect of piles on contaminant migration, in conjunction with the University of Sheffield (Environment Agency, 2006a; Emmett, 2005). Physical modelling was completed to assess the effects of driven piles (steel circular tube, square and H piles) and CFA piles installed into layered ground. Small-scale physical models of piles were driven or bored through a sand layer and clay layer into a lower sand layer. This replicated installing piles through a clay aquiclude into an aquifer.

The change in permeability and the deformations caused by piling were measured and photos of soil deformations were taken as the piles were installed (through a viewing window in the test cell).

The results showed that if a clay layer is greater than two pile diameters thick the driven circular piles are sealed (and this should also apply to square section piles) and do not form a migration pathway for contaminants. Thinner clay layers would have increased permeability and cause leakage. Steel H piles will cause leakage in clay layers with a thickness less than eight pile diameters because of voids formed in the corner by clay plugging between the flange and web. Good sealing was achieved with CFA piles regardless of the thickness of clay and unless piles are penetrating a very thin aquiclude the performance of CFA and driven piles is the same.

The amounts of soil pushed down through the clay by driven piles are small. Less material is dragged down from above as the clay strength increases. Drag down can be minimised by the use of conical tips, but given the small volumes involved, the risk of adverse effects is low in most sites. It is likely that conical tips will only be required in the case of very thin low permeability layers and significant contamination. The study also looked at the pile influence when driving through layered soils (Figure A1.4).

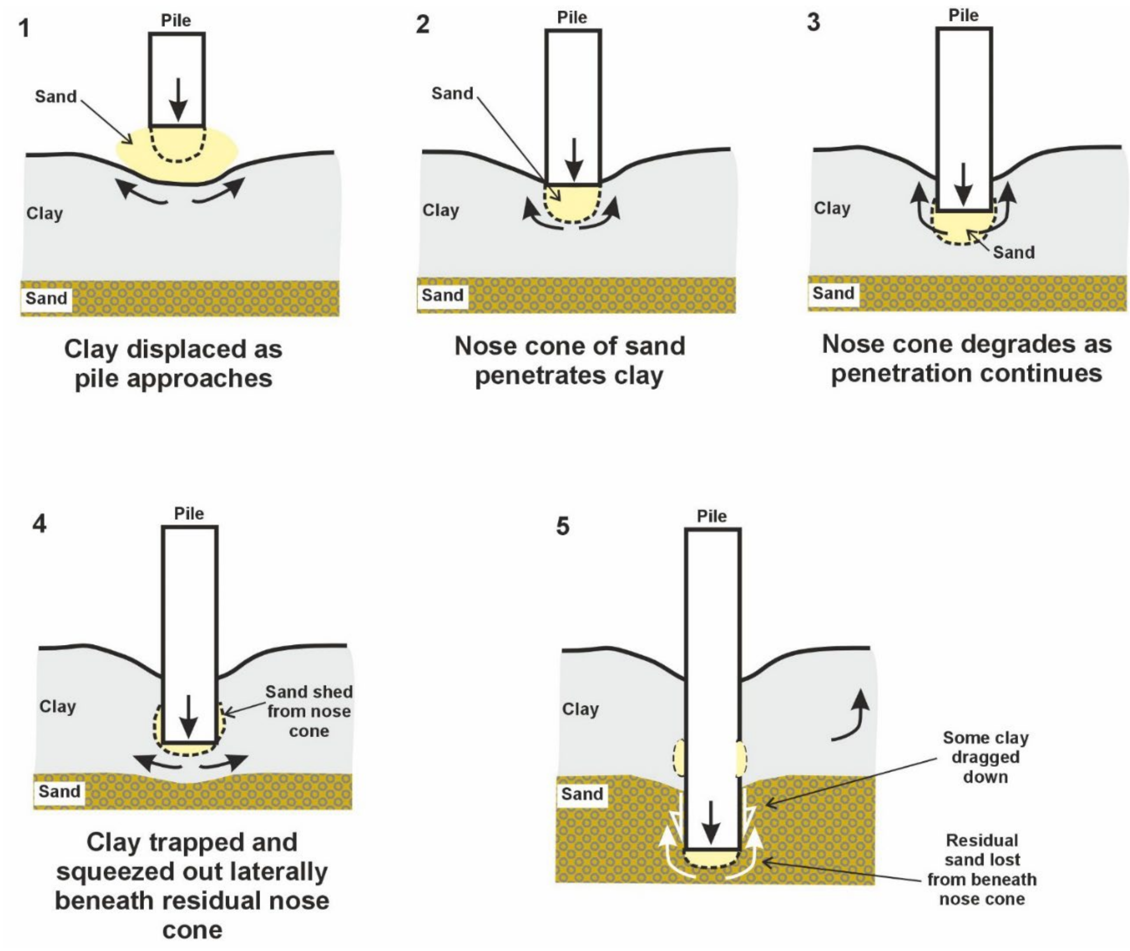


Figure A1.4: Schematic diagram of penetration stages in layered soil (Environment Agency, 2006a)

The authors did caution that the results were for a ductile clay and may be different for brittle stiff over consolidated clay. This is addressed in research carried out in Japan (see below). These results and conclusions are the same as those from the work at the University of New Orleans described previously in this section.

Research in Japan has been carried out on the impact of piles penetrating clay barriers (Takemura *et al.,* 2009; Kamon *et al*., 2005; Katsumi *et al.,* 2010; Amatya *et al.,* 2006). In Japan off shore landfills have been constructed that rely on thick marine clay deposits as a natural basal liner. These areas are now being considered for redevelopment and piled foundations are required. It was necessary to understand the risk of piling through the barriers with respect to contaminant migration into the underlying sand and gravel.

The impact on the natural clay barriers subjected to open and closed end (conical tip) steel pile construction was investigated using laboratory-scale models on a geotechnical centrifuge. Two different model clay soils were modelled: soft clay and stiff over consolidated clay with an over consolidation ratio of 2 to 5. Each model test had a group of 10 or 11 piles driven through a modelled 10 m depth of clay. Pile construction and pile lateral loading were simulated both in 1-G and High-G environments besides conducting advective-diffusive transport modelling for very long periods in the centrifuge (effective time of 60 years). Deformation of the ground due to pile deflection under lateral loading and its impact on leakage, and the change in resistivity of ground in the vicinity of pile due to contaminant movement were monitored. On completion of the centrifuge tests the models were excavated and samples of the soils taken for chemical analysis. An assessment was then made of groundwater flow and contaminant transport around the piles and compared to a pile free area.

Test results demonstrated that piling through soft ground did not cause an increase in the permeability of the clay barrier and migration of contaminant down the sides of the pile did not occur, irrespective of the types of pile and their stiffness. It was also concluded that piling would not drag down contaminated leachate during driving. The adherence between the clay and pile surface was adequate to prevent side wall seepage along the pile if the pile is installed vertically. This may not be the case for raking piles, which are not often used in developments but may be used in infrastructure projects (e.g. to resist lateral loads at bridge abutments).

Lateral loading and movement of piles did not cause leakage down them in soft clay even with a movement at the pile head of 13% of the pile diameter.

However, in the stiff clay there was some slight contaminant migration into the clay barrier during driving, although this may have been caused by an issue with the model. The closed end pile showed slightly more migration which may have been due to the formation of thin microcracks, a smeared zone or gap between pile and surrounding soil. It was considered that this would not be an issue at field scale and it did not reach the base of the modelled 10 m thick barrier. Therefore the thickness of any barrier is a consideration in a pile risk assessment.

Where the overlying sand was dragged down into the barrier, contaminant migration to half the barrier depth occurred (modelled depth of 5 m). The nature of a contaminated material above a clay barrier is therefore an important consideration in any FWRA. Lateral movement of piles in the stiff clay did not cause migration of contamination down the pile, it was much lower than in the soft clay. This was attributed to the small amount of movement at the waste/barrier interface (1% of pile diameter).

The authors concluded that:

- Pile construction through a soft or stiff clay barrier (modelled thickness 10 m) should not cause increased contaminant migration with or without conical tips;
- For soft clay there is no extra flow or leakage caused by driven piles;
- For soft clay lateral pile deflection does not cause extra flow or leakage through the clay;
- For stiff clay there is a slight deterioration of the soil (increased permeability around the pile) in the normal gravity model, which is probably attributed to a thin smear zone or micro cracks. Such deterioration was not seen in the piles driven in the high gravity model. The authors concluded that driving piles under the stress conditions equivalent to a real field scale is acceptable even for the stiff clay tested in this study. Lateral pile deflection also caused very minor effects on the barrier quality; and
- Sand intrusion into the barrier from above can have a significant detrimental effect on contaminant migration into the clay barrier. An adequate thickness of clay should

be considered in order to minimise the effect of such intrusion during pile construction.

Permeameter testing discussed in Katsumi *et al.* 2010 measured the transmissivity of the steel/clay interface in a permeameter. Four different clays were used and tested (marine clay, kaolinite, Fukakusa clay, and mixed clay).

The results provided an equivalent permeability for the interface of <1 x 10^{-9} m/s for driven steel tube piles through normally consolidated clays. For the clays tested there was a clear relationship between clay permeability and the interface transmissivity (lower permeability the lower the transmissivity) as shown in Figure A1.5.

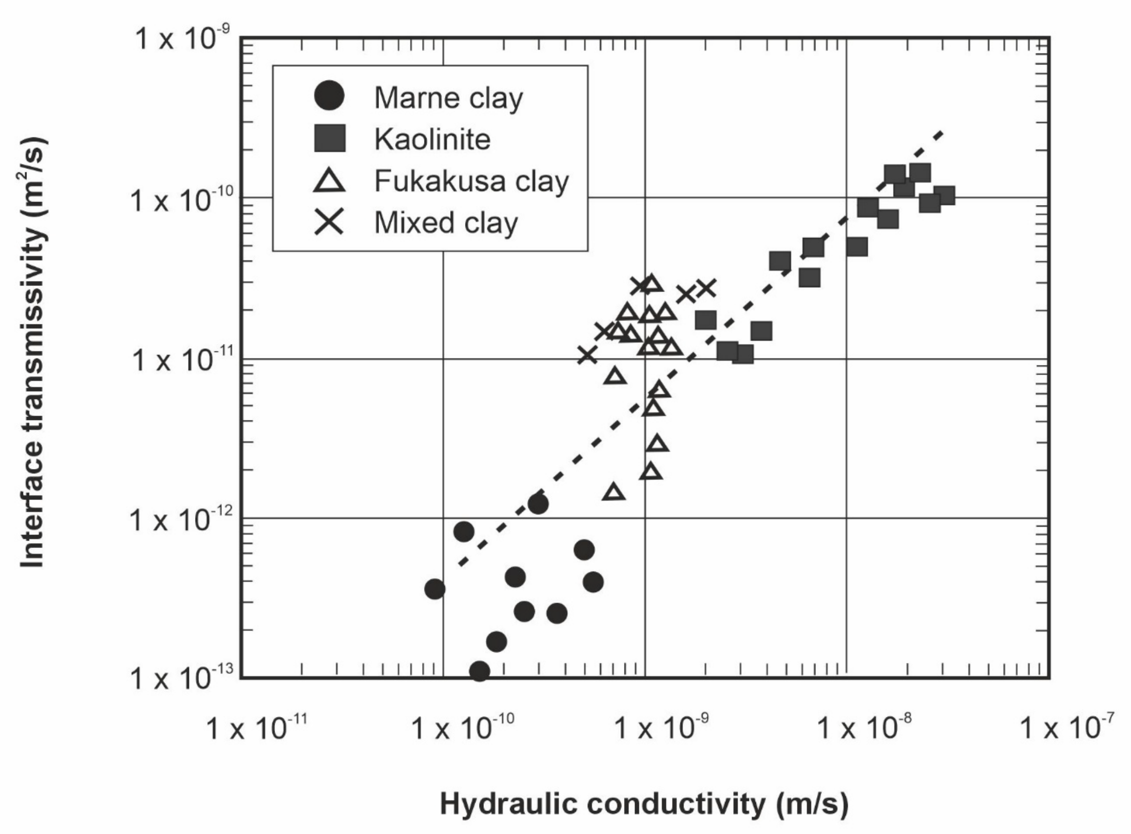


Figure A1.5: Interface transmissivity vs hydraulic conductivity for normally consolidated clay. Used with permission of Springer Nature BV from Katsumi *et al.,* 2010; permission conveyed through Copyright Clearance Center, Inc.

The results from the tests were used to calculate an equivalent permeability of a virtual clay column representing a pile (Figure A1.6).

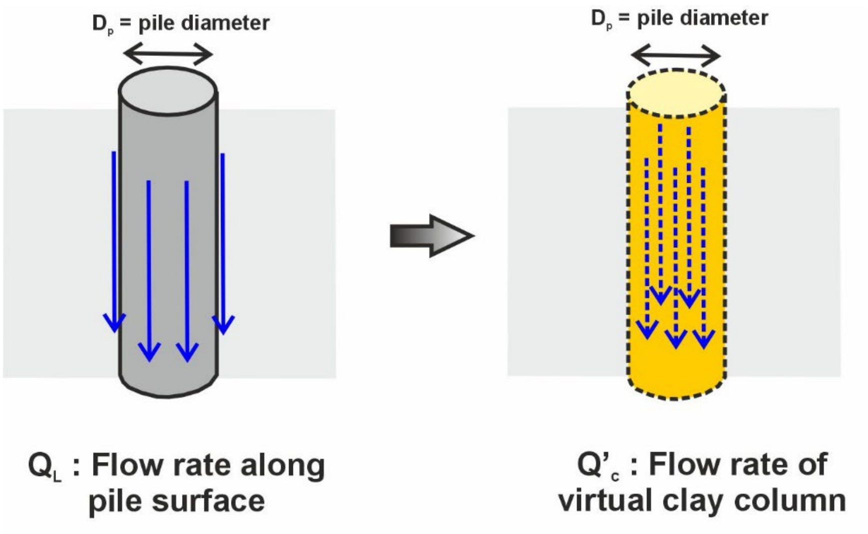


Figure A1.6: Virtual clay column. Used with permission of American Society of Civil Engineers from Kamon *et al.* 2005; permission conveyed through Copyright Clearance Center, Inc.

