The changing nature of groundwater control for temporary works

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Abstract

Groundwater control for temporary works uses a range of methods to allow below-ground construction in stable and workably dry conditions. Common strategies include control by pumping (dewatering), with or without physical exclusion (cut-off walls). The fundamental principles of groundwater control have been well established for many decades, with practice-led improvements in hydrogeological understanding, materials and technology driving the gradual enhancement of methods over much of the 20th century. Contractors developed considerable expertise but commonly adopted an at least partly reactive approach to managing groundwater. Over the past 30 years this has had to change, partly as a result of increased environmental regulation of groundwater abstraction and discharge but also the requirement for shorter programme timescales for deeper and larger projects with the related need to consider and where necessary mitigate any potential adverse impact on neighbouring structures. This paper discusses how traditional groundwater control strategies are evolving in response to these challenges and the increasing focus on reducing carbon emissions in construction. Consideration is also given to the range of soil permeability suitable for the application of dewatering techniques, and the related issue of sources of risk and uncertainty in design and procedures for managing these.

Introduction

Groundwater control for temporary works involves the application of strategies to allow below-ground construction (e.g. for basements, sub-structures and tunnels) to be made in stable and workably dry conditions. These objectives can be achieved by a range of methods, some of which exploit significantly different geotechnical processes. The nature of temporary groundwater control techniques is initially discussed in the context of other geotechnical temporary works activities. This is followed by an exploration of the environmentally-driven and project-related factors that have driven change in groundwater control strategies over the past 30 years. It is noted that the universal requirements to reduce cost, minimise risk and shorten programs have to be considered in the context of environmental concerns and associated regulation and increasingly the imperative to curb greenhouse gas emissions. While much of this discussion is in the context of the regulatory regime in UK, similar environmental regulations now apply in almost all countries. The paper then summarises some of the developments in technology and techniques that have helped designers and contractors meet project requirements for the temporary control of groundwater within the prevailing regulatory constraints.

Monitoring, particularly of groundwater levels, flow rates and sometimes surface settlements, is typically an essential element of any groundwater control scheme. While developments in computing, communications and control systems have and continue to drive significant improvements in geotechnical monitoring systems, this is not the main focus of this paper.

Groundwater control in the context of other temporary works

Groundwater control is one of a variety of engineering methods potentially used for temporary works, with the objective of enabling construction, without necessarily forming part, of the permanent works. Pallet and Filip (2018) list a range of temporary works methods including excavation support and propping, formwork and falsework, scaffolding, temporary earthworks, and works to ensure the stability of temporary plant such as cranes, hoists and piling rigs.

Groundwater control is typically achieved via two strategies, which can be used separately or in combination. These are control by pumping (known as dewatering) and control by exclusion. Commonly used methods are summarised in Table 1. Further details are given in Cashman and Preene (2021).

There is a useful distinction between pumping methods:

- Open pumping methods, which allow groundwater to enter an excavation, from where it is then removed by pumping (Figure 1a). Because water is drawn directly into the excavation, this can lead to instability if particles are washed from soil or rock in the slopes and base of the excavation. This approach has the further disadvantage that groundwater levels cannot be lowered in advance of excavation.
- Pre-drainage methods, which use wells to lower groundwater levels in advance of excavation works (Figure 1b). The method draws water towards the wells, not into the excavation, avoiding troublesome seepages and reducing the risk of groundwater-induced instability.

Exclusion methods can be divided into three categories:

i. Cut-offs comprising very low-permeability walls or barriers physically inserted or constructed in the ground (Figure 2a). The primary purpose of many cut-offs is to provide physical support for an excavation (i.e., to act as a retaining wall), with control of groundwater a potential secondary benefit. Cut-offs can be permanent, for example secant piles, or temporary, for example sheet piles if they are removed.
ii. Ground treatments that reduce the permeability of the soil or rock in-situ around an excavation (Figures 2b and 2c). Treatments can be permanent, for example permeation grouting, or temporary, for example artificial ground freezing. These techniques can be used for shaft sinking and tunnelling, or with cut-off walls to form a base plug, Figure 2c.
iii. Use of a fluid pressure to counterbalance groundwater pressures in shafts and tunnels (Figure 2d).

Compared with other temporary works activities, groundwater control has some particular attributes:

i. The ground, and obviously groundwater, plays a key role in groundwater control, so the success of a groundwater control strategy is highly dependent on having good (and relevant) ground and groundwater investigation information. While this is not a factor unique to groundwater control systems, the influence of groundwater conditions is often more significant than for many other temporary works activities. Each groundwater control technique has a specific range of application, particularly in relation to the permeability of the ground (Figure 3a and 3b). There are examples of groundwater control measures being ineffective when applied in the wrong conditions (Preene, 2020).
ii. Many groundwater control methods are truly temporary – for example where a pumped groundwater control system is used, groundwater levels will typically recover to original levels in the days and weeks after pumping stops at the end of construction. This also means that there is an important maintenance requirement – if pumps break down, or if pumping is interrupted for other reasons, groundwater levels will rise and the stability of the excavation may be compromised.
iii. Groundwater control is typically not codified in detail by national or international design standards. For example, while Eurocode 7 (BS EN 1997-1:2004) includes a section on dewatering, its requirements are limited to general comments that the design should be based on the results of ground investigations, the objective of

design should be to achieve stable excavations, and that dewatering systems should be reliable and subject to monitoring.

iv. The activities involved in the control of groundwater, particularly abstraction and discharge, have the potential to impact on the environment, groundwater resources or neighbouring structures well beyond the site boundary. As a result, some groundwater control techniques are subject to national or local regulation (e.g. by the Environment Agency in England). The regulatory approval process may take several months and can impact construction programmes.

This puts most groundwater control methods into a category where expertise is concentrated in a small number of specialist organisations. According to Powrie (1990), 'Dewatering is regarded by the civil engineering profession in general as something of an art, the practice of which is best left to the cognoscenti', and this is still largely the case today. The current paper discusses some of the present and future challenges of groundwater control applications for temporary works, with the objective of sharing knowledge and experience in this field.

Overview of factors driving the evolution of groundwater control methods

While the fundamental principles have not changed, groundwater control methods - like many temporary works activities - have undergone a largely practice-led evolution over several decades; some examples of this evolution are given in Table 2. This has been, and continues to be, driven by:

- Improvements in materials, plant and equipment and technology (including data systems, control and power supply).
- Deeper understanding of hydrogeology and design methods, including better and more rapid access to groundwater monitoring data.
- Demand-led need for bigger, deeper and more complex excavations with less interference with construction operations from methods to physically support the soil or rock.
- Regulation, in the late 20th century relating mainly to direct environmental impacts of abstraction and discharge (such as protecting groundwater resources) but increasingly focusing on curbing greenhouse gas emissions (principally carbon dioxide, often abbreviated to "carbon") as well.
- The ever-present need to reduce costs and to complete projects more rapidly with outturn costs close to pre-construction estimates.

Developments in technology and hydrogeological understanding, combined with project-led demand, have led to a widening in the complexity and range of application, and improvement in the efficiency and effectiveness of, pumped groundwater control systems. There is also a history of technology transfer, whereby a method used in other industries (e.g. mining) is subsequently used in construction temporary works. This is one way that better groundwater control techniques may be developed in the future.

Commercial pressures to control and where possible reduce costs are always present in the construction industry. Changes that impact on temporary works and groundwater control strategy also arise from several other quarters including evolving environmental regulation, societal demands relating to climate change, project scope and risk management.

Examples of the influence of regulation include the banning of potentially toxic ingredients in chemical grouts, and increased control (and eventual abandonment) of compressed air tunnelling in response to identified health risks to workers. Increasing environmental regulation of pumped groundwater control methods may also influence the future development and / or application of such methods.

The remainder of this paper will review the challenges of developing appropriate schemes for temporary works groundwater control, focusing on the future challenges of increased regulation and the need to assess environmental impacts and carbon emissions between very different techniques. Project-related requirements and some recent developments in techniques and technology are also considered.