Flow rate-equivalent hydraulic conductivity is defined as the hydraulic conductivity of a virtual clay column which is assumed to have the same diameter as the pile and the same flow rate as the leakage flow rate from the interface between the clay and the pile as above in Figure A1.6. If the diameter of the pile is D_P (m), the flow rate along the pile surface, Q_L (m/s), can be calculated as:

$$Q_L = \pi D_P K_L i$$

For the virtual clay column, flow rate Q'_c (m^3/s) may be calculated as:

$$Q'_c = \frac{\pi D_P^2}{4} k_{eq,f}\, i$$

Where $k_{eq,\,f}$ is the hydraulic conductivity of the virtual clay column (m/s). Assuming Q_L = Q'_c then the following equation provides the flow rate hydraulic conductivity for the pile:

$$k_{eq,f} = \frac{4K_L}{D_P}$$

The results are shown in Figure A1.7. Flow rate-equivalent hydraulic conductivity values for the piles range from 1×10^{-12} to 1×10^{-9} m/s for normally consolidated clays.

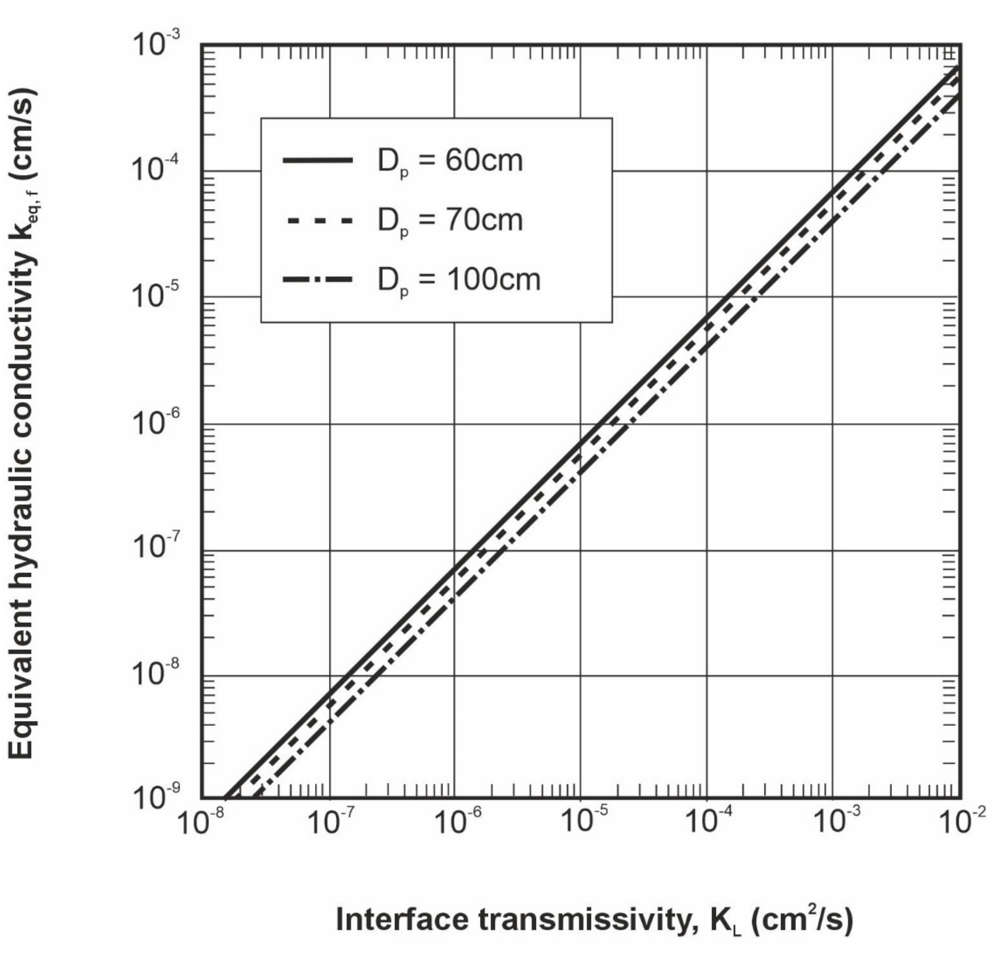


Figure A1.7: Relationship between interface transmissivity and equivalent hydraulic conductivity. Used with permission of American Society of Civil Engineers from Kamon *et al.* 2005; permission conveyed through Copyright Clearance Center, Inc.

Field monitoring data showed that when piles were installed through normally consolidated clay there was significant negative skin friction occurring. This shows the clay strongly adheres to the driven piles if the clay is deformable enough. In addition lateral pressure would close up any gaps. Therefore interface leakage should be negligible. In Japan a hydraulic barrier is required to have a minimum permeability of 1 x 10^{-7} m/s and a minimum thickness of 5 m.

Minder *et al*. (2020) considered the effect of corrosion in driven steel piles that penetrate clay barriers and whether it would increase contaminant migration down the sides of the piles. The anaerobic corrosion of steel leads to the release of ferric iron, which can exchange the adsorbed cations of clay minerals. The main hypothesis is that this changes the clay pore structure, and locally increases its permeability, creating preferential paths for contaminant transport.

Corrosion can also affect redox conditions in the immediate vicinity of a pile, which can lead to the precipitation of other ferrous phases or the reduction of structural iron in clay minerals. This can potentially increase the hydraulic conductivity of the clay.

Tomlinson and Woodward (2015) indicate that corrosion of steel piles in soils takes place both above and below the groundwater level. The maximum rate for one-sided steel corrosion normally occurs over a zone that is 0·5 m above and below the groundwater level. The United States National Bureau of Standards established the maximum rate for one-sided steel corrosion in disturbed soils as 0.08 mm/year. Thus a closed driven steel pile with a 6.35 mm thick wall, may lose about a half of its thickness, over 50 years of service. This is not critical for the pile-bearing capacity but may affect permeability of some clays around a pile.

Minder *et al*. (2020) conducted laboratory permeation tests in consolidation cells and also completed flow column tests using iron rich pore fluid. Based on the results of these tests, a constitutive model for the coupled chemo-mechanical behaviour was modified to account for different pore-fluid chemistry and incorporated into a finite-element code, to solve the problem of iron diffusion originating from a corroding source. The results were applied to a case study where steel piles had been driven through a 15 m thick clay layer into an underlying sand aquifer. The clay had a high montmorillonite content and was therefore expansive.

The results of the assessment showed that the combined action of diffusion, corrosion and increased convection, resulted in an overall increased transport rate and therefore a significantly earlier arrival of critical concentrations of the pollutant in the aquifer that was initially protected by a hydraulic barrier. Once this barrier is perforated by foundation piles subjected to corrosion, in some cases small concentrations can arrive in the aquifer up to four times earlier than implied by the initially low hydraulic conductivity.

The release of iron and its adsorption onto clay minerals increases the permeability of the soils (Figure A1.8). However, the increase is less than one order of magnitude, and on many sites this may not be significant.

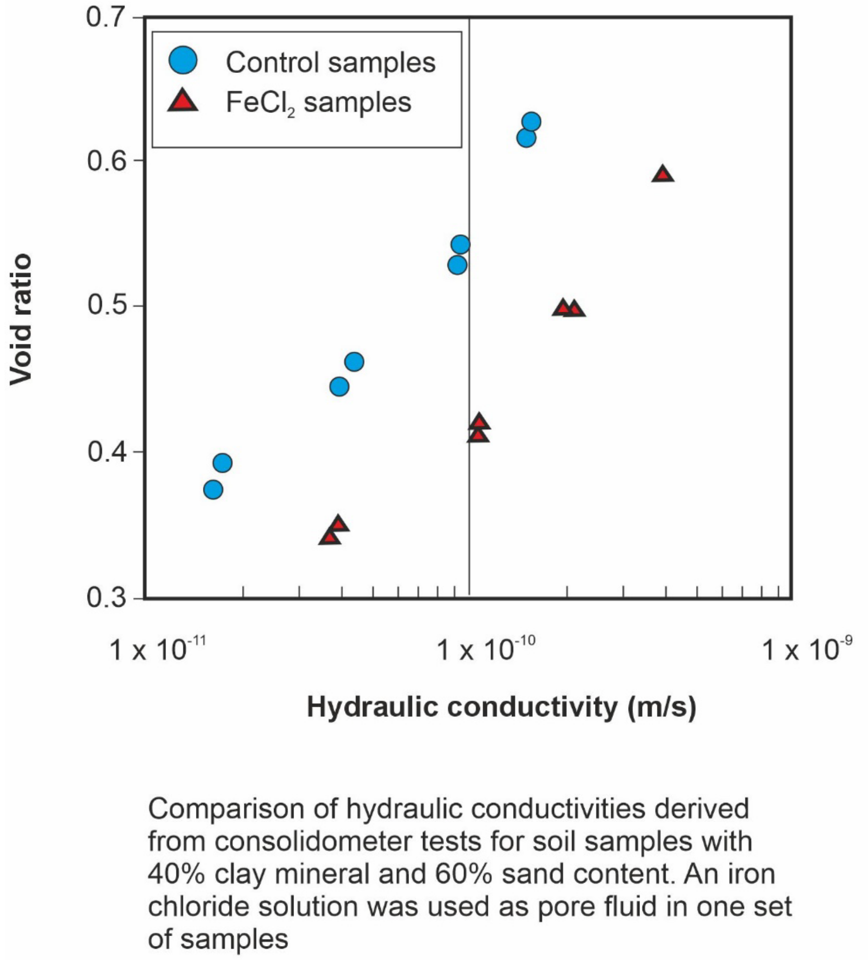


Figure A1.8: Effect of iron ions on permeability of clay. Used with permission of Emerald Publishing Limited from Minder *et al.,* 2020; permission conveyed through Copyright Clearance Center, Inc.

Although the research shows that corrosion in steel piles and its effect on permeability should be considered in a pile risk assessment the following should also be considered:

- The effects were found in montmorillonite rich clay (high plasticity). It is not clear if similar effects would be as significant with other clay mineralogy with a low plasticity;
- The effect is localised around the pile and reaches a 0.35 m radius from pile wall after 140 years;
- The increase in permeability is less than one of order of magnitude around the pile; and
- Contamination would reach an aquifer regardless of the pile, it just occurs more quickly when the piles are present (in the case study this was 140 years without compared to 30 years with piles).

In contrast to Minder *et al*. research by Rintu and Rani (2017) found that iron in the form of ferric chloride decreased the permeability of high and low plasticity clay. Tüfekçi *et al.* (2010) found that ferrous iron had no effect on the permeability of clay.

Çinar (2015) found that chlorinated solvents (TCE and PCE) can cause cracking in clays. Contact with pure chlorinated solvents does not have any effect on the basal spacing of clay minerals even after extended contact up to 319 days with sodium-montmorillonite clay and calcium-montmorillonite. However, contact of water-saturated sodium-smectites with DNAPL led to basal spacing changes and significant cracking over the time frame of weeks to months. The author concluded that passive contact with chlorinated DNAPL may lead to basal spacing changes in the sodium smectite clay minerals in the clay layers at these sites. The shrinkage of the basal spacing may result in cracking of clay allowing enhanced contaminant transport into the clay layers.

The chlorinated solvents also accumulate in low permeability clay layers and act as a reservoir of contamination that could more easily migrate towards or down the pile. These mechanisms are not fully understood and further research is warranted.

A1.4 Preferential pathways for ground gas migration

The key reference relating to ground gas migration around piled foundations is Wilson and Mortimer (2017). This has subsequently been supplemented by the information in the case studies in Appendix 2.

In most sites in the UK where diffusive flow of gas through the ground will be dominant (i.e. the gas source is not recent landfill or mine workings), large displacement-driven piles or replacement piles will not cause preferential pathways for ground gas migration. This assumes the piles are constructed with reasonable standards of workmanship and quality assurance in appropriate ground conditions (e.g. obstructions will not damage driven tube piles). Wilson and Mortimer (2017) advised that there is no reason to increase the category of risk associated with ground gas, or the characteristic situation (CS) in BS 8485 (BSI, 2019), because piled foundations are being used.

The only situation where gas migration may potentially be enhanced by piles other than H or I piles is where driven or bored piles penetrate a stiff over consolidated clay layer that is very thin (thickness less than two pile diameters) at shallow depth and that covers a gas source under pressure. However, even if an annulus does form or the permeability of the surrounding ground is increased, the effect may not have any practical significance. This will depend on the number and location of piles and on the gas pressure at the source. Where gas is driven by diffusion, piles would need to be at a very close spacing to have any practical impact on risk. Where gas flow is driven by pressure, the gas flows may be greater than flow by diffusion. Pile spacing again is a critical factor as well as the horizontal permeability of the ground which affects how fast gas can migrate from the gas reservoir to the piles.

In the majority of situations the use of driven or bored piled foundations will not provide a preferential pathway for gas migration towards the underside of a building and there will be no justification for increasing the scope of gas protection required on a site. Where there is a potential for the piles to provide a preferential pathway this does not increase the CS of the site (which is based on the gas risk posed by the source materials, irrespective of development type or building construction). It is not therefore valid to state, for example, that the use of piles will increase the CS from CS2 to CS3. The risk assessor should undertake a more detailed assessment of the influence of the piles and whether any increased gas flow up piles will be significant and require enhanced protection measures. For example, if there are few piles at discrete pile caps any increased gas flow up piles (if it does occur) may not be significant when compared to the gas flow from the ground surface across the whole building area.

It has been reported that lateral movement of the pile head in driven piles (pile whip) can occur (Talbot and Card, 2019). The Steel Construction Institute (SCI) has made it known that it considers that issues relating to whipping are overstated and that, by careful selection of pile, it can be eliminated (SCI, 2001). The original reference (Fleming *et al*., 1992) indicated it was an issue with slender steel H piles which are not widely used in the UK. Furthermore, consultation with several UK piling contractors indicates that this effect is rarely, if ever, seen and even if realised it will be minor. It will also be limited to the top of the pile and is not likely to be significant in most situations. Thus it will not form a preferential pathway for gas migration up driven piles (CL:AIRE, 2021). It should not be used as a blanket reason not to use driven piles where ground gas is present, nor to increase the gas risk classification on a site. One of the most common causes of whip in slender piles in the past has been overdriving in hard ground conditions. Other causes have been driving into stiff over consolidated clays, incorrect alignment of the piling hammer and use of raking piles (not likely in development sites). Whip can be avoided by good installation practice and avoiding use of driven piles in unsuitable ground conditions. It is not likely with modern piling equipment used for developments in the UK.

Driven hollow steel piles may form preferential pathways up the inside of the tube if they are left open (they are often infilled with sand and/or concrete which limits or prevents significant gas migration). The inside of the piles will not form a pathway if they are driven all the way through the gas source into an underlying stratum, especially if that stratum is clay or the toe of the pile is below groundwater.

Current industry practice and understanding is that ground improvement using stone columns provides a preferential pathway for gas migration from the ground to the underside of a building. However, this assumption has been challenged by ground improvement contractors. The following should be considered (Figure A1.9):

- In situations where the stone column penetrates a barrier to an underlying gas source it provides a more permeable pathway from the source to the underside of the building. However, even if it is considered possible that a preferential pathway could develop, the influence on the gas risk will depend on the number of columns, gas pressure and horizontal permeability. A significant effect is only possible where gas is under pressure and/or the columns are very closely spaced.

- Where stone columns are simply installed into the gas source (e.g. into made ground) they may not provide a preferential pathway compared to overall emissions from the whole building area. The installation of the stone columns densifies the ground around them which will reduce the permeability. Thus the risk assessor should consider whether emissions via the stone columns are likely to be greater than those from the building area, taking account of the reduced permeability.

- Where stone columns are only used below foundations (and not the floor slab) the top may be sealed by the foundation concrete which will reduce the risk of direct emissions from the stone columns occurring.

- Where stone columns are also used below the floor slabs and connect to the sub-base they have been implicated in gas emissions on two sites in Gorebridge and Redditch. This is discussed in the case studies in Appendix 2. The mechanism by which gas entered buildings is likely to have been expansion of gas that had accumulated in the columns between low pressure events. Whether the risk is significant will depend on the volume of the unsaturated pore space in the stone columns and the rate of gas accumulation in them.
- In low gas generation situations (e.g. alluvium) the risk posed by ground gas is already low and any increase from using stone columns will be negligible in most cases, even if there are confined sources such as peat layers. However, if there are numerous columns connected to the sub-base, gas could potentially accumulate in the columns and then be drawn into the building during low pressure events. As above whether the risk is significant will depend on the volume of the unsaturated pore space in the columns and the rate of gas accumulation. Peat deposits are normally saturated and also have a low permeability, which reduces gas emissions to negligible levels.
- There may be a short term increase in gas flow up the columns in cohesive deposits caused by dissipation of excess pore water pressure from the surrounding clay into the columns. Watts *et al.* (2001) reported that installation of stone columns into soft clay caused high pore water pressure to develop in the surrounding cohesive soil. The majority of the increase dissipated quickly after treatment was complete, with low dissipation of the residual pressure over the following two to four months. There were also instances of air escaping from adjacent stone columns during treatment (as a result of air jetting at the vibrating poker). Where several columns remained flooded at the surface during periods of high groundwater level, gas bubbling was noted for many months after treatment (again due to alleviation of excess pore pressures in the soil).

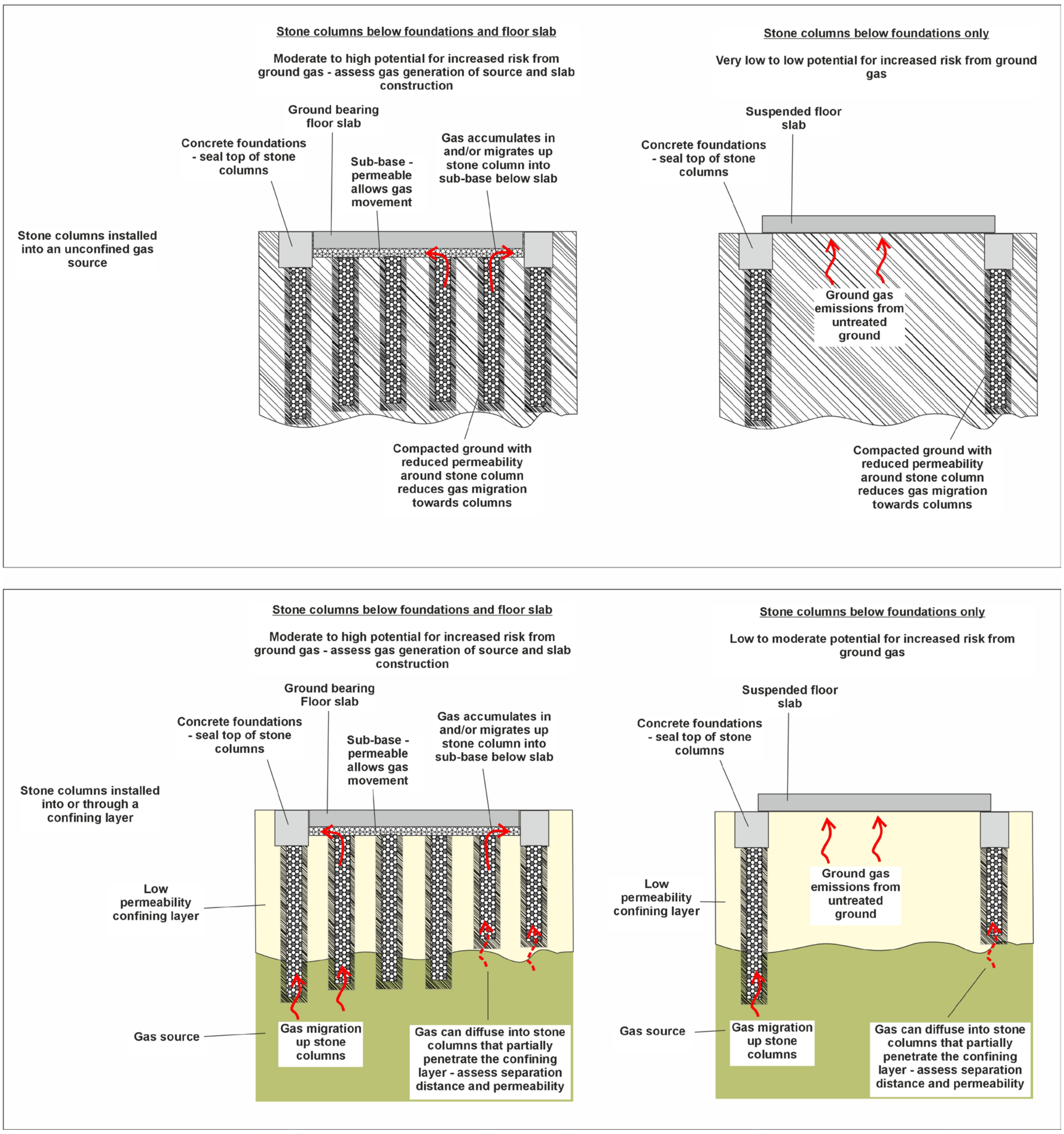


Figure A1.9: Stone columns and preferential pathways

A1.5 Effect of pile installation on gas emissions

The effect from installation of all pile types on the surrounding ground is localised. Compaction or disturbance of soils only occurs up to a few pile diameters out from the face of a pile.

Whilst this may locally increase the soil gas pressure, it is not likely to be sufficient to cause off site migration of gas. It can locally increase vertical gas emissions during installation around the top of the pile, but there will not be long term emissions.

The Environment Agency undertook a comprehensive research project in conjunction with the University of Sheffield (Environment Agency, 2006a) that looked at soil displacement around piles. Displacement of soil from driven piles extended a maximum of 1.5 pile diameters and the main zone of displacement was only 1 pile diameter. This is a small area of ground and not likely to have any significant effect on gas movement through the ground over a wide area, even when considering installation of pile groups.

Vibration from impact or vibratory driven piling or ground improvement can affect the wider area. It is a short term effect and not likely to cause significant sustained pore gas pressure and lateral movement of gas through the ground over large distances. It does not cause sustained excess gas pressure in the ground to support lateral movement. Modern equipment has also reduced the amount of vibration in the surrounding ground caused by pile driving. Vibration can cause loosely compacted soils to densify which reduces the soil pore space. This could potentially reduce the volume of gas that the soil can hold. Again, the effect is likely to be limited in most cases and unlikely to generate sufficient excess gas that could sustain off site migration, but could cause a temporary increase in vertical emissions around the top of the pile or stone column.

Bored piles and CFA piles do not cause any significant deformation or vibration and will have no effect on gas movement through the ground (and off site) during installation.

Note that when piling or completing ground improvement works into ground that may contain ground gas a risk assessment should be completed to assess the health and safety hazards during construction. The assessment should specifically consider the risk of pressurised gas being encountered and flowing at a high velocity up the pile bore. The risk of encountering highly pressurised gas increases with increased depth of the pile. Ground improvement works are not likely to extend to depths that would encounter pressurised gas. However some deep pile or barrette foundations may do so in certain situations (e.g. if extending below the Lower Lias Group in Bedfordshire or Buckinghamshire).

A1.6 Leaching from cement paste or loss of support fluid

If piles are installed into groundwater that has sufficiently high velocity, leaching or wash out of wet cement paste can occur prior to it setting. Farmer (1969) describes laboratory experiments to determine the effect of groundwater flow at various velocities on leaching of cement from a concrete pile. The research concluded that the most severe groundwater velocities likely to be encountered in matrix flow in soils, will be insufficient to cause leaching of cement from well graded, correctly placed concrete in a fluid state.

Surface leaching to a limited depth could occur at groundwater velocities in excess of 0.05 m/s (such velocities could occur in fractured rock).

The initial set of concrete when it stops being workable is around two to four hours. Final setting time (when it becomes solid) is between 24 and 48 hours. The concrete continues to gain strength after the final set and should reach its design strength within 28 days. Once it has reached its design strength scouring or wash out of cement by groundwater is not likely because the velocity will not be high enough.

Leaching of the concrete from piles has occurred in a project due to high groundwater flow velocities in granular layers within a substantial thickness of alluvium. Pumping for dewatering of an excavation resulted in groundwater flow at depth which caused inclusions in a significant number of piles. This was picked up by integrity testing and also the failure of test piles. The high groundwater flows would not have been evident during the site investigation (because the pumping was carried out as part of the construction). This highlights the importance of considering the whole ground model and potential future influences on groundwater velocity to ensure the correct piling method is used. In this case driven piles or cased bored piles would have been more suitable.

There is the potential for leaching of contaminants from the concrete but in practice the risk of this occurring is very low in most cases. The main considerations are potential leaching from cement replacements such as ground granulated blast-furnace slag (GGBS) or fly ash. Additives such as plasticisers may also be a potential concern.

Estokova *et al.* (2015) looked at leaching of metals from concrete. The results indicated that leaching from concrete containing GGBS is minimal and should not pose a risk to groundwater. Hillier *et al*. (1999) also found no significant leaching of metals from well cured concrete. Müllauer *et al.* (2015) looked at the leachability of concrete made with Portland cement, fly ash and GGBS. The release of substances during leaching is by dissolution of surface phases and/or by dissolution and diffusion in the pore water. The solubility of trace metals depends on several factors including bonding in hydration products, the ability to form aqueous complexes and precipitate-controlling phases. There is no correlation between the total amount of trace metals in concrete and leachability.

Replacement of cement with fly ash can result in greater amounts of trace metals such as vanadium, chromium and lead in concrete. However, the use of the fly ash results in a denser concrete which reduces the release of metals by diffusion.

The study tested leaching of aluminium, calcium, sodium, potassium, sulfur, silicon, barium, cobalt, chromium, copper, nickel, lead, strontium, vanadium and zinc from various concrete mixes including fly ash and GGBS. The results of the tests indicate that the addition of cement replacements (fly ash up to 40% or GGBS at 70%) and a lower water-cement ratio reduces the porosity of concrete and thus the potential for leaching. The leachable concentration of all the substances tested was a small proportion of the total content.

The release of alkalis into the eluate at the concrete surface occurs primarily by diffusion from inside the concrete. Thus, lower porosity reduces the release of alkalis. Replacement of cement by fly ash or GGBS can reduce the amount of dissolvable alkalis contributing to release.

In contrast to the alkalis, calcium, aluminium and sulfur release occurs, owing to the dissolution of portlandite, trisubstituted calcium aluminate ferrite (Aft) and, if present, alumina ferric oxide mono (AFm), mainly in the surface concrete directly in contact with the eluate. The contribution of diffusion from deeper in the concrete is secondary.

The release of vanadium is determined by the dissolution of vanadium substituted ettringite and/or calcium vanadate in the concrete surface, rather than diffusion of vanadium out of deeper concrete layers where it is fixed at the high pH of the pore solution. Cement replacement by fly ash can increase the total vanadium content of concrete significantly. However, only about 2% of the total content is available for release in the tank leach tests.