Environmentally-driven factors

Regulatory requirements

Groundwater resources have been formally protected by regulation in parts of the UK since the Water Resources Act 1963, with later provision to license and protect abstractors. Dewatering (for construction and for mines and quarries) was formerly largely exempt from regulatory oversight but recently The Water Abstraction and Impounding (Exemptions) Regulations 2017 have removed this exemption in England and Wales. For the construction industry the consequence of this is that, with a few exceptions relating to short term pumping at very low flow rates, groundwater pumping activities now generally require consents for abstraction and discharge of groundwater. The regulations distinguish between transfer of groundwater from one source of supply (groundwater) to another (to a lake or river) and removal of water from the groundwater system (e.g. discharge to sewer). Significant exemptions to the licensing requirements may also apply where the abstracted groundwater from a dewatering system is recharged back to the aquifer. Responsibility for managing water resources was devolved away from Central Government in the UK so that the regulatory authority, exemptions, and procedures differ between different nations in the UK.

Obtaining the necessary consents requires the design team to determine, in advance of construction, the abstraction flow rate required to achieve the drawdown needed to maintain stability of the excavation or structure. This information feeds into an assessment of the possible impact on groundwater-dependent features, licensed abstractors and neighbouring structures. Some precision is required in this process since an overestimate may require enhanced mitigation measures and could possibly result in denial of consent if the regulatory authority considers that water resources or groundwater dependent features may be at risk. On the other hand, an under-estimation runs the very real possibility of significant delay to the works if actual flow rates required are found to be above the licensed rate such that a new consent application is required. The precision needed, particularly in medium to low permeability soils, is often greater than that required to design the dewatering scheme. The need for precision in flow assessments has greatly expanded the requirement for pumping tests for projects where a pumped groundwater control scheme is planned. It has also spawned the development of non-standard pumping tests using short screens or multiple wells to maximise the relevance of the parameters obtained; examples are given in Roberts and Holmes (2011) and Holmes et al (2018).

Internationally, regulations to protect water resources, including groundwater resources, now exist in most countries. The arrangements may differ appreciably, reflecting local conditions; but the requirement for reliable prior assessment of groundwater control flow rates and water quality together any associated potential for adverse impact on the environment or neighbouring structures is almost universal.

Societal demands relating to climate change

Reduction in emissions of greenhouse gases, including embedded emissions associated with construction materials, is now a major driver for the design of both temporary and permanent works. The European Federation of Foundation Contractors (2022) notes that construction materials, particularly concrete and steel, have high embedded emissions and designers should focus on minimising their use. Controlling groundwater levels and pore water pressures can be an effective strategy to reduce material requirements, particularly for temporary works. For example, the required depth of a concrete secant pile embedded retaining wall will be partly controlled by loading from external pore water pressures and it may be feasible to reduce the depth, and corresponding material requirements, if external pore water pressures can be lowered or eliminated during construction. Once the structure is complete it will typically be designed to have sufficient weight and structural integrity to resist groundwater pressures. This may well include permanent props (e.g. floor or roof slabs) at multiple levels, not present during construction.

An interesting case study is given by Casey et al (2015), which compared solutions to mitigate high groundwater uplift pressures for a large station box in East London using either concrete tension piles or groundwater pumping. This showed that the carbon emissions embedded in the tension pile solution were significantly greater than those associated with the pumping solution even if pumping is continued for the full 80-year design life of the structure. Direct comparisons are not straightforward and may change over time. For example, the carbon emissions for tension piles are almost entirely indirect emissions associated with the concrete and steel whereas for the pumping solution the emissions are dominated by the operational power to drive pumps, which would be expected to reduce over time as electricity is increasingly generated from renewable and low carbon sources.

Project-related considerations - risk management

Groundwater control has long been considered a high-risk construction activity for a range of reasons including:

- Lowering groundwater levels increases the vertical effective stress on the strata below the initial groundwater level, which inevitably results in the compression / consolidation and settlement of the ground. While the risk of ground settlements large enough to cause damage / distress to nearby structures can be a concern in soft soils it may be overstated, particularly for dense granular soils or stiff clays where even significant lowering of groundwater levels for temporary works purposes may result in modest settlements. Screening and assessment of structures is typically required to determine the level of risk concerned.
- The hydraulic gradient towards a pumping system in a granular soil is relatively shallow so that the influence of a dewatering system sometimes extends to a considerable distance beyond the site boundary. It is likely to be rather greater than the zone of direct influence generally associated with excavations, retaining walls and tunnels, where the maximum lateral extent of the settlement trough is generally equivalent to approximately the depth of the structure.
- Lowering the groundwater level beyond the site boundary can adversely impact groundwater-dependent features or existing licensed abstractors, and can mobilise any existing groundwater contamination. These risks need to be considered, including mitigation measures where necessary, in the environmental consent application process. The groundwater control design process often needs to be fairly advanced before it becomes apparent whether any concerns are potentially significant.
- The time to process license applications is quoted by the various regulatory authorities as several months, from when a valid application has been made. This

> period does not include the time required to gather the necessary information, prepare reports and impact assessments and the time for any pre-application discussions with the regulatory authorities - all of which may considerably extend the application process.

Some hydrogeological settings may present significant risks that need to be addressed but in other settings the risks may be overstated or misunderstood owing to common misconceptions. For example, Figure 4a illustrates a ground profile where lowering the groundwater levels in a sandy gravel (typical of the River Terrace Deposits in London) could result in the underdrainage of the overlying soft silty clay (of alluvial origin), with a risk of surface settlement and the potential to impact adjacent structures (if present). A case in which similar pumping from a coarse granular layer below alluvial clays and peat resulted in settlement damage to buildings in the vicinity is reported by Powrie (2014), and discussed in Preene (2020).

The ground profile in Figure 4b is similar but the natural groundwater level is already within the gravels below the soft clays; hence lowering the groundwater level in this case cannot underdrain the soft alluvial clay and the risk of damaging ground settlements is likely to be minimal.

The contract specification for a recent large infrastructure project in London included a requirement that groundwater pumping could only be used in the temporary works for a deep excavation providing there was no change in pore water pressure beyond the site boundary. This effectively prohibited dewatering in the Thanet Formation (formerly known as the Thanet Sand) and Chalk Group, which comprises the London Lower Aquifer. The London Lower Aquifer has been subject to very substantial changes in groundwater level over the past 150 years. Initial overexploitation of groundwater resources from the mid 19th century led to a reduction in groundwater levels of up to approximately 70 m in central London. This was followed by a period of significant recovery in groundwater levels from about 1950. Over the past 40 years it has been recognised that allowing groundwater levels to fully recover would have an adverse impact on the stability and serviceability of critical infrastructure and property in central London and a process of managed control has been implemented (Environment Agency 2018). Given this background a contractual prohibition on temporary dewatering in the Lower Aquifer made no practical, commercial or environmental sense and was largely circumvented during construction.

Developments in technologies and techniques

Electrically powered plant

The evolution of project requirements and regulations outlined above have and will continue to drive changes in groundwater control techniques and strategies in the construction industry. There has long been a trend away from diesel towards electrically powered pumping equipment due to a range of factors including:

- Reduced noise (particularly important for continuous 24 hr pumping)
- Reduced maintenance down time and costs
- Reduced need for fuel and oils on site, minimising risk of leakage and contamination
- Improved options for system control such as automatic starting of standby pumps
- Improved options for plant performance monitoring (including remote on-line monitoring)
- Improved options for warning and alarm systems
- Improved air quality (particularly in tunnels, shafts and other confined spaces).

The increasing use of renewable sources to generate mains electrical power and the overriding requirement to reduce greenhouse gas emissions has added impetus to this trend and a new focus on electrification of installation plant, particularly for in-tunnel installations (Figure 5).

One of main drive shafts for the Tideway Project in central London was located 70 m away from a major public water supply well abstracting from the chalk, which forms the major part of the Lower Aquifer (Figure 6). Abstraction flows for the supply well were approximately 60 l/s, but subject to demand and frequently interrupted. Groundwater levels in the Lower Aquifer at the shaft fluctuated in response to the public water supply well stopping and starting. When operating continuously the supply well achieved a drawdown (relative to unpumped water levels) at the shaft of approximately 12 m, which was just sufficient to allow construction of the TBM (tunnel boring machine) launch adits from the shaft using sequential excavation methods (SEM) and sprayed concrete lining (SCL) techniques.