The release of chromium is due to the dissolution of hexavalent chromium (Cr(VI)) substituted AFt and, if present, AFm in the concrete surface region and, to a lesser extent, diffusion. Cement replacement by fly ash or GGBS with a higher chromium content does not increase the release of chromium proportionately. At most 2% of the total is able to dissolve in the tank leach test, the remainder being incorporated as Cr(VI) in calcium silicate hydrates or precipitated as trivalent chromium (Cr(III)) in the hydroxide.

Barium and strontium are released by diffusion and surface dissolution processes. Although replacement of cement by fly ash can increase the total content significantly, the release in leachate decreases.

Zinc release occurs mainly by surface dissolution controlled by hydroxides, silicates or calcium silicate hydrates with incorporated zinc.

The release of copper, nickel, cobalt, and lead is minimal for all binder compositions owing to the low solubility of these metals in the eluates and the pore solution.

Leach testing was undertaken in Ireland on samples of peat stabilised with various binders including fly ash, furnace slag and gypsum (RSK ENSR, 2004). This identified that as reactions between the soil and binder begin, the pH rises to between 11 and 12. When cement is used, the pH rises to 12.5 as the cement reacts with moisture in the soil to produce calcium hydroxide. However, it identified that the risk of migration of the uncured cement or the calcium hydroxide was low because of the speed of the reactions. The RSK ENSR report indicates that the German Cement Works Association and Institute for Construction Research has carried out extensive research into the environmental effects of cement products. Substances that could potentially enter groundwater are soluble alkalis and trace elements. However, most trace elements in cement are insoluble and the only one that could be released is Cr(VI). This is only available in a small contact zone (less than 60 mm) and only for a short period until the cement cures (less than 24 hours) and does not cause any lasting or significant impact on groundwater. In the hardened state the chromium is insoluble.

The RSK ENSR report provides the results of leaching tests on samples of crushed concrete. These results showed that heavy metals are fixed in the hardened concrete and the quantities released into leachate are minimal.

Taylor *et al*. (2018) discuss the use of bentonite to support piles drilled into Chalk in East London. The interaction of the Chalk and bentonite was of concern. Prior to the design of the piles and specification of the support fluid detailed stratigraphical logging of the

Chalk strata in boreholes was carried out using known marker bands such as flint bands and marl seams. This helped to develop a ground model. Other investigation methods were employed to assist in developing the Chalk stratigraphy, including downhole geophysical techniques, fluid temperature, fluid flow, resistivity, density, calliper and natural gamma measurements. Other downhole tools, such as downhole optical imaging, were also used. An important aspect of the design was understanding the behaviour of the bentonite support fluid when used in Chalk. There were concerns about the possible interaction of the bentonite with the Chalk and therefore bespoke laboratory tests were carried out on core samples using two commonly used bentonite types. The tests were carried out at two bentonite concentrations with Chalk samples from three depths as well as control samples without Chalk.

In general, the results from downhole optical imagery correlated with the recovered Chalk cores and confirmed the absence of voids and any degraded rock, which minimise bentonite losses. There was little loss of bentonite during working pile construction. However, during construction of a test pile, bentonite losses were much higher in an area of Chalk affected by faulting and were reported to be up to 2 m^3/h (Ganesharatnam *et al.,* 2018). During working pile construction, a standpipe piezometer tip was installed approximately 2 m from the first working pile. It was monitored regularly during and after construction and no bentonite leakage was observed.

Permeability values of the Chalk at the level of the pile toes (from permeability tests using packers) ranged from 1.3 x 10^{-8} m/s and 1.4 x 10^{-6} m/s. The permeability of the Chalk is governed by bulk loss through discontinuities rather than permeation through the Chalk mass. The variation in permeability was therefore considered by the authors to be primarily due to the extent of fracturing within the Chalk local to the *in situ* test pocket.

Groundwater samples from the Chalk were tested to check if the ions present in the groundwater might have an impact on the bentonite slurry. The results indicated that the groundwater chemistry was not expected to have any impact on the properties of the bentonite slurry (Jefferis, 2014). The primary concern of the authors was the impact of the filter cake on the shaft friction of the pile. However, the type of investigation they carried out is also important to determine the risk of loss of bentonite and its impact on groundwater quality.

The results of testing on the slurry and Chalk mix for various properties (density, pH, Marsh Funnel test, viscosity, fluid loss and gel strength) demonstrated that the mix of bentonite and Chalk into a slurry had no effect on fluid loss or filter cake thickness. Another important result is that the filter cake developed a very low permeability within 14 seconds of pressure application. The filter cake permittivity (permeability divided by thickness) was ten times less than that of the Chalk disc. This would minimise fluid loss into the Chalk.

However, bored piling into Chalk is complicated and there are several examples where the presence of solution features has led to large-scale loss of concrete into the ground and failure of piles (e.g. The Guardian, 2021). The site investigation should be thorough and the potential for this to occur should be considered when choosing a suitable piling method.

A1.7 Turbidity

In recent years there has been an increased recognition of the potential risks to groundwater abstractions from turbidity that can be created by piling. There is currently no authoritative UK guidance on how to assess this risk (Rolfe and Speed, 2023). Turbidity is a significant concern in the Chalk aquifers of south east England because they are an important water supply resource. There is little information on the migration of Chalk turbidity through Chalk aquifers to abstraction boreholes during construction activities. However, there have been instances during ground investigations for High Speed (HS) 2 when turbidity has increased at an abstraction borehole due to drilling work below groundwater level.

The Chalk is a dual permeability aquifer in which flow rates are very low through the rock matrix and much higher through fissures. In some areas the fissures are enlarged by solutional weathering which can result in extremely fast flow rates. Typically, permeability is highest in the valleys and lowest in the interfluve areas.

Planning consents for developments in sensitive areas such as the SPZ 1 of a public water supply borehole often include conditions to assess and mitigate risks to the abstraction, and can specifically require turbidity to be assessed.

The reason for this is that water companies are required by the Drinking Water Inspectorate (DWI) to regularly test groundwater for turbidity. Turbidity is used as a marker for risks from pathogens such as Cryptosporidium and E. coli. However, the turbidity test does not differentiate these from mineral particles (Rolfe and Speed, 2023). If increased turbidity is detected, regardless of the source, the operator has to shut down the abstraction until mitigation has been implemented (Burris *et al.*, 2020). Increased turbidity can also compromise the disinfection process, and where the abstracted water is treated using membrane filters then the filters can become fouled by the turbidity, resulting in replacement costs running to potentially millions of pounds. Anderson (2009) also indicated that high turbidity can be associated with elevated polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons, and radioactivity because many contaminants adsorb onto the mobile soil or rock particles, which then transport high concentrations into the wells. Under low turbidity conditions these constituents usually do not impact the borehole water quality.

The consequences of causing turbidity at a supply borehole are therefore very severe for both the water company and the polluter and it is in everyone's interest to minimise the risk of it occurring because of piling or ground improvement works.

The turbidity of water to be disinfected must be less than 1.0 nephelometric turbidity unit (NTU). In areas where background turbidity is elevated, water companies may apply their own more stringent criteria, which can be as low as 0.2 NTU. These are lower than the UK Drinking Water Standard of 4 NTU when supplied at consumer's taps (DWI, 2016).

The period of most concern to water companies with respect to the risk from turbidity is when demand is very high and the resilience in the supply system is lowest (between May and September inclusive). Timing is therefore important in planning the construction works and with regard to the most appropriate mitigation for turbidity risks. However, this does not mean that it can be ignored at other times of year.

The low target values that must be achieved by the abstractor, present a significant challenge to pile designers, contractors and risk assessors. Rolfe and Speed (2023) suggest that a qualitative approach can be employed to assess the risk of piling causing excessive turbidity. By development of a robust conceptual site model (CSM) similar to those used for land contamination risk assessment, the potential risks can be qualitatively assessed. The principles of source, pathway and receptor creating a potential pollutant linkage are similar to those set out in the LCRM guidance (Environment Agency, 2023). For the piling CSM the greatest emphasis is on the pathways and the source. The development of a scale cross-section is strongly recommended to both inform the assessment and to communicate it to regulators.

Where qualitative assessment identifies potential risks, semi-quantitative assessment can be undertaken to better understand risks and inform mitigation measures. In higher risk scenarios the CSM could be further developed with site-specific fracture details. The research by Farmer (1969) described in the previous section could be used to assess whether groundwater velocities are sufficiently high to transport turbidity to an extraction well. Information on particle sizes of the turbidity in Chalk is provided by Anderson (2009). The particle size distribution of particles mobile in the Chalk aquifer is small and varies from about 100 microns (µm) down to less than 1 µm.

A1.7.1 Sources of turbidity

Chalk generally comprises coccoliths, foraminifera and other shell debris, cemented together to lesser or greater degrees. The coccoliths are particularly small, being several µm across. Any construction work can result in disintegration of the Chalk mass into these fine particles which, when the work is below or close to the groundwater level, has the potential to induce turbidity in groundwater. Due to their small size these particles do not settle quickly and can rapidly migrate through fissures in the aquifer, especially under pumping conditions within the cone of depression of an abstraction borehole.

The primary source of turbidity during piling is mechanical abrasion of the rock producing a microscopic rock ‘flour’ in suspension in groundwater. Different piling methods are likely to result in different degrees of turbidity. Loss of cement fines before cement has cured is also a concern if groundwater velocities are above a critical threshold (see Farmer, 1969) as is loss of support fluid. The turbidity created will also be a function of the strata in which the piles are installed. No studies were identified that quantify the turbidity created by piling. However, qualitative assessment can quickly identify methods that are likely to create more turbidity. Rotary methods are likely to generate turbidity, particularly when operating in rock or fine-grained strata, due to the mechanical action of the rotating parts abrading the rock or soil. For context, measurement of turbidity during drilling of 194 mm diameter boreholes in Chalk using a tri-cone rock roller reported turbidity in thousands of NTU (maximum of 4,240 NTU), while rotary cored boreholes generated up to 452 NTU (Burris *et al.,* 2020), although it is uncertain whether either would be representative of piling turbidity because the rotation of piling augers is much slower than drilling rigs. Driven piles are expected to produce less turbidity not least because they are less likely to penetrate as far into the Chalk or rock as some bored piles. However, driving is thought to de-structure the Chalk, leaving a low strength “putty” around the shaft (Jardine *et al.,* 2018) potentially causing some turbidity.

Particle size of the aquifer will be important in determining extent of turbidity migration, with finer particles migrating further in an aquifer since they can be held in suspension at lower velocities and migrate through smaller pore or fissure sizes. Particle size will be largely a function of the geological strata. In a sandstone, particles formed should mainly be sand sized since the bonds between grains will be weaker than the bonds within grains. Analysis of settled turbidity produced by tunnel boring machines in Chalk reported 80% of particles to be <10.5 μm and 20% <0.1 μm (Burris *et al.,* 2020), which was attributed to the size of intact coccoliths in the Chalk (approximately 10 μm) and fragmentary material, respectively.

For turbidity to migrate beyond the source area then the groundwater velocity must be greater than the settlement velocity of the particles to keep particles in suspension. For intergranular flow, the porewater velocity is unlikely to exceed settlement velocity, whereas in fractured rock the groundwater fracture velocity can exceed settlement velocity (Burris *et al*., 2020; Farmer 1969)). In SPZ 1 the groundwater velocity and gradient can exceed those under natural conditions, with both increasing nearer to the abstraction point.

The lateral and vertical location of the source relative to the receptor will also be important in determining the risk. Piles installed in saturated strata to a similar depth as the abstraction intake will be at greater risk than piles that are much shallower than the intake, and risks increase with lateral proximity to the abstraction (see Figure A1.10).

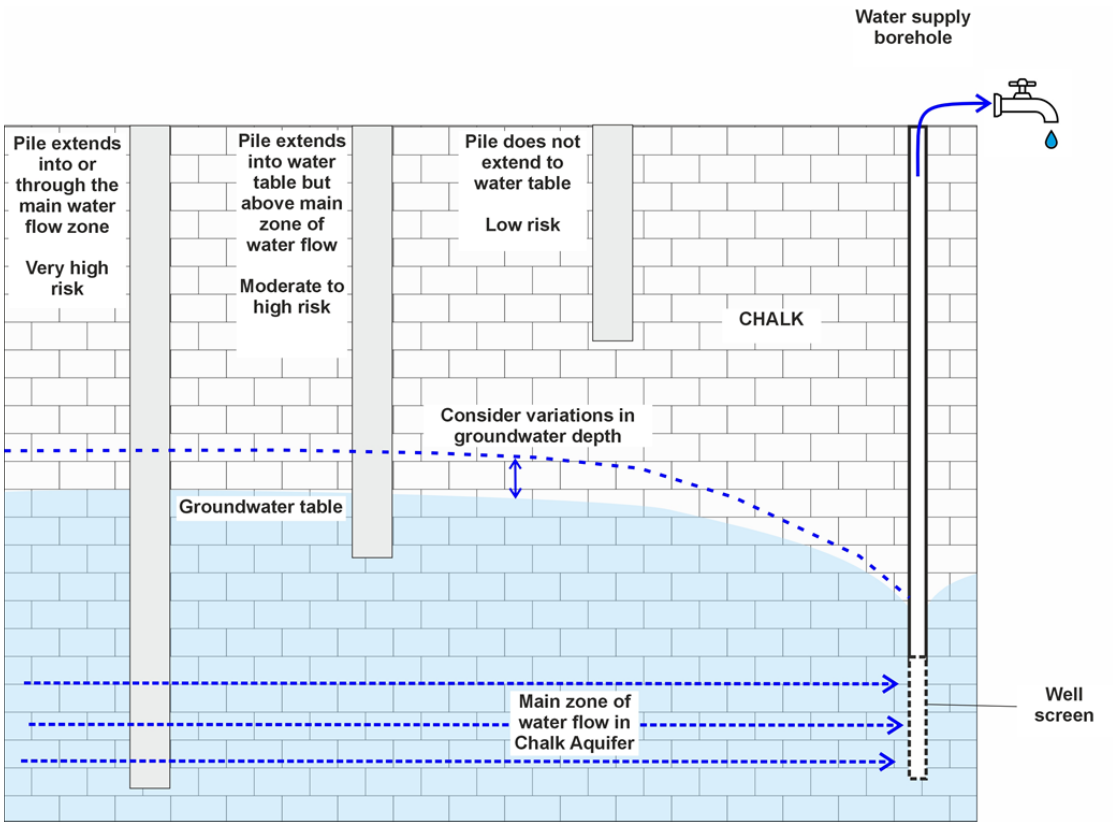


Figure A1.10: Risk of turbidity from piling in Chalk

The scale of the project will affect the source magnitude, with both the number and depth of piles, and the duration of piling affecting the release rate of particles.