The traditional approach would have been to design a dewatering scheme capable of achieving 12 m of drawdown at the shaft and to run this continuously so that, when pumping from the public water supply was interrupted, groundwater levels would remain below the target level for safe adit construction. This would have resulted in approximately 24 m of drawdown when the public water supply pump was operational, with groundwater of drinking water quality being discharged to the Thames, wasted energy consumption for the dewatering system operation and the risk of adverse impact on other licensed groundwater abstractors in the vicinity. The solution was to use variable speed drive dewatering pumps, programmed to respond to changes in groundwater level in a piezometer at the site boundary.

Figure 7 shows the Lower Aquifer groundwater level at the shaft, the target groundwater levels and the dewatering system abstraction flow rate. The dewatering system flow rate can be seen to be near zero, rising to 40-50 l/s when the public water supply pumping is interrupted. Periods of excessive drawdown occurred when the public water supply was operated at elevated flow rate; and the prolonged period of continuous dewatering pumping in January to March 2019 corresponded to the cessation of pumping from the public water supply well following the mechanical failure of the pump. This is an interesting example of how operation of a resource that is protected by regulation (the public water supply well) can adversely impact construction works, and how modern electrical pumping systems can be controlled to mitigate the risk.

In-tunnel/shaft dewatering techniques and strategies

Tunnelling and shaft sinking using the sequential excavation method (SEM) with sprayed concrete lining (SCL) support has several advantages over other techniques including speed of construction and flexibility in shape. The technique exploits the inherent strength of the ground to allow rapid sequential excavations, each of which is supported by SCL before the next advance. Conventional dewatering techniques for SEM tunnels involve vertical or inclined wells installed from the ground surface in advance of the face, avoiding both the artesian conditions and logistical challenges inherent with the installation of in-tunnel wells that penetrate out through the tunnel lining. Over the last 30 years, however, in-tunnel and in-shaft dewatering techniques have been applied, both to control groundwater where surface access is difficult and to gain direct access to the water bearing strata at tunnel level (Figure 8). The most efficient approach is often a combination of surface and below ground dewatering techniques.

Roberts et al (2015) and Soler et al (2016) give examples of in-tunnel wellpoints that are particularly appropriate when targeting thin or intermittent granular beds of water-bearing soils where a closer well spacing of 1 to 3 m may be required. Prior to the mid-1990s, standard surface dewatering and installation equipment was taken underground but over the last 25 years specialist in-tunnel and in-shaft systems, equipment and techniques have been developed. Figure 9 shows a compact in-shaft ejector station with inclined ejector wells drilled inclined through the concrete secant pile wall shaft lining to reduce external hydrostatic loads and to control seepage into the base of the shaft. Surface access restrictions meant that a conventional vertical well system outside of the shaft was not an option. Installation of wellpoints or ejector wells from a tunnel or shaft into pressurised granular soils (with a groundwater head significantly above the level of the drill rig) requires the use of a specialist insert grouted into the tunnel or shaft structural lining. The insert is fitted with a blowout preventer (BOP) to control ground loss and water flow during installation. Lost bit drilling is then used to drill through the insert to place casing to the target depth; the well screen and liner are then installed as the casing is withdrawn.

An example of an in-tunnel dewatering scheme for a cross passage between two running tunnels (previously driven by TBM) is illustrated in Figure 10a and 10b. A water-bearing granular bed had been identified at and below the tunnel invert, which was targeted with an array of downward inclined wellpoints installed from one of the TBM drives. The dewatering strategy involved installation of the initial wellpoint array with procedures for monitoring and 'toolbox' measures (a term used in tunnelling to describe specific additional groundwater control measures, applied in response to observed conditions). Here these toolbox measures comprised supplementary wellpoint installations, only installed if required. Probe drilling, shown in red, would then be carried out to prove stable conditions in advance of the cross-passage excavation.

Artificial recharge systems

Artificial recharge of groundwater back to the ground has become an increasingly important groundwater control strategy for several reasons, including as an environmental risk mitigation measure (e.g. Holmes et al 2018); as a settlement risk mitigation measure (e.g. Roberts and Holmes 2011; Powrie and Roberts 1995); and as a means of disposal where other options are not available or have a high cost. In Tel Aviv, Israel, discharge of groundwater to sewer is prohibitively costly so that almost all discharge from construction dewatering systems in the shallower aquifer is recharged. This is a deliberate policy to preserve groundwater resources. Access and space constraints in the city mean that water from dewatering systems is generally recharged to a deeper aquifer 50 to 200 m below the site.

Successful design of an artificial recharge system usually requires a data from a relatively detailed hydrogeological investigation supported by appropriate, often numerical, modelling. The investigation is required to provide the ground profile, groundwater levels, basic hydrogeological modelling parameters, realistic values for well yields, and to assess the risk of loss of recharge capacity due to clogging. In addition to investigating the design of the abstraction system, the modelling also needs to provide a good understanding of the risk and extent of any feedback (between artificial recharge flows and the pumping wells), and of the extent and potential impact of any local increases in groundwater level around the location of recharge wells, trenches or infiltration ponds. Successful implementation and operation of an artificial recharge system requires real-time monitoring of flows and groundwater levels to identify any capacity loss in the system and allow development of a strategy and programme for the redevelopment and cleaning of the recharge wells to recover capacity.

Vacuum deepwells

As noted in Table 2, ejector wells have been in regular use in North America since the 1950s. The first major use of ejectors in the UK was for the Conwy crossing in North Wales (Powrie and Roberts 1990). Ejector wells are an effective technique for providing vacuum assisted drainage in fine granular soils with permeability in the range 10^{-7} to about 10^{-5} m/s. Ejectors are based on the venturi effect, whereby water is pumped through the constriction of a nozzle to reduce pressure and provide suction according to Bernoulli's Principle. Ejectors can pump both air and water hence, if the well head and annulus are sealed, when the well is emptied of water a vacuum will develop, which assists the drainage of water from fine-grained soils. An important benefit of ejector wells is that they do not require a flow of groundwater and can be run 'dry' for extended periods without damage. Ejector wells have several drawbacks, however:

- They have low mechanical efficiency, hence high energy consumption relative to the abstraction flow rate.
- The system requires priming, which effectively prevents the implementation of an automatic restart if leakage causes loss of the recirculating water.
- A single high pressure supply pump will operate 40 or more ejector wells, so that a fault with the supply pump immediately leads to the outage of many wells (the same is true for a wellpoint system).

The centrifugal borehole submersible pumps used in deepwells do not suffer these drawbacks but cannot pump air and rely on the flow of groundwater for cooling, lubrication and hydrodynamic stability. If the well head and annulus are sealed, however, a surface vacuum pump can be used to apply a vacuum to the well liner to achieve vacuum assisted drainage. A simple assessment of well yields using the empirical methods from Preene and Powrie (1993) gives the results in Table 3, as an aid to the selection of such systems at the design stage.

The minimum yield for a submersible pump is approximately 0.15 m^3/hr, which from Table 3 suggests that flow rates may be viable for vacuum deepwells in aquifers >5 m thick with permeability >2 x 10^{-6}m/s. Apart from the significant difficulty in reliably assessing permeability and well yield in such fine-grained soils there are also other factors in play, such as redundancy or conservatism in design which results in a greater number of wells for a scheme and a corresponding reduction in individual well yield. A lower practical permeability limit for vacuum deepwells in a 5 m thick aquifer is approximately in the range 2 x 10^{-6} to 5 x 10^{-6} m/s.

The range of applications of groundwater control pumping methods in granular soils, Figure 3a, which dates from the mid-1990s, has been updated to reflect some of the developments noted in this paper, see Figure 11. The key changes are,

- Inclusion of vacuum deepwells as a recognised technique which covers some of the range which was formerly the exclusive preserve of ejector wells,
- Recognition that, for shallow drawdowns, single stage wellpoints are typically effective and more efficient than ejector wells at targeting soils with a permeability <1 x 10^{-5} m/s, and
- Recognition that sumps and drains are effective for drawdowns of 1 or 2 m providing the permeability is not so low that vacuum assisted drainage is required.