Other sources of turbidity include natural background of mineral particles in the aquifer, precipitation of solutes such as manganese and microbial contamination by bacteria and protozoa. The natural turbidity can also be affected by weather events such as intense rainfall and changes in groundwater level. Operation of the abstraction will also affect the turbidity of abstracted water. Stop/re-start cycles or changes in abstraction rate are major factors.

Erosion of cement from fresh concrete can potentially cause turbidity where groundwater flows are high (Farmer, 1969). Bentonite support fluids could also potentially cause turbidity. However, it is normally used to form a filter cake on the pile walls to prevent loss of fluid onto the ground so the risk should be low if good quality control procedures are followed, and the ground is well characterised in the site investigation. The main risk will be if a pile hole encounters a void and the bentonite can move out of the hole. If the void is well connected to the aquifer this could result in migration. However, when the bentonite is not agitated it will form a gel which will limit the potential for migration. Consideration of the flow velocity is required to assess the risk of particles migrating into the aquifer.

A1.7.2 Pathways

This is likely to be the most critical part of the turbidity assessment, since in most cases it will not be possible to change the receptor, and there will be other constraints on the choice of piling method such as ground strength, cost and contamination migration. For a pathway to be present the source zone must be connected to the receptor by strata that have pore sizes large enough to allow particles to migrate and a sufficiently high groundwater velocity. The focus on velocity is a significant variation from typical solute transport CSMs. The most likely scenario for this is karstic features or well-connected fractures in rock, with Chalk aquifers being at particular risk. It has been shown that in Chalk, groundwater velocity in fractures can exceed 2 km/day indicating potential for rapid transport of turbidity from site to the abstraction well.

Where piles do not penetrate the abstracted strata, there is unlikely to be a complete pathway, provided that one of the following applies:

1. Water flow is via the porous matrix and the strata into which the piles are installed are of such a grading that turbidity migration is prevented; or

2. Piles are installed into a stratum separated from the aquifer below by a fine grained stratum that can act as a filter. If the piles do generate turbidity in the upper stratum it is prevented from reaching the aquifer by filtration through the fine grained layer. The fine grained stratum must be intact beneath the entire piled zone and for sufficient distance down-hydraulic gradient to protect the underlying aquifer. Whilst there is no defined minimum thickness for such a stratum to prevent migration of turbidity, confidence that the stratum will be continuous and of suitable material will increase with increasing thickness. Where an assessment is reliant on such a protective stratum then it should be supported by the proven thickness on site as well as desk-study information including off site boreholes where available and review of other references such as British Geological Survey memoirs.

Attenuation and removal of turbidity caused by suspended sediment will be mainly by settlement of particles due to low groundwater velocity. Matrix filtration is also a key process in Chalk turbidity occurrence, that provides protection from the incidence of rainfall turbidity, but also is the cause of short term turbidity on start-up in most Chalk boreholes (Anderson, 2009). Other mechanisms are dispersion within the aquifer and dilution at the receptor.

A1.7.3 Receptors

In most cases the receptor will be a potable groundwater abstraction which could be operated either for public supply or by a private operator. Groundwater fed surface waters may also be considered if in close proximity to the foundation works.

A1.7.4 Risk assessment

Once a potential pollutant linkage has been identified, then qualitative assessment can be undertaken using the approach for land quality based on the S-P-R model (Burries *et al.*, 2020; CIRIA, 2001). Where risks are greater than 'Low', then further assessment or mitigation will be required. Fate and transport models for dissolved phase contamination are not suitable for assessing turbidity migration, and review by others has not identified a practicable method for modelling migration of particles in fracture flow systems (Burris *et al*., 2020), therefore traditional quantitative risk assessment is not appropriate. Semi-quantitative assessment based on the work by Farmer (1969) relating to particle size and settling velocity, and also considering dilution at the receptor may be appropriate.

If more detailed quantitative methodologies are proposed for complex sites their use should be agreed in advance with regulators and a site investigation should be designed to collect sufficient data to make use of the model robust. The cost of collecting supporting data may be prohibitive for most sites. Examples of the types of detailed testing that have been undertaken for the HS2 project in Hertfordshire (HS2, 2019) include:

- Signal tests (pumping tests in which the response to pumping or changes in pumping rate in an aquifer are measured at receptors such as other aquifers, water courses or boreholes) to determine whether a hydraulic connection exists between an aquifer and superficial deposits. This allows an understanding for example of whether a layer of putty Chalk restricts the interaction between the two;
- Signal tests and permeability tests to determine transmissivities of an aquifer; and
- Analysis of surface water body drawdown data to determine what proportion of water abstracted from a well is derived from surface water bodies.

A cost benefit exercise will usually be required to determine whether it is more cost effective to modify the foundation solution to reduce risks or to undertake other mitigation during piling.

The risk assessment should consider whether changes in pumping rates at the abstraction borehole could re-instigate migration in the future.

A1.7.5 Mitigation

Where turbidity risks cannot be addressed by risk assessment, then foundation design changes may provide a lower cost, reduced timescales and more certain solution than other mitigation approaches. By altering the number, depth and diameter of piles it may be possible to terminate piles in strata overlying the aquifer and/or above groundwater level.

If the foundation solution cannot be changed to reduce risk, then the most common mitigation measure is to undertake groundwater monitoring for turbidity during piling. Monitoring adjacent to the piled area allows any turbidity increase to be detected at the earliest opportunity. Monitoring can also exclude the site as a source if turbidity at the abstraction increases from another cause. Baseline and post-completion monitoring will also be required. The baseline monitoring is important to determine background turbidity levels and avoid unfounded claims that piling is causing turbidity. The longer the baseline period the more likely it is that natural peaks in turbidity are understood and less likely that works will be affected by elevated results within the natural range. Sentinel monitoring boreholes must be suitably located down-hydraulic gradient of the piled area, installed to similar depth as the pile bases and fitted with a filter pack representative of the aquifer material. An upgradient borehole is required to assess changes in groundwater flow direction and changes in background turbidity from natural causes such as heavy rainfall. The frequency and duration of each monitoring period will be site-specific and should be agreed with the stakeholders at the earliest opportunity.

The site monitoring data should be complemented with turbidity data from the receptor borehole to show any seasonal trends or other events that affect turbidity. These data can also be used to inform the design of the monitoring programme, which will also need to consider lag-times and potential cumulative effects.

Where piles are installed in lower permeability strata, then monitoring at the end of each day may be sufficient. Whereas, for piles installed in fractured rock with a short travel time to the receptor then real-time monitoring with telemetry and automatic alarms may be required. Real-time monitoring also offers the option to reduce piling rate to reduce turbidity.

For larger projects, consideration can be given to scheduling piling to commence near a monitoring well so that worst-case data can be collected at the earliest opportunity.

Turbidity targets will be site-specific and will need to be agreed with stakeholders. The targets are often a defined increase relative to baseline conditions. When setting targets it is important to recognise the detection limits of the proposed monitoring instruments to ensure that the target can be detected. There also need to be defined actions and timescales when threshold limits are exceeded. This should be a progressive escalation of actions depending on the exceedance of the thresholds. It is also important that monitoring data are shared with regulators as they are collected and not simply compiled into a report at the end of a project. This allows regulators to look for early warning signs that limits may be exceeded and allow preventative action to be taken.

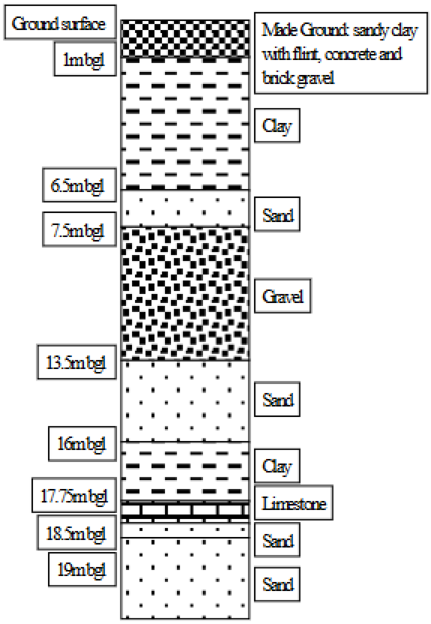
Alternatives to monitoring that have been implemented include funding or indemnification for the abstractor to undertake additional treatment of abstracted water before disinfection, or abstracting turbid groundwater adjacent to the source and treating it before discharge to ground. However, these are likely to be prohibitively costly and time consuming to agree with other stakeholders and implement, even if agreement can be reached.

A1.7.6 Conclusions

Assessment of turbidity risks from piling can be undertaken by qualitative assessment of S-P-R linkages based on a robust understanding of ground conditions. In many cases this will be sufficient to demonstrate that risk is acceptable without further works. Where the qualitative assessment identifies potentially unacceptable risks then the risk can be controlled by implementation of mitigation measures.

For larger projects where numerous piles will be installed into an aquifer within a SPZ a significant amount of investigation and testing may be required to understand the risks to public water supply boreholes and to design and specify appropriate mitigation measures. In this case semi-quantitative methods may be used, but should be agreed in advance with regulators.

Appendix 2: Case study examples

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 five to seven 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.	
 **Figure A2.1: Site stratigraphy**	*Local hydrogeology and environmental setting:* The stratigraphic sequence present at the site is shown in Figure A2.1 and comprises about a metre of made ground, consisting of sandy clay with occasional flint, brick and concrete, overlying over 5 m thickness of alluvial clay. Underlying the alluvium were approximately 6 m of dense sands and gravels (River Gravel deposits) and, underlying these, a stiff silty clay with dense silty sands comprising the Lambeth Group (formerly known as Woolwich and Reading Beds). The alluvial clay may be considered to be an aquiclude, while the Lambeth Group have variable permeability. The River Gravel deposits are considered to be a Secondary Aquifer. Underlying the site, below the Lambeth Group, is the Upper Chalk, which is considered to be a Principal 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 sulfate, pH and ammonium ion aggressivity.

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.

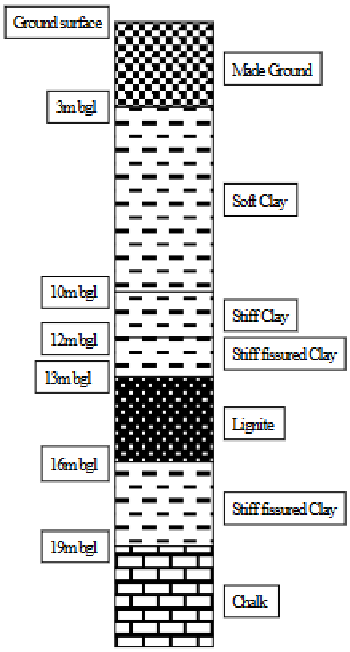


Figure A2.2: Site stratigraphy

Local hydrogeology and environmental setting:

The stratigraphic sequence present at the site is shown in Figure A2.2. Made ground beneath tidal storage tanks on the site consisted of 1-1.5 m of PFA. Below this a 0.5-1.0 m 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 10 m depth in this material and an organic odour was noted. The alluvium was underlain by a stiff organic clay comprising the Lambeth Group. The alluvial clay and the Lambeth Group may be considered to comprise aquicludes. The site is underlain by Chalk at a depth of approximately 19 metres below ground level (mbgl). The Chalk is considered to be a Principal 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 Principal 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.

CFA 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.

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.

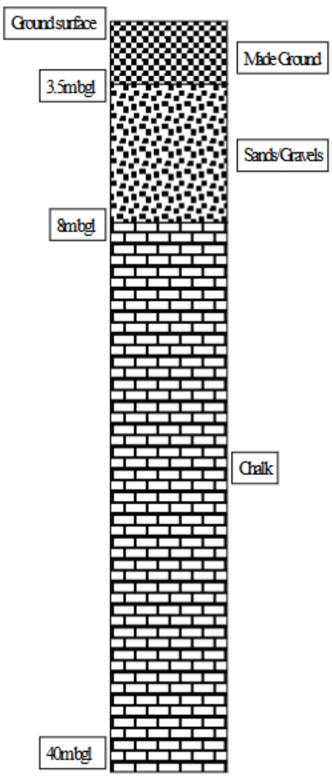


Figure A2.3: Site stratigraphy

Local hydrogeology and environmental setting:

The stratigraphic sequence for the site is summarised in Figure A2.3. In summary, the site comprises a maximum of 3.5 m of made ground overlying alluvial sands and gravels. Pockets of peat were also present. Underlying the site, at a depth of approximately 8 mbgl, was the Chalk.

The underlying Chalk is a Principal 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 Principal 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 Environment Agency required that auger piling techniques were to be used.

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

CASE STUDY 4: PILING FOR MOTORWAY TUNNEL CONSTRUCTION

Description of site and proposed development:

The proposed work included the drilling of 1.2 m 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 PCBs, which are considered hazardous to human health.