Note that Figure 11 is an aide to understanding the range of application of the various pumping methods for groundwater control rather than a primary design tool. It also gives some guide to risk in situations where the range of permeability values at a site are close to or reach across one or more boundaries. Drawdowns greater than the 20 m vertical scale used in Figure 11 can be achieved but invariably require high quality geotechnical and hydrogeological information and expert advice to confirm that conditions are suitable. Techniques which have depth limitations, such as suction lift for wellpoints, require the pumps to be installed at the standing groundwater level to achieve the maximum drawdowns shown.

Figure 11 does not of course apply for cemented soils or rock where open pumping is often significantly more widely applicable although other factors, such as poor discharge water quality due to entrainment of fine particles, can be a factor in selection of methods.

Conclusions

Groundwater control strategies for temporary works have evolved as a result of improvements in materials, equipment and techniques. The need for new equipment and strategies for groundwater control have also been driven by advances in other construction techniques, for example the increased use of SEM and SCL methods for shafts and tunnels. In the UK and many other countries environmental regulation, which aims to protect groundwater resources, groundwater-dependent ecology and the water quality of ponds, watercourses and the sea, has become a major driver for changes in working practices particularly over the last 30 years. Improvements in hydrogeological understanding have led to enhancements and an increased range of applicability of some dewatering techniques.

The principal driver for change in construction industry practices over the coming years is likely to be the requirement to curb greenhouse gas emissions. Cement and steel are both carbon intensive to produce and their use is typically the largest contribution to the carbon emissions of a construction project. Minimising their use is now a guiding principle for designers. and is an increasingly significant factor in the selection and design of temporary works groundwater control measures. Temporary groundwater cut-offs, such as sheet-piles that can be removed, should minimise emissions with the added benefit of preserving groundwater flow paths in the long term. The use of groundwater cut-offs incorporating concrete/cement or steel that are not required for the permanent works and that will remain as a permanent barrier to flow, will need much greater scrutiny of carbon emissions in future. The same applies to temporary anchors or tension piles that are used to resist hydrostatic uplift or lateral loads. Groundwater pumping systems have relatively low carbon emissions, which makes then an attractive alternative method for temporary control of groundwater ingress or excess pore pressures.

There can be tension between minimising greenhouse gas emissions on the one hand and short-term environmental protection and construction risk on the other. Over the last 30 years there has been increasing focus by clients and contractors on restricting the use of groundwater pumping systems (dewatering systems) in favour of groundwater exclusion methods (cut-offs) with the aim of reducing risk of off-site impacts. The complex and sometimes lengthy regulatory regime for obtaining environmental permits for pumping methods has served to further drive this trend, but an increasing focus on reducing greenhouse gas emissions may go some way towards reversing it.

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Table 1: Groundwater control methods commonly used in temporary works

Method	Applications	Example methods
Pumping methods (also known as dewatering methods)		
Open pumping	Can be used for control of surface water run-off and shallow groundwater (including perched water and residual seepages into excavation) in rock and coarse-grained soils, where the flow of groundwater into the excavation is unlikely to cause instability. May generate silt or sediment laden discharge water, causing environmental problems if pumped water is not adequately treated prior to discharge	• Sump pumping • Drainage ditches • French drains
Pre-drainage pumping	Applicable to a wide range of soils and rocks, including cases where ensuring stability of the excavation is a key factor. Artificial recharge may be used to return some or all of the pumped water back to the ground	• Wellpoints and suction wells • Horizontal wellpoints laid by trenching machine • Deepwells with submersible pumps • Ejector wells • Electro-osmosis
Exclusion methods		
Cut-off walls	Cut-off walls are typically vertical. Some methods can be used to form structural elements of the permanent works (e.g. concrete diaphragm walls or secant pile walls used to form basement walls). Other methods are temporary only and can be removed at the end of construction so that no permanent groundwater barrier remains.	Permanent methods • Vibrated beam walls • Cement-bentonite slurry trench walls • Soil-bentonite slurry trench walls • Concrete diaphragm walls • Concrete secant pile walls Temporary methods (if removed at end of construction) • Steel sheet-pile walls • Steel combi-pile walls
Ground treatment	Specialist methods reduce the permeability of the in-situ soil or rock; often there is a corresponding increase in strength. Some methods can be used to form non-vertical elements including barriers to enclose tunnels and other underground spaces or to form basal plugs below excavations.	Permanent methods • Permeation grouting • Rock fracture grouting • Jet grouting • Mix-in-place grouting methods Temporary methods • Artificial ground freezing
Application of fluid counter pressures	Applicable to confined excavations (typically tunnels and shafts) which can be isolated so that fluid counter pressure can be applied	• Compressed air tunnelling and shaft sinking • Earth pressure balance (EPB) tunnel boring machines (TBMs) • Slurry tunnel boring machines (TBMs) • Caisson sinking by the wet caisson method

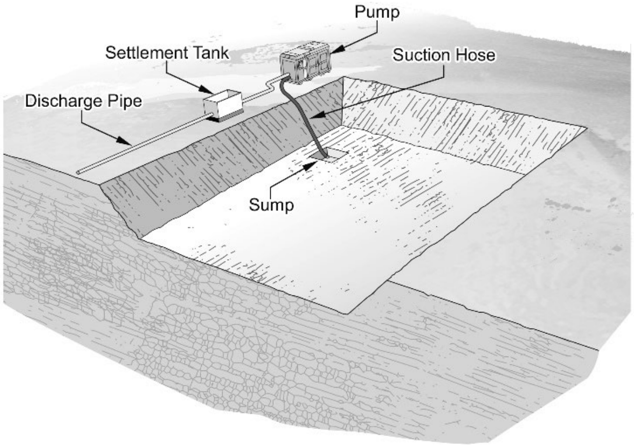
Table 2: Historical development of selected groundwater control methods (based on information from: Cashman and Preene, 2021; Preene and Chrimes, 2021)

Method	**Key principles of the method**	**First reported applications**	**Later improvements in methods**
Pumping methods			
Wellpoint systems	Closely-spaced small diameter wells pumped by a suction system, installed in rings around or lines alongside excavations.	Abyssinian tube wells (also known as Norton tube wells) were developed and used by the British Military from the 1860s onwards.	Modern wellpoint systems typically install wells by water jetting, a method that was developed by Thomas Moore in 1925 in New Jersey, USA. Plastic materials, used for wellpoint risers and pipework, were introduced in the 1960s and 1970s Installation of wellpoints from inside tunnels was perfected on the Storebaelt project in Denmark in the 1990s From the 2000s onwards energy efficiency and emissions controls promote the use of electrically driven pumps and lower emission diesel units
Deepwell systems	Widely spaced wells, pumped by electric submersible pumps in modern practice.	Very early applications were by Marc Isambard Brunel when sinking the Rotherhithe Shaft on the Thames Tunnel in 1824 and by Robert Abraham in 1830, during foundation construction for the Westminster New Bridewell prison. The first large scale application was by Robert Stephenson in 1835–6 for the Kilsby Tunnel on the London to Birmingham Railway.	Electrical submersible pumps were first used in dewatering wells in Germany from 1896, including for the Berlin U-Bahn underground railway. Plastic materials, used for well screens and pipework, were introduced in the 1960s and 1970s Developments in electronic equipment allowed automation of temporary pumping systems to be introduced from the 1980s Improved field sensors, internet connectivity and wireless data networks led to a dramatic expansions of remote monitoring and control systems in the early 2000s
Ejector well systems	Arrays of wells pumped by a water-driven nozzle and venturi system.	Jet pumps (the basis of the method) were developed in the 1850s, but were first applied for groundwater control in the United States in the 1950s, with jet pumps as used in water supply wells.	
Exclusion methods			
Steel sheet-piling	Interlocking steel sections driven or pushed into the ground to form a continuous wall	Cast-iron sheet piles were first used in the early 1820s on the North Pier of Bridlington Harbour.	In the early 1900s the method of steel sheet-piles connected by interlocks (clutches) was developed by Tryggve Larssen, in Germany.

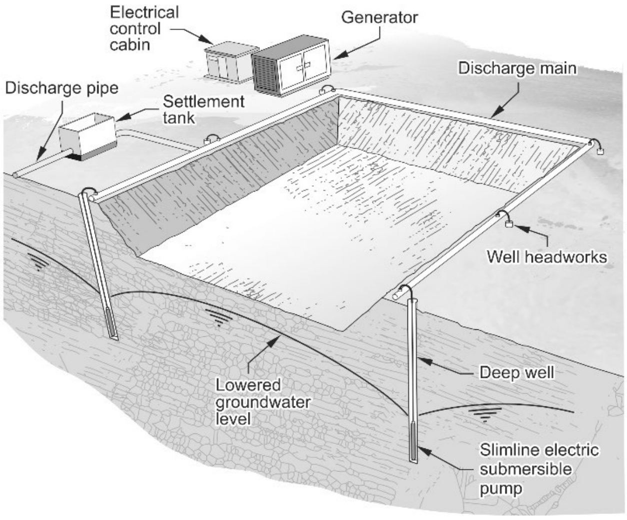
Method	Key principles of the method	First reported applications	Later improvements in methods
Permeation grouting and rock grouting	Injection of fluid grouts to block water pathways without disturbing the soil or rock structure	The first applications of cement grouting were in France between 1797 and 1818, and the method was first applied in the UK in the 1850s.	Chemical grouts were developed in the 1920s. These have a lower viscosity, allowing penetration of smaller soil pores and rock fissures. The first reliable method was the Joosten process, patented in Germany in 1925.
Artificial ground freezing	Low temperature refrigerant is circulated in closely-spaced freezeholes, to create a wall of frozen groundwater and soil/rock.	The method was first used in the UK for shaft sinking at a colliery in South Wales in 1862.	From the 1960s onwards liquid nitrogen was used on some projects as an alternative to chilled brine.
Compressed air tunnelling	Tunnels and shafts under construction are pressurised with air to approximately balance groundwater pressures.	A system for compressed air tunnelling was patented in 1830 by Sir Thomas Cochrane.	From the mid 20th century the health risks to workers in compressed air environments gained greater attention. By the Millennium the use of compressed air methods in most countries was limited to carefully controlled conditions with specialist medical supervision.

Table 3: Assessment of well yields in fine soils using empirical methods from Preene and Powrie (1993) with shading indicating viable deepwell flow rates.

	Permeability			
	5.0 x 10^{-7}m/s	**1.0 x 10^{-6} m/s**	**2.0 x 10^{-6} m/s**	**1.0 x 10^{-5} m/s**
Screen Length	**Well yield**	**Well yield**	**Well yield**	**Well yield**
1 m	0.008 m^3/hr	0.017 m^3/hr	0.034 m^3/hr	0.170 m^3/hr
5 m	0.042 m^3/hr	0.085 m^3/hr	0.017 m^3/hr	0.848 m^3/hr
10 m	0.085 m^3/hr	0.170 m^3/hr	0.339 m^3/hr	1.696 m^3/hr

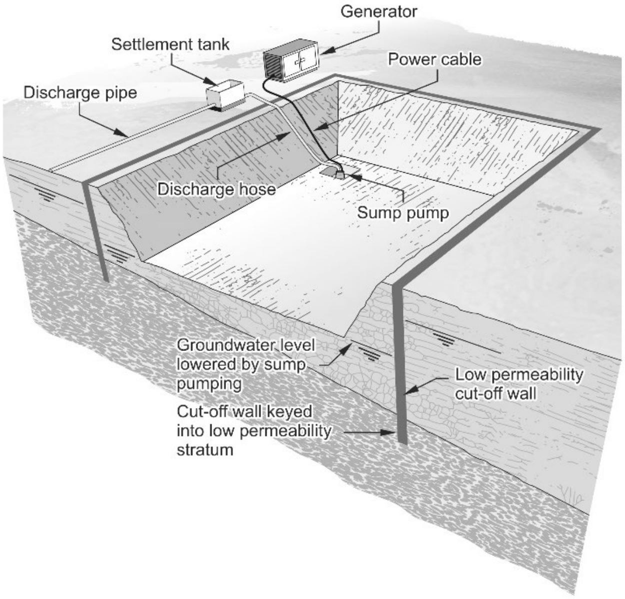


a) Open pumping (example shown is a sump pumping system)

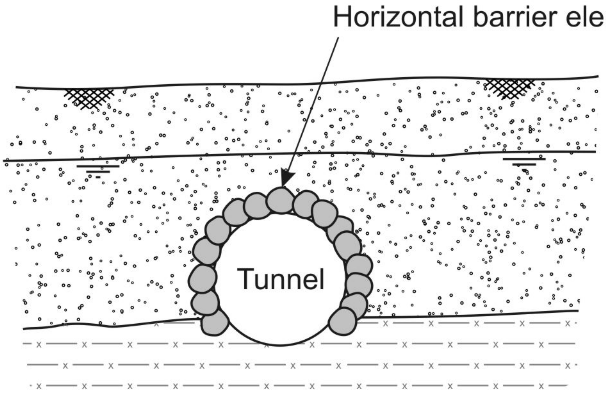


b) Pre-drainage pumping (example shown is a deepwell system)

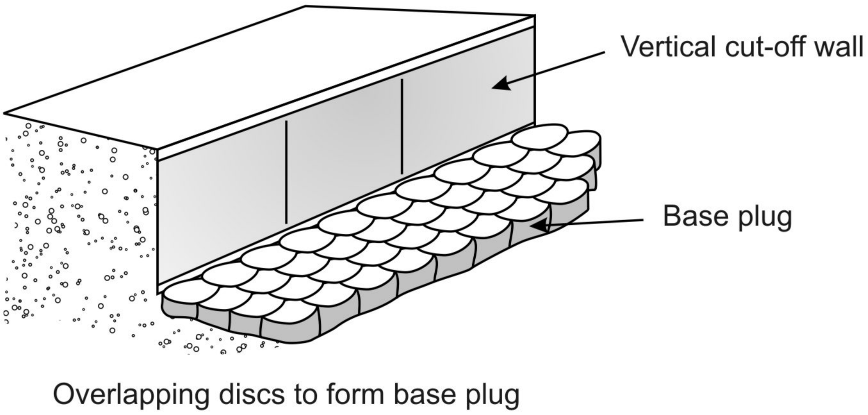
Figure 1: Examples of groundwater control by pumping (reproduced from Cashman and Preene, 2021, with permission)



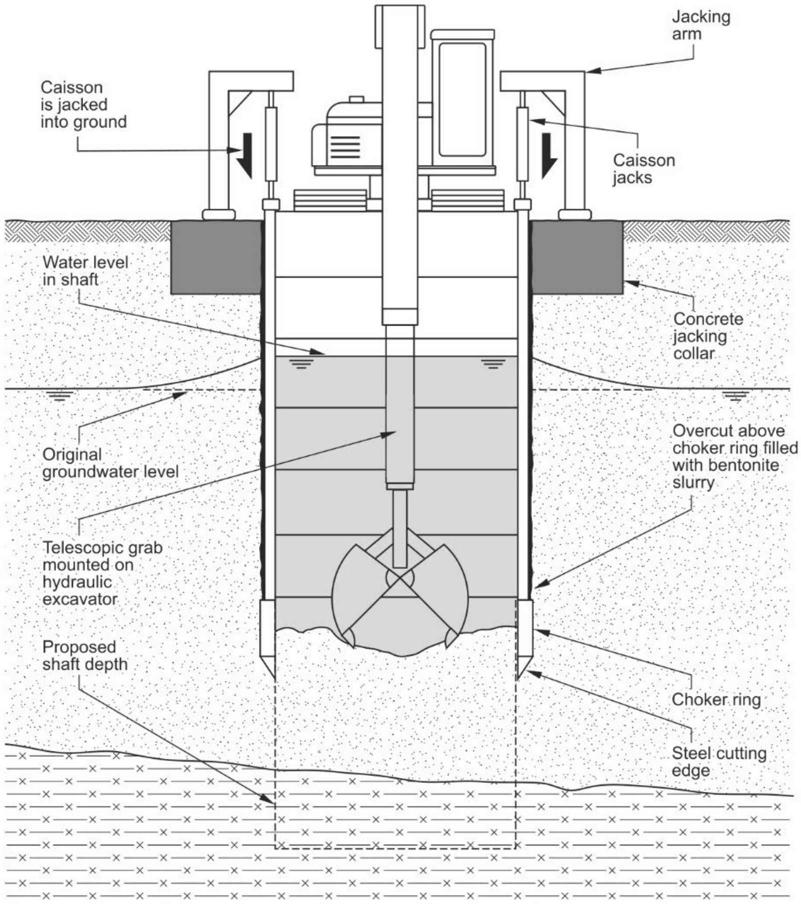
a) Groundwater exclusion using vertical barriers sealed into a low permeability stratum below the excavation



b) Horizontal barrier elements of ground treatment used to exclude groundwater from a tunnel under construction