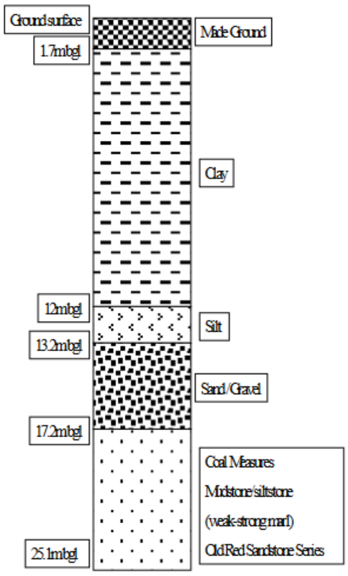


Figure A2.4: Site stratigraphy

Local hydrogeology and environmental setting:

The stratigraphic sequence encountered at the site is summarised in Figure A2.4. 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 6 m) using temporary casing. The bore was filled with a weak slurry mix and the 1.2 m diameter pile bored through the set slurry.

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 200 kN to 875 kN. 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.

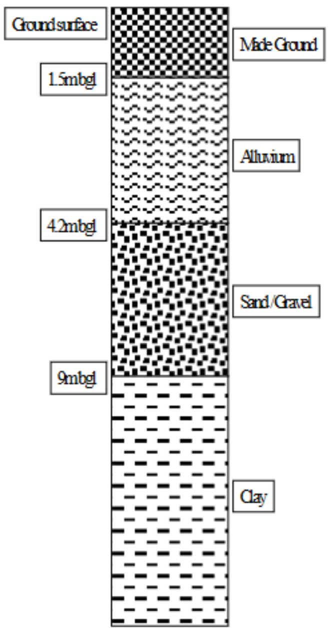


Figure A2.5: Site stratigraphy

Local hydrogeology and environmental setting:

The stratigraphic sequence found at the site is summarised in Figure A2.5. Made ground was encountered at the site to a depth of 1.50 m 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 sulfide 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 CFA piles of nominal 300 mm and 400 mm diameter were used, founded in the London Clay. CFA 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.

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, sulfate, boron, copper, nickel and zinc within the made ground. PFA found with a petrochemical odour returned elevated toluene and cyclohexane extract concentrations. Elevated carbon dioxide levels were also recorded.

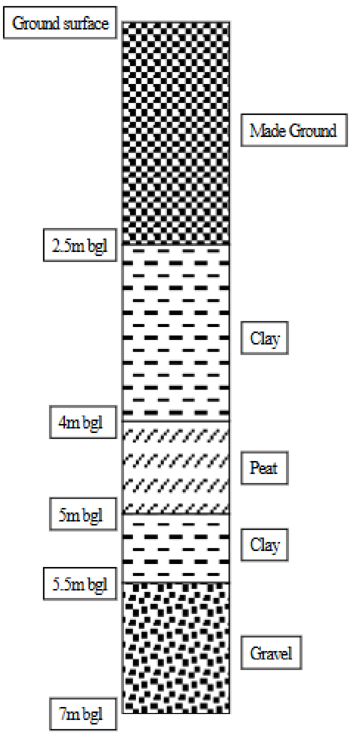


Figure A2.6: Site stratigraphy

Local hydrogeology and environmental setting:

The stratigraphic sequence present at the site is summarised in Figure A2.6. Made ground was found over much of the eastern half of the site, consisting of 0.4-3.2 m of 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 7.4 m. 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 within 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 precast 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.

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.

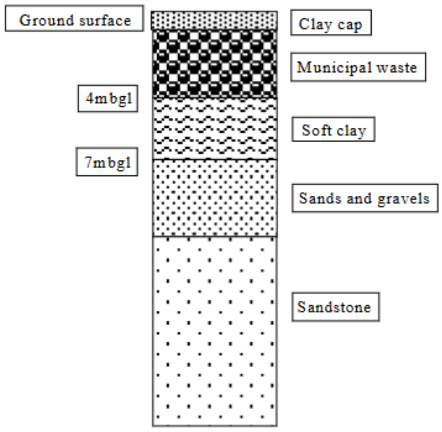


Figure A2.7: Site stratigraphy

Local hydrogeology and environmental setting:

A schematic stratigraphic sequence is shown in Figure A2.7. Typical soil conditions comprise 3-4 m of fill material overlying 3 m 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 Principal Aquifer in the vicinity of the site.

Implications for piling and ground engineering:

The regulator 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 Principal 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.

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 m of the natural ground (Reading Formation). 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. 0.5 m of clean cover (soil) was proposed to 'cap' areas of open space. The developer proposed to use vibro stone piles, extending 2 m into the Reading Formation (i.e. below the winter groundwater level) to provide foundations for all of the buildings.

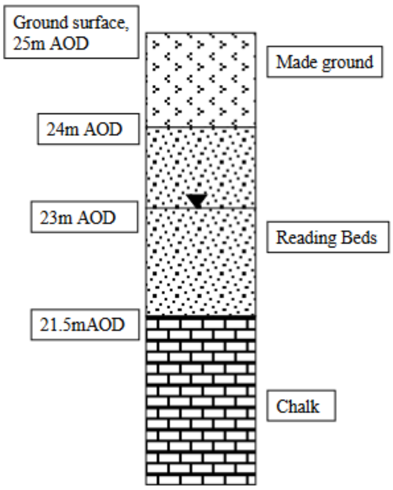


Figure A2.8: Site stratigraphy

Local hydrogeology and environmental setting:

The stratigraphic sequence present at the site is shown in Figure A2.8, and comprises about 1 m of made ground (brick, slag, sand) overlying 2.5 m of Reading Formation (a poorly consolidated silty sand), which in turn overlies a thick sequence of the Upper Chalk.

The Reading Formation are classified by the Environment Agency as a Secondary Aquifer, whilst the underlying Chalk is a Principal Aquifer and is used locally for public water supply. This site lies within the catchment (SPZ 3) of a public water supply abstraction borehole. The Reading Formation are known to be in hydraulic continuity with the underlying Chalk aquifer and there is a vertical hydraulic gradient downwards from the Reading Formation into the Chalk.

Implications for piling and ground engineering:

Conceptualisation of the situation gave the regulator 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 Formation 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.

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.

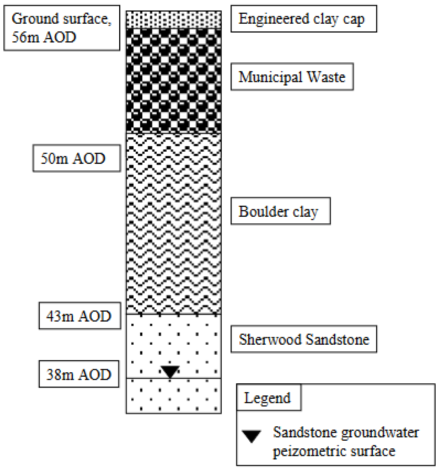


Figure A2.9: Site stratigraphy

Local hydrogeology and environmental setting:

A schematic stratigraphic sequence is shown in Figure A2.9 and comprises a metre of clay over 5 m of domestic waste materials. The landfill is founded on 7 m of boulder clay, which overlies the Permo-Triassic Sherwood Sandstone, a Principal 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 m 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 risks considered most likely were:

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; and
3. Penetration of the clay cap, with resultant increase in leachate generation.

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

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 wastes, 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 20 m 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 170 m 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 acceptable limit.

CASE STUDY 11: EFFECTS OF DRIVEN PILES ON GROUND GAS EMISSIONS

Description of site and proposed development:

A former landfill site was remediated by excavating the waste and processing it to manufacture soils to be used in the reinstatement of the void. The potential for the manufactured soils to generate gas was controlled by limiting the allowable organic content. However, the soils would produce some ground gas.

The foundation solution was driven piling (precast concrete).

Ground and ground gas setting:

Gas monitoring indicated some gas generation in the fill and also dissolved methane was present in the pore water. Methane concentrations in the monitoring wells were up to about 80%. The hazardous gas flow rates from the wells when not flooded was indicative of CS3 when assessed in accordance with BS 8485 (BSI, 2019). There were some detectable surface emissions at the site consistent with CS3. The conceptual site model is shown in Figure A2.10.

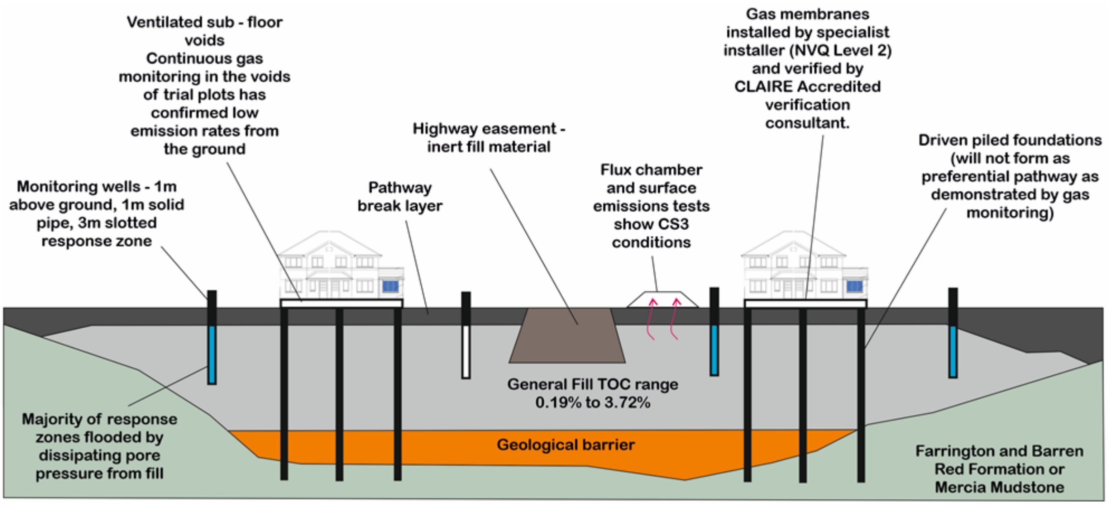


Figure A2.10: CSM

Implications for piling and ground engineering:

Piling did not affect gas concentrations in the monitoring wells. It did however influence the flow rates from monitoring wells. This was because the pore pressure increase in the cohesive fill from piling resulted in increased pore water pressure dissipation into the wells, rather than gas flow (the compacted cohesive clay fill has low air voids). In any event the effect was temporary and reduced over about six or seven months (Figure A2.11).

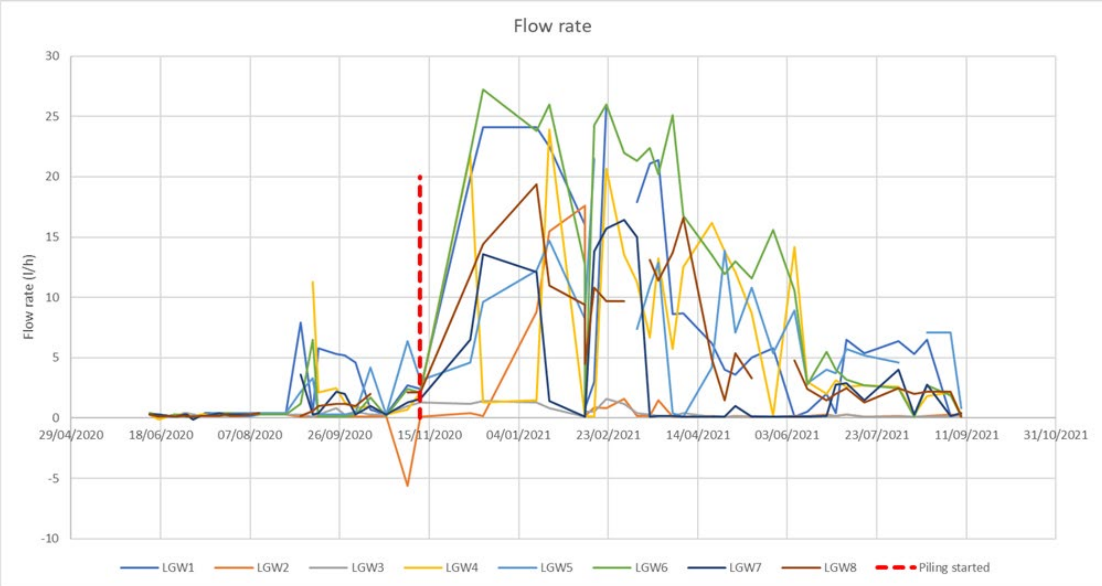


Figure A2.11: Flow rate increase due to piling (as a result of pore water pressure increases)

Monitoring around the top of driven precast concrete piles driven into the fill material did not give any significantly elevated results (using a tuneable diode laser that only detects methane) with the maximum concentration recorded of 7 ppm which is of no practical significance and shows the piles were not providing a preferential pathway for gas migration (Figure A2.12).

Figure A2.12: Monitoring for methane with tuneable diode laser

In addition, monitoring around the perimeter of the landfill showed that there was no off site ground gas migration as a result of the piling. Thus the use of driven piles did not adversely affect the long term ground gas risk at this site.

CASE STUDY 12: PILING THROUGH LANDFILL CAP FOR HOSPITAL AND RESIDENTIAL DEVELOPMENT

Description of site and proposed development:

A hospital and residential development was proposed for a former domestic landfill site in Victoria, Australia. Piled foundations were required to support the structural loads from the proposed buildings, which were to be five to seven storeys high.

The landfill material was covered by a clay cap which would be penetrated by the piles. As well as the landfill cap, which remained in place below the buildings at a minimum of 2 m thickness, significant landfill gas mitigation measures were incorporated into the building including the reinforced concrete floor slab construction, a thick and durable gas resistant membrane and sub floor venting system (formed using a 90 mm thick open void former) with high level vent stacks

Local hydrogeology and environmental setting:

The CSM for the site is shown in Figure A2.13.