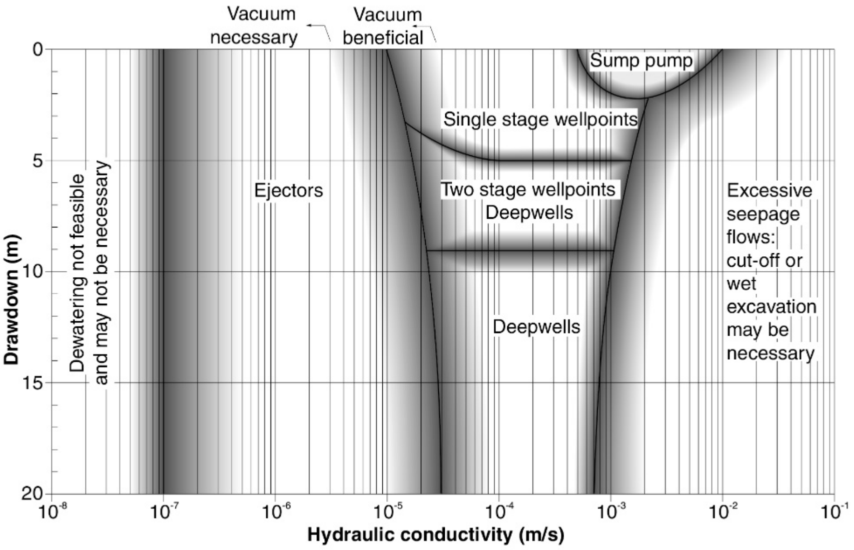


c) Vertical barriers used in combination with a low permeability base plug formed by ground treatment methods

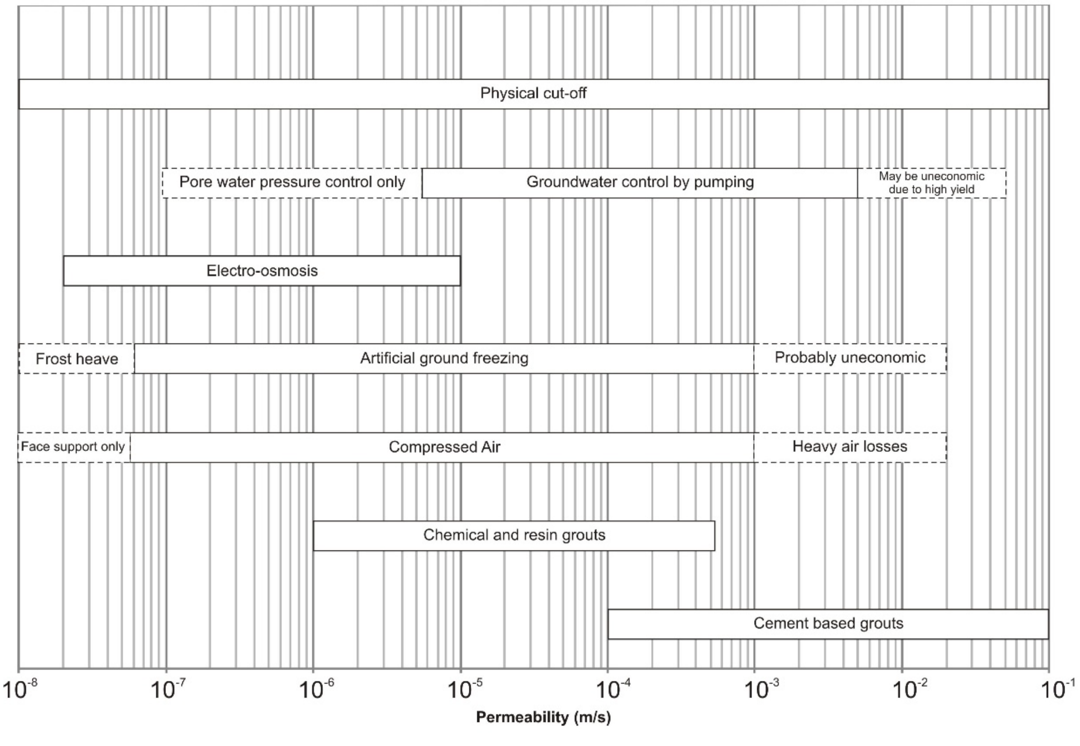


d) Shaft construction by the wet caisson method, where water inside the flooded caisson provides a fluid counter pressure to balance groundwater inflows

Figure 2: Examples of groundwater control by exclusion (reproduced from Cashman and Preene, 2021, with permission)

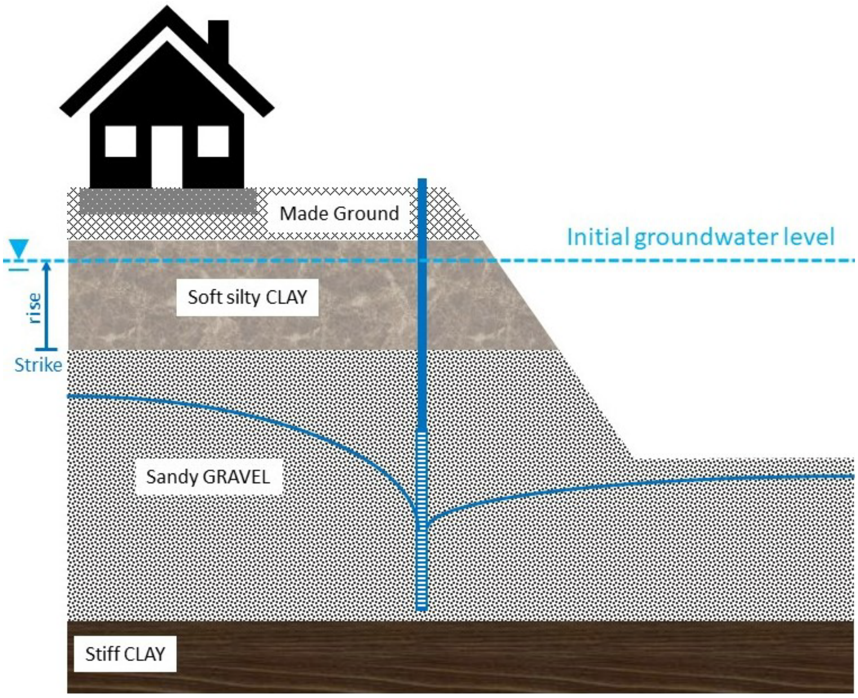


a) Range of application of groundwater control pumping methods in granular soils (from Preene et al., 2016; reproduced courtesy of CIRIA: www.ciria.org)

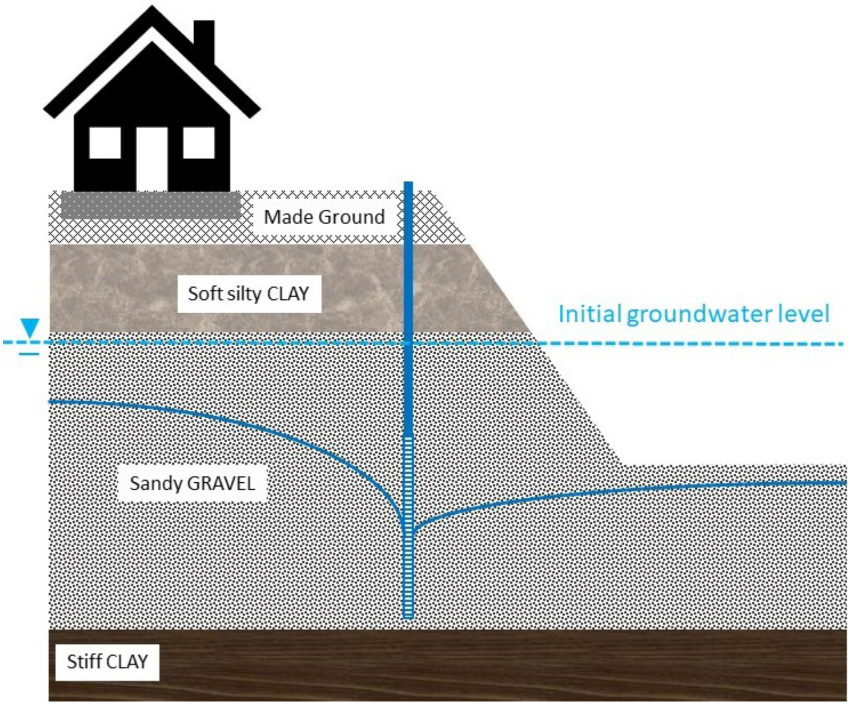


b) Tentative economic ranges for groundwater exclusion methods in soils (from Preene et al., 2016; reproduced courtesy of CIRIA: www.ciria.org)

Figure 3: Guidance on the range of application of groundwater control methods



a) High risk of dewatering-related settlement if groundwater level is lowered – soft silty clay will be underdrained and hence will consolidate



b) Low risk of dewatering-related settlement if groundwater level is lowered – soft silty clay is above the natural groundwater level and will not be affected by groundwater lowering

Figure 4: Examples of the impact of hydrogeological setting on risk of settlement due to lowering of groundwater levels

Figure 5: Installation of in-tunnel wellpoints in a tunnel heading (constructed by SEM/SCL methods) using an electrically driven drilling rig (Image courtesy of WJ Group)

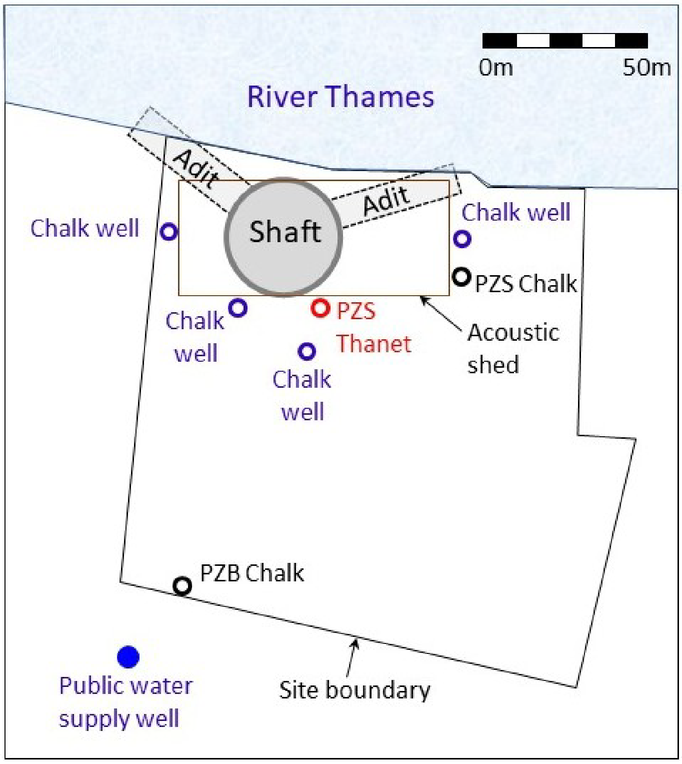


Figure 6: Plan view of Tideway project drive shaft and adit located 120 m distant to a public water supply well

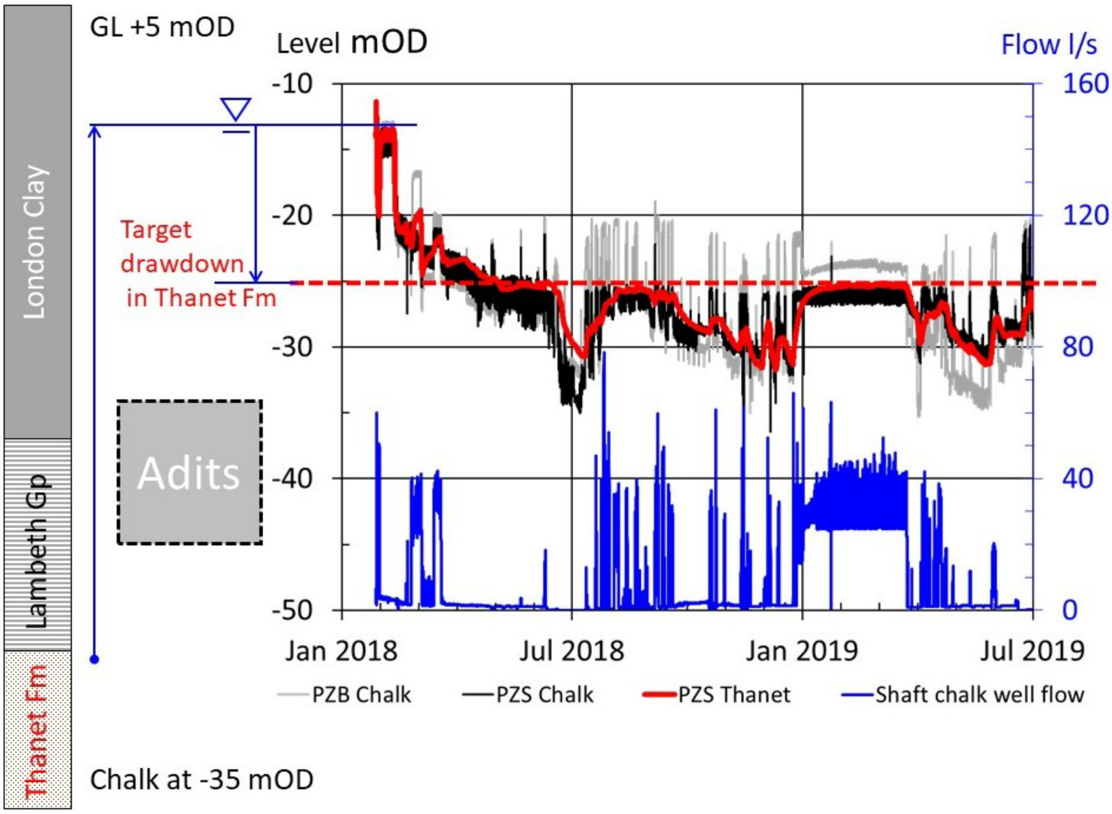


Figure 7: Ground profile and plot of groundwater levels and dewatering system abstraction flow