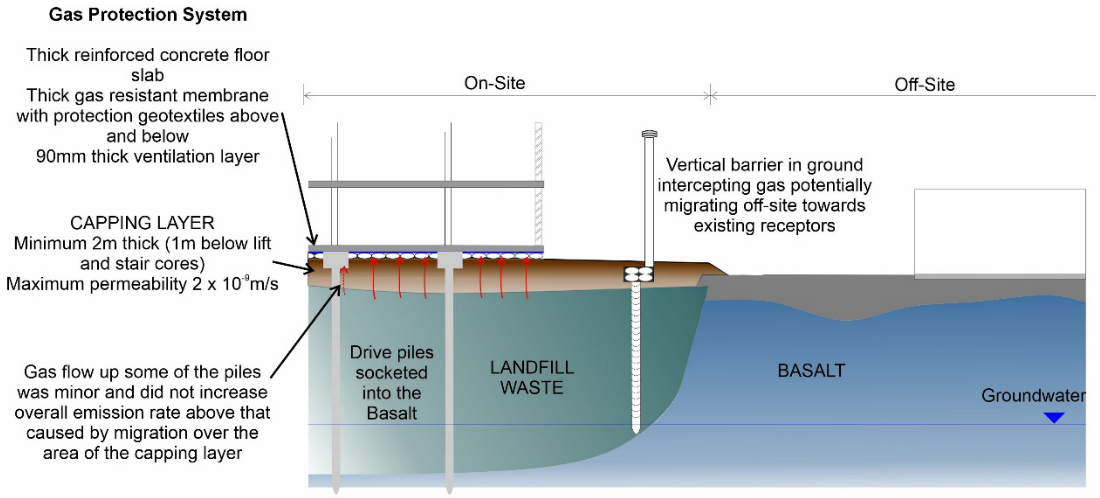


Figure A2.13: CSM

Implications for piling and ground engineering:

A review of piling options concluded that driven precast concrete piles would be the best solution for the site from both a geotechnical and geoenvironmental perspective. Gas monitoring around the top of the piles after installation showed that there was some limited gas migration up the side of the piles (Figure A2.14). However, it was not sufficient to influence the risk to the proposed development. It did not result in an increase in the scope of gas protection provided to the buildings, which is shown in Figure A2.15.

Figure A2.14: Gas monitoring around the top of driven precast concrete piles

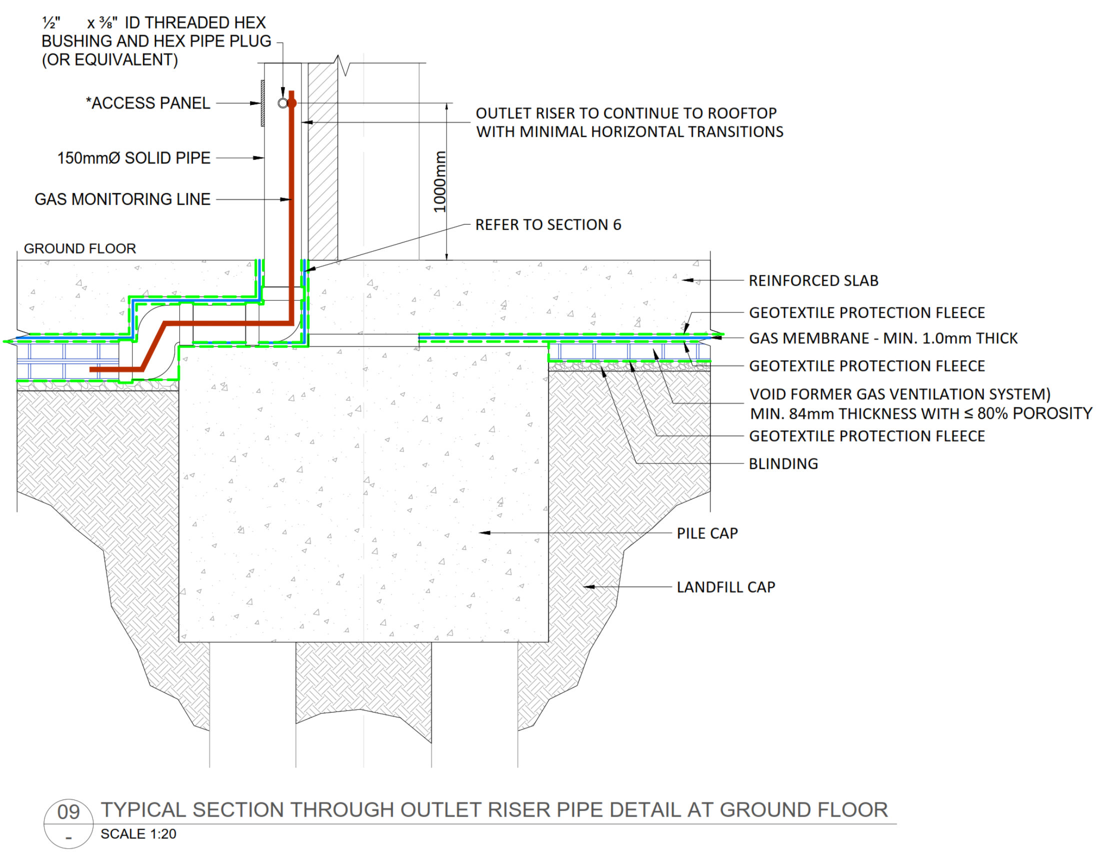


Figure A2.15: Landfill gas mitigation measures above piled foundations

Post-construction monitoring in the under slab ventilation layer also confirmed that, even with the gas migration up the side of some piles, the design gas concentrations in the underflooring venting system were not exceeded (maximum 0.5% methane recorded in outlet risers and 0.3% in the void).

CASE STUDY 13: PILING THROUGH BACKFILLED COLLIERY SPOIL, MIDLANDS

Description of site and proposed development:

A warehouse was constructed over the site of a former open cast coal mine (quarry) that had been backfilled. The building structure was supported on piled foundations and the floor slab was also supported on precast concrete driven piles with flared heads (on a 3.2 m by 3.2 m grid).

Following completion of the warehouse a future tenant required alterations to the warehouse that required the floor slab to be removed and reconstructed.

Ground and ground gas conditions:

The site was underlain by between 2 m and 38.5 m of colliery spoil and mine washing lagoon deposits (which contain coal dust).

Gas monitoring detected methane at concentrations up to 30% with one well recording up to 60.1% (with minimal carbon dioxide and oxygen). The primary risk driver was methane and the site was classified as CS3.

Prior to this work, vapour pins were installed through the slab and monitored. Methane was present in isolated locations but not specifically related to pile locations (Figure A2.16).

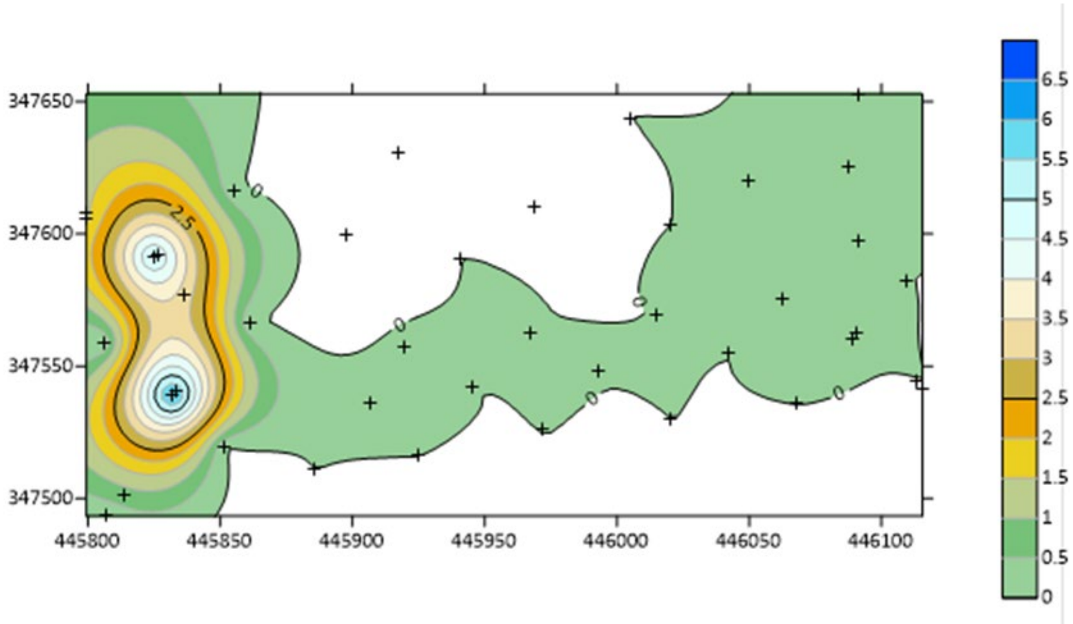


Figure A2.16: Methane concentrations in vapour pins

This shows that the piled foundations were not acting as a preferential pathway for gas migration towards the underside of the slab.

Implications for piling and ground engineering:

During removal of the slab, the exposed formation was monitored for methane on a daily basis on a close grid including the pile locations, over an eight week period (atmospheric pressure varied from 975 mb to 1018 mb with a period of sustained low pressure (<1000 mb) of about 15 days). The monitoring used a tuneable diode laser that has a limit of detection for methane of 1 ppm. The formation gas monitoring did not generally detect gas concentration above 10 ppm. There were some isolated minor results up to 5112 ppm that occurred in different locations and at different times and were not sustained or repeated. They were not correlated with changes in atmospheric pressure. The highest concentrations all reduced within 15 minutes. The higher level ambient air alarms at body height did not alarm so the results recorded at formation level were not indicative of hazardous conditions and furthermore were not associated with the piles.

The area was also provided with infra-red flammable gas detectors at head height at regular spacing (Figure A2.17). These have a limit of detection for flammable gas of 0.05%. Flammable gas was not detected at any time.

Figure A2.17: Area monitoring for flammable gas above exposed piled foundations

CASE STUDY 14: GAS EMISSIONS UP BI MODULUS COLUMNS, RESIDENTIAL DEVELOPMENT, MIDLANDS

Description of site and proposed development:

The site was being developed for managed residential development. The car parking area was to be supported on bi modulus columns installed into made ground and soft clays of the glaciofluvial deposits.

Local geology, hydrogeology and environmental setting:

Ground conditions comprise made ground to varying depths overlying glaciofluvial deposits. Bedrock comprises Mercia Mudstone.

The made ground comprises up to 5 m of sands, gravels and clays with fragments of siltstone, sandstone, limestone, brick, concrete, plastic metal and wood. There is nothing within the made ground that could generate large volumes of ground gas. It had a low total organic carbon content and was generally classified as inert waste.

The glaciofluvial deposits comprise up to 6.5 m of soft/very soft clay which is locally organic. Peat was present in one area of the site. The soft materials overlie sand and gravel.

Groundwater levels are between 0.9 and 3.7 m depth.

Concerns about settlement of the car parking and roads resulted in the adoption of bi modulus columns on a rectangular 3 m grid.

The columns comprise an upper 400 mm diameter (approximately) stone column section that is 3 m long. The lower section is approximately 280 mm diameter controlled modulus column that extends to between 6 and 10.5 m depth.

The CSM for the site is shown in Figure A2.18.

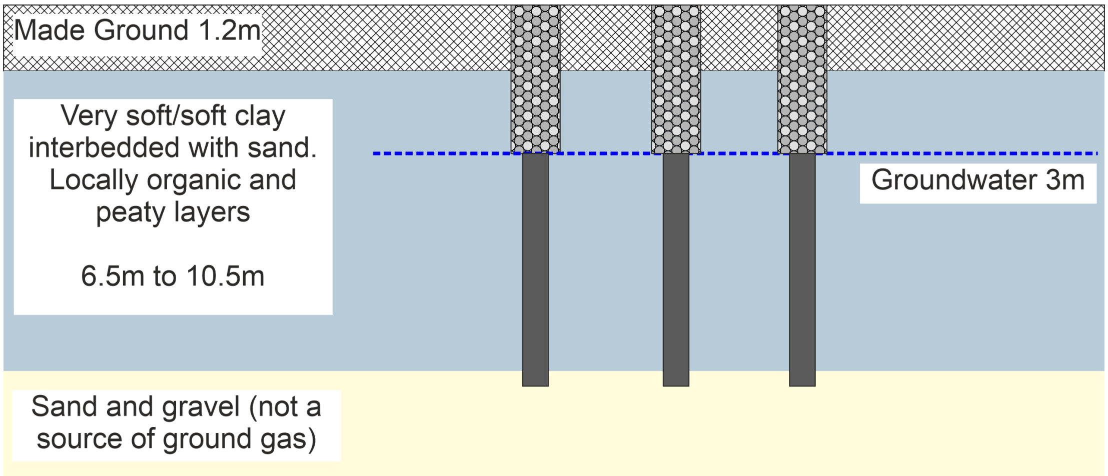


Figure A2.18: CSM

Methane was present in the made ground and the glaciofluvial deposits and its presence was random and not correlated with the presence of peat or organic clays in the wells.

Implications for piling and ground engineering:

Gas monitoring over one area of the bi modulus columns (blue shaded area on Figure A2.19) on one occasion did not detect any gas emissions at the surface of the columns. Barometric pressure was 1005 mb.

The monitoring used a tuneable diode laser that has a limit of detection for methane of 1 ppm. The formation gas monitoring did not generally detect gas concentration above 2.4 ppm.