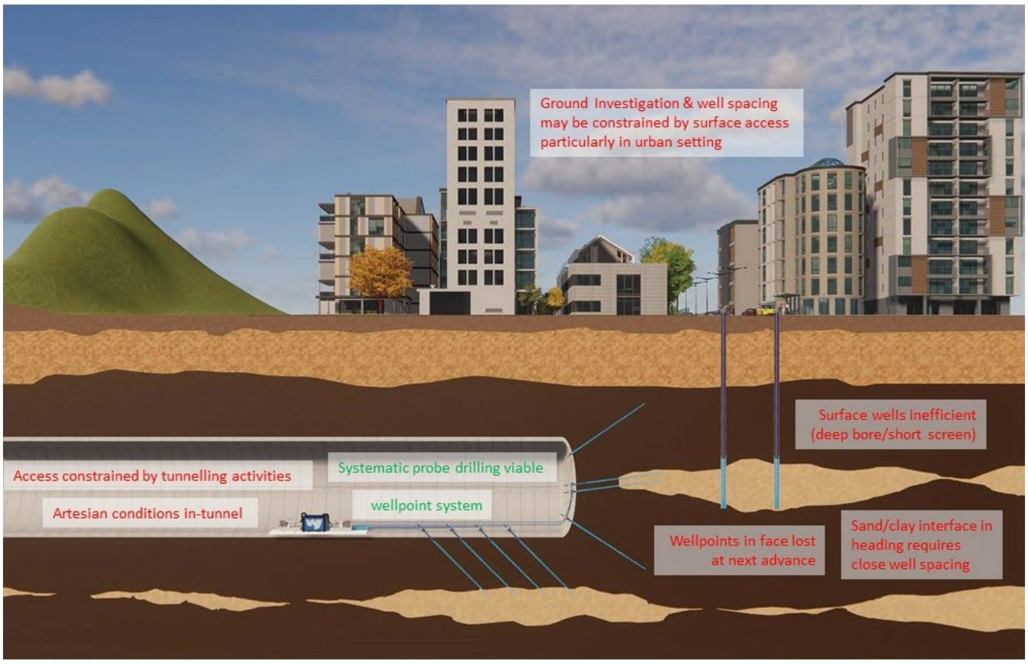
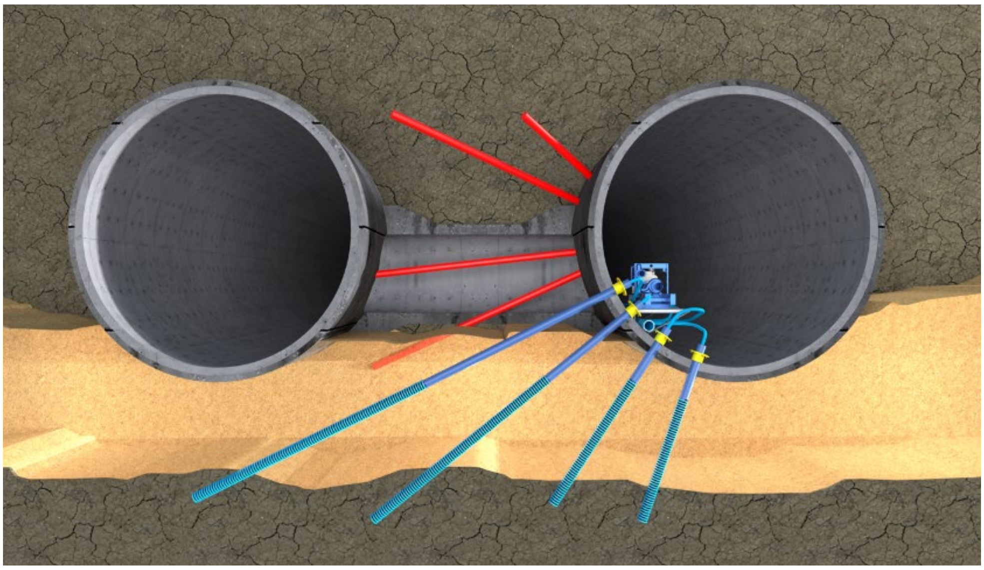
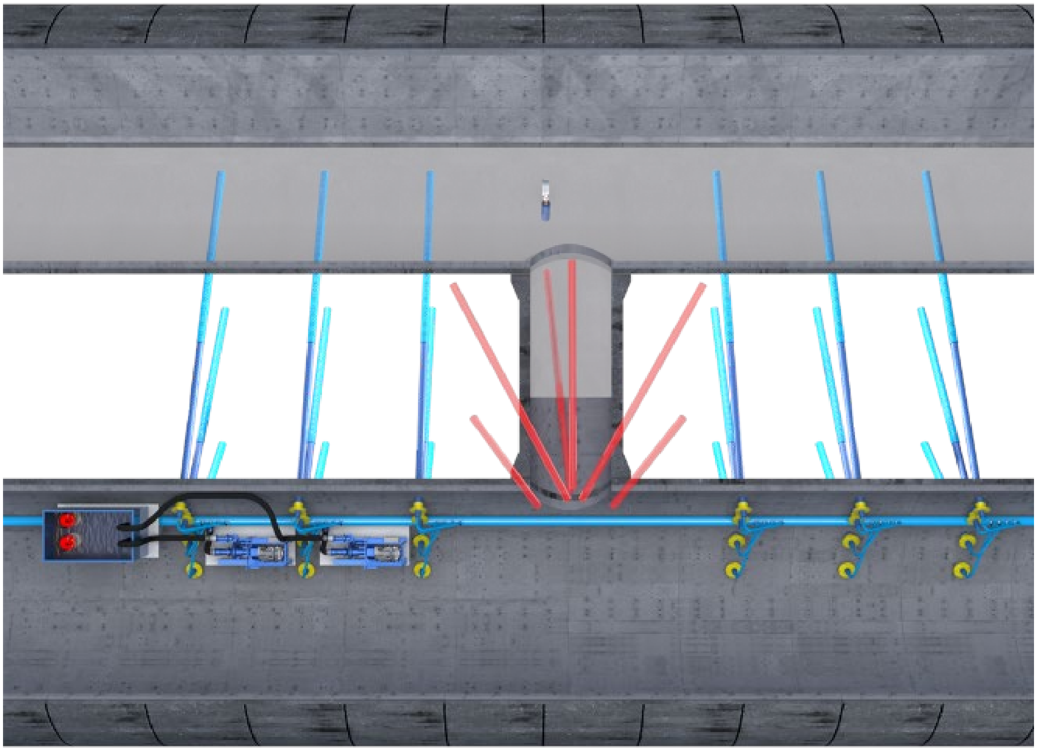


Figure 8: Groundwater control for tunnels: surface dewatering compared with in-tunnel dewatering techniques

Figure 9: Compact ejector pumping station for use in shafts or tunnels with inclined ejector wells installed through a concrete secant pile wall to control external hydrostatic pressures and base seepage inflow (Image courtesy of WJ Group)



a) Cross section



b) Plan view

Figure 10: Layout for in-tunnel dewatering for a cross passage with a water bearing granular horizon below invert

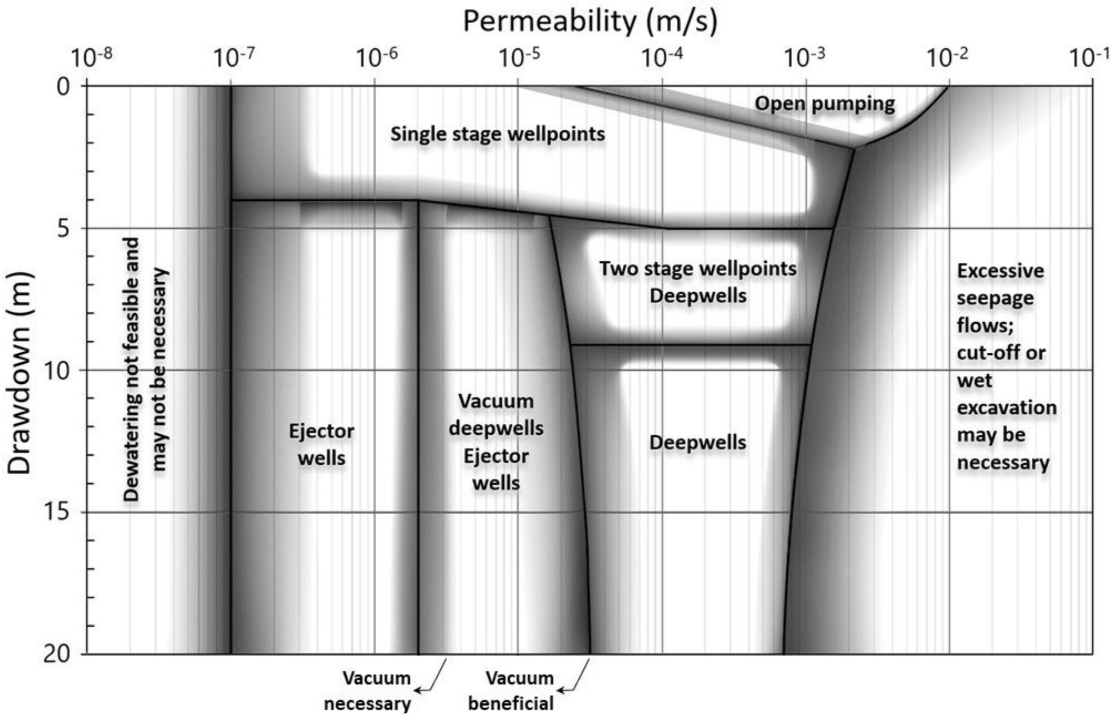


Figure 11: Revised range of application of groundwater control pumping methods in granular soils (updated from guidance in CIRIA Report C750 (Preene et al, 2016)