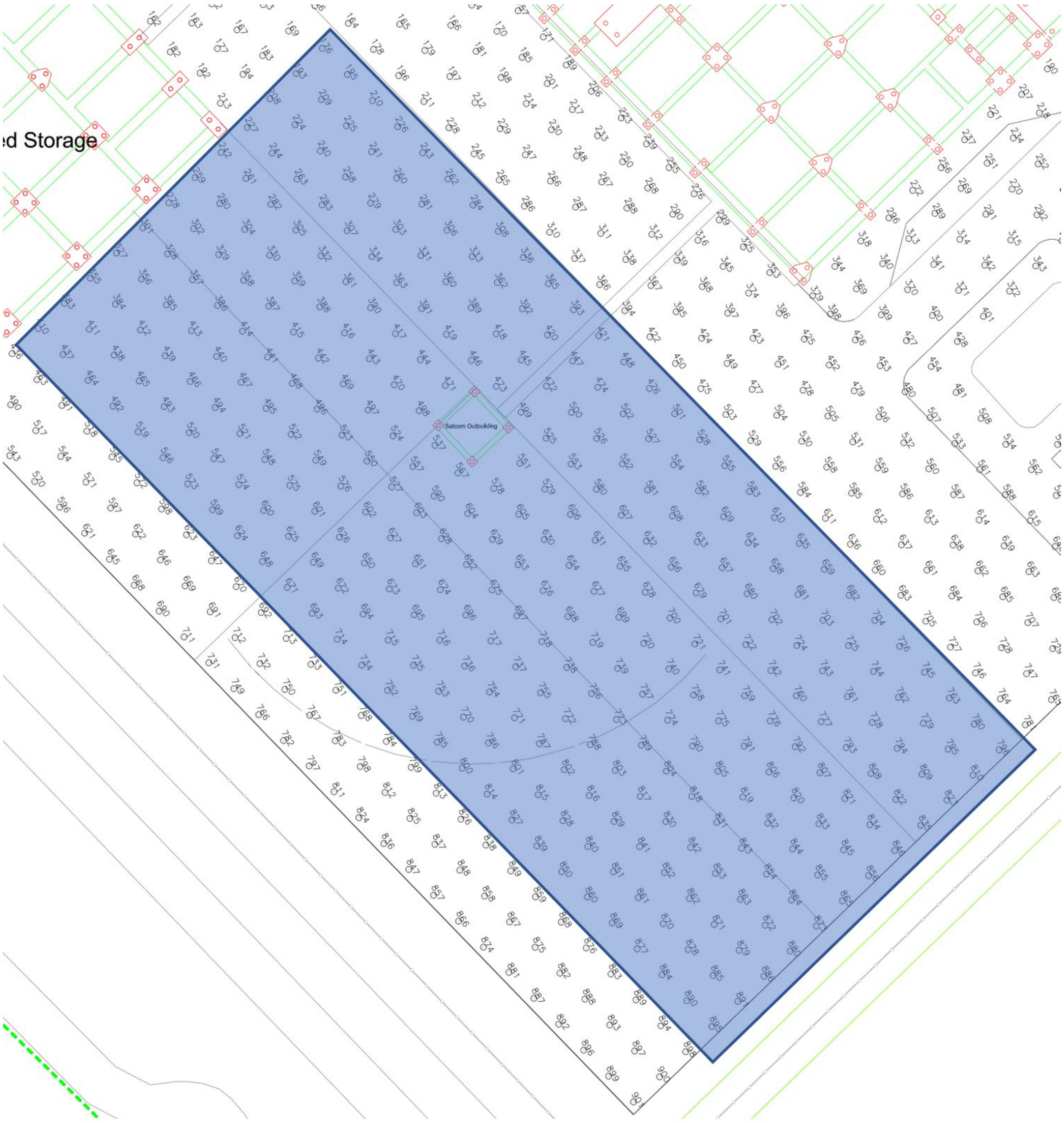


Figure A2.19: Area of tuneable diode laser survey over stone columns (blue shaded area)

CASE STUDY 15: STONE COLUMNS OVER SHALLOW MINE WORKINGS, GOREBRIDGE, SCOTLAND

Description of site and proposed development:

The site was originally developed for housing in 1957. These houses were demolished in 1999. Construction of the new housing development commenced in 2007 and was completed in June 2009. The houses were occupied from this point up to about 7 September 2013 when residents of 89 Newbyres Crescent became ill with symptoms of carbon dioxide poisoning. Shortly afterwards, residents at number 87 reported similar symptoms.

It was found that carbon dioxide from shallow mine workings below the site was entering some of the buildings (10 of the 64 properties). The houses had shallow spread foundations that were located on glacial till that had been subject to ground improvement using stone columns. The stone columns were also used below ground bearing floor slabs.

Local hydrogeology and environmental setting:

Ground conditions comprised up to 2.5 m of made ground overlying glacial till to depths between 4.7 to 11.2 m. The made ground was described as sandy gravelly clay or clayey gravelly sand and contained varying amounts of pottery, brick, wood, textiles, etc. There was no evidence of large volumes of domestic waste or similar material that could generate large volumes of carbon dioxide by degradation. The glacial till was described as generally cohesive and comprising sandy gravelly clay with abundant granular and silt bands.

There was evidence of shallow coal workings and shafts on the site and recommendations were made to undertake grouting of these prior to development.

The CSM for the site before it was redeveloped is shown in Figure A2.20. The older houses had shallow foundations and there was a reasonable thickness of glacial till between the foundations and floor slabs and the Coal Measures below where the gas could be present.

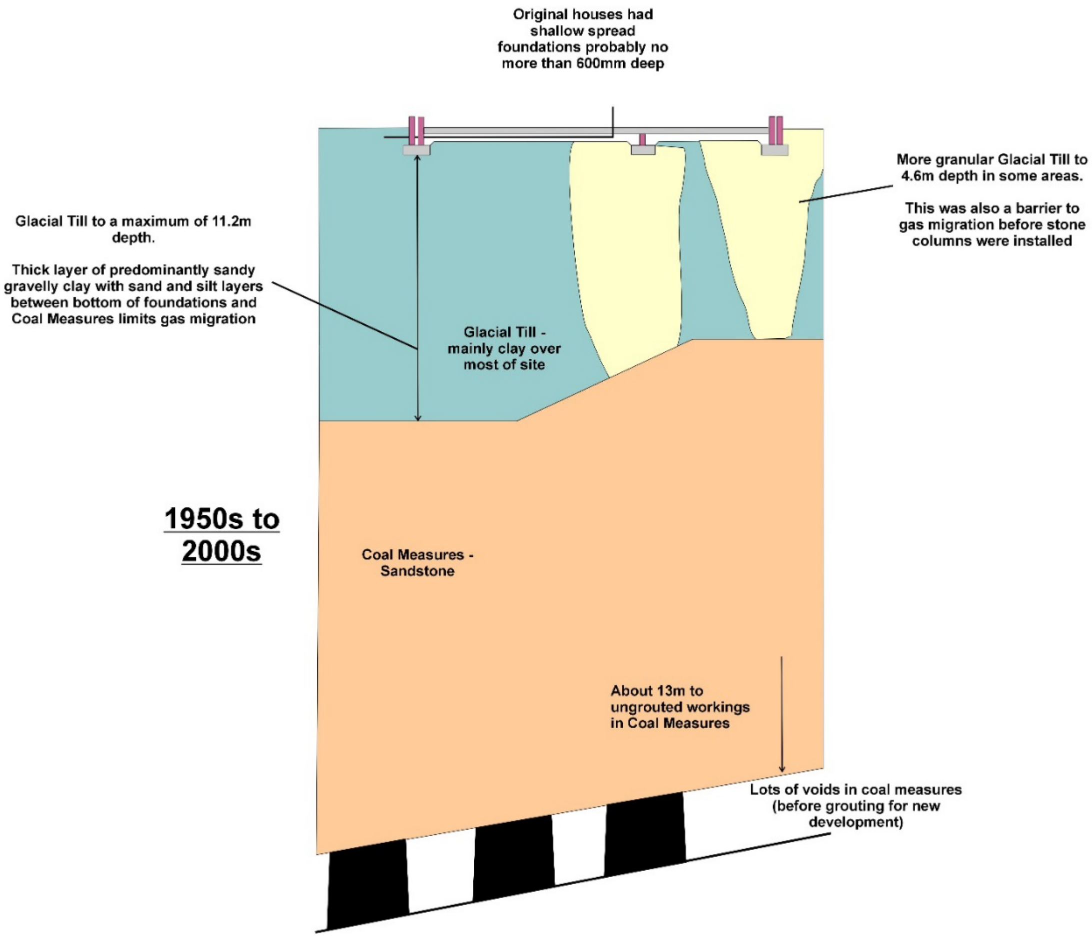


Figure A2.20: CSM with older houses on site prior to redevelopment

The CSM for the site once the new development was completed is shown in Figure A2.21.

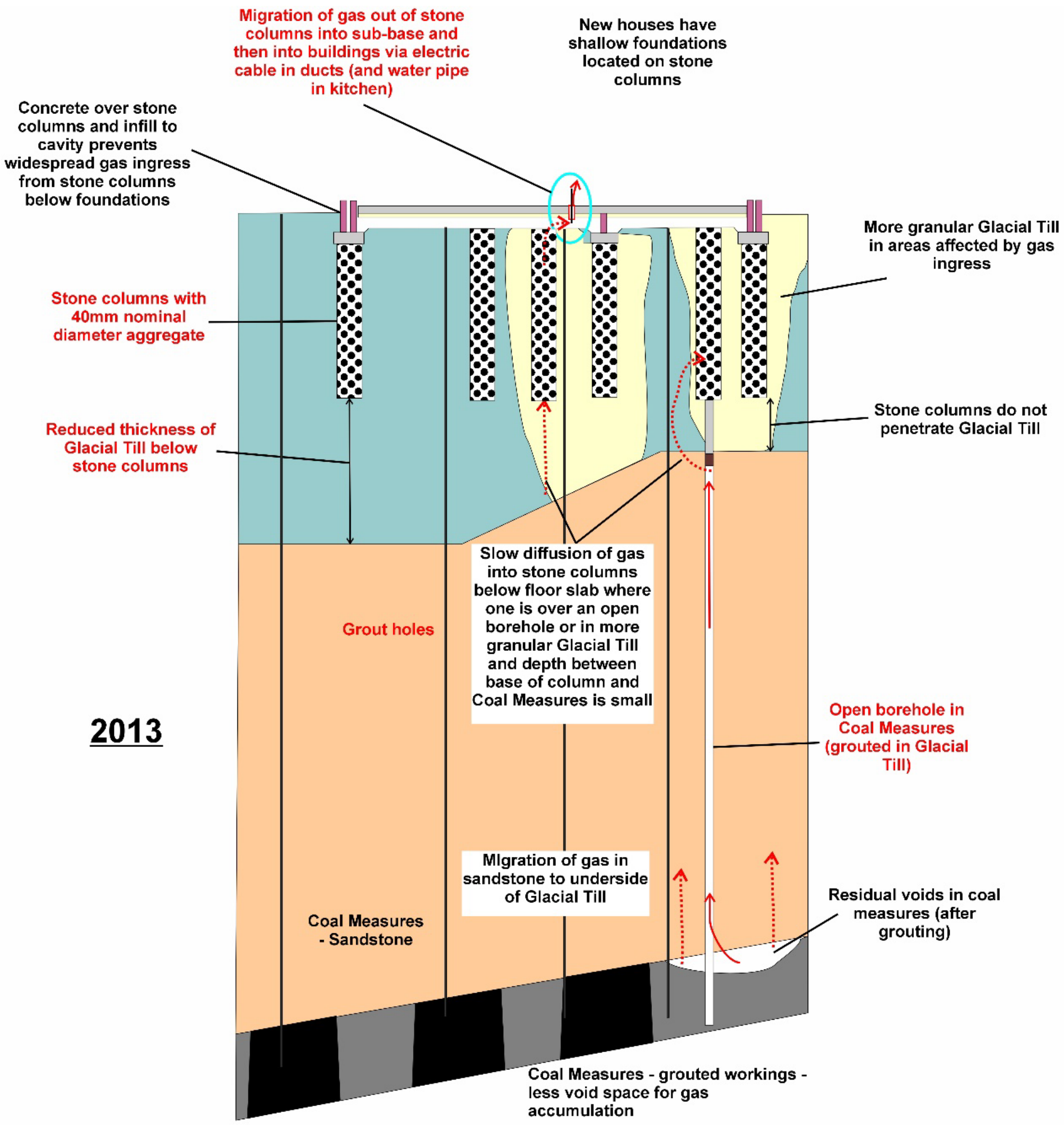


Figure A2.21: CSM post new development with stone column foundations

Crucially the stone columns did not fully penetrate the glacial till. However, two mechanisms for gas migration from the old coal workings into the houses that have been suggested and are related to the stone columns (but not clearly proven) are:

- Flow of gas through fractured sandstone and then diffusion through the more granular glacial till into the stone columns where a reservoir collected and intermittently flowed into the house during low/falling pressure events (when enough gas had accumulated).
- Stone columns intercept poorly sealed site investigation boreholes or grout holes and flow occurred directly up the unsealed holes into the stone columns.

In both cases it is likely that the majority of gas migration was via the columns below the floor slabs rather than foundations, and then the gas migrated from the columns into the sub-base and up unsealed ducts.

Note that there were also other potential pathways not related to stone columns.
Implications for piling and ground engineering: The implications from this case study are that stone columns can create either preferential pathways for gas migration or a reservoir where gas can accumulate in the ground until sufficient volume is present to allow it to migrate into overlying buildings in volumes that can cause a hazardous concentration. The stone columns do not have to fully penetrate a low permeability confining layer to pose a risk where there are shallow mine workings below. Careful assessment of the risk posed when using stone columns in sites affected by mine gas is required. This should include an assessment of the likely timescales for gas to diffuse through any confining layer below the base of the column and reach concentrations in the pile that could pose a risk.