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CONSTRUCTION DEWATERING IN CHALK

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CONSTRUCTION DEWATERING IN CHALK

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Abstract
Construction dewatering is often required to control groundwater when excavations are made in Chalk, which is a relatively soft fissured limestone. The rate of groundwater inflow and any associated instability in an excavation are controlled by the hydrogeological setting and the degree of weathering of the Chalk. Structureless Chalk or highly weathered structured Chalk may exhibit groundwater-related instability comparable to coarse geotechnical soils such as sands and gravels. Conversely, less weathered structured Chalk may act like massive fissured rock, where large water inflows can occur along pre-existing bedding planes, fissures and other geological features such as sheet flints. The applicability of construction dewatering techniques is strongly influenced by permeability, which can be related indirectly to weathering grade of Chalk. This paper includes data on 49 case histories, from literature and the Authors' experience, of construction dewatering in Chalk and presents guidance on dewatering methods to be used in different grades of Chalk; this is an update of previous guidance in Roberts and Preene (1990). Recommendations are given for appropriate ground investigation techniques relevant to construction dewatering, including well pumping tests and dewatering trials.

Introduction
Chalk is a relatively soft fissured limestone rock of Cretaceous age present beneath many areas of the UK and north-western Europe. The potential problems that can affect geotechnical engineering works in Chalk are well documented (Lord *et al*., 2002). A particular challenge in Chalk is dealing with groundwater when constructing excavations and tunnels that extend below groundwater level.

In terms of its geotechnical and hydrogeological properties, Chalk is a very diverse material. In its more highly weathered structureless forms Chalk can act like both fine grained and coarse grained geotechnical soils and can suffer from 'running' conditions or 'blows' where uncontrolled groundwater pressures destabilise the base and sides of an excavation. Conversely, the less weathered structured grades may act like massive fissured rocks, where inflow to excavations occurs only along pre-existing bedding planes, fissures or other geological features. Groundwater inflows can vary from minor nuisance seepages to major inflows with associated risks of instability and inundation.

Around 25 years ago, as part of a major symposium on Chalk (Burland *et al*., 1990), the Authors produced a paper discussing some experiences of construction dewatering, and suggested a relation between suitable dewatering and groundwater investigation techniques and the Chalk weathering grades used at that time (Roberts and Preene, 1990). In the intervening time there has been considerable improvement in knowledge of geotechnical and groundwater problems in the Chalk. Part of the reason for this improvement is the extensive construction dewatering activity in the Chalk, associated with major tunnelling and construction projects such as the Jubilee Line Extension, Channel Tunnel Rail Link (now known as HS1) and Crossrail (Elizabeth Line), among others. When reviewing the literature on construction dewatering in Chalk, the Authors were surprised to find that Roberts and Preene (1990) was still the main reference providing guidance on dewatering in Chalk.

This paper presents an update on best practice for the investigation, design and execution of construction dewatering in Chalk. It reviews current knowledge on groundwater problems in Chalk, summarises published literature of dewatering projects, and combines this with the Authors' experience.

Hydrogeology of Chalk

The Chalk is an important aquifer[1] in the UK that is widely exploited for water supply. Detailed studies of its hydrogeology are summarised thoroughly elsewhere (Downing *et al*., 1993; Allen *et al*., 1997), and will not be rehearsed here. However, much of the literature relates to groundwater resource issues, the design of water supply wells and the migration of contamination. The hydrogeological factors affecting construction projects are subtly different to those addressed in most of the literature. The structure and degree of weathering (as expressed in the assessed grade of the Chalk, see Spink, 2002) are important, as are various other geological aspects (the engineering geology of the Chalk is discussed in detail by Mortimore, 1993; 2012). The current paper will attempt to integrate these aspects to present a summary of potential groundwater problems affecting excavations in the Chalk.

Chalk is present beneath several areas of the UK (Figure 1). It forms the downland of southern England, the Wolds of eastern England and the white cliffs of East Yorkshire, Antrim and areas of the coast of the English Channel in southern England. In geological terms, the Chalk of England is often considered as being divided into three provinces, each with different lithological properties.

- The Northern Province Chalk tends to be harder than its southern counterpart, and is covered in many areas by Quaternary Deposits (such as Glacial Till).
- The Southern Province is part of the Anglo-Paris Basin and includes central London and the Thames Valley. In this province the Chalk is overlain in some areas by Palaeogene deposits (e.g. the Thanet Sand and Lambeth Group in London) or by Quaternary deposits (e.g. River Terrace Deposits in east London or the Thames Valley upstream of London). In the Wealden district it has been eroded to expose older rocks in the Weald anticline.

[1] In the context of this paper aquifer refers to a permeable water-bearing stratum of soil or rock, irrespective of whether it is used for water supply. Aquitard refers to lower permeability strata or beds that do not transmit water freely and can act as a significant restriction to groundwater flow.

- The Transitional Province including the Chilterns and East Anglia in which some characteristics of both the Northern and Southern Province exist in different areas. Here the Chalk is often overlain by Palaeogene or Quaternary deposits.

It has long been known that the flow of groundwater in the Chalk is dominated by flow through fissures or other discontinuities, rather than by water percolating in a diffuse manner through the matrix of the rock. The matrix porosity ranges from 0.1 to 0.5 and is commonly of the order of 0.35. The pores in the matrix of the rock contain significant quantities of water, but are of sufficiently small size that the matrix has a very low permeability (10^{-8} to 10^{-9} m/s is quoted by Price *et al*., 1993) and the matrix water is almost immobile under the pumping action of construction dewatering systems or water supply wells. For most practical purpose the mobile water in the Chalk is restricted to permeable fissures that are typically associated with the structure of the Chalk and can comprise bedding layers, flint bands (particularly sheet flints), and networks of steeply dipping joints. Chalk, being a limestone, has a significant solubility to water, and fissures can become enlarged as a result of long-term groundwater flow, potentially resulting in the development of zones of enhanced permeability and karst flow systems (Banks *et al*., 1996). The distribution of permeable zones is further complicated by the presence of weathered zones within the Chalk, where the bedding and jointing has been disrupted. The fracture porosity of the Chalk is low, generally of the order of 0.01 to 0.03.

For most construction projects in the UK, the nature of the Chalk encountered is described against a framework of different grades of Chalk – commonly known as the CIRIA grades, after CIRIA Report C574 Engineering in Chalk (Lord *et al*., 2002). In this paper, the term Chalk grades refers to the CIRIA grades. Spink (2002) discusses the background to the development of Chalk grades, and the methods of assessing grade from field samples.

Table 1 takes the suggested ranges of permeability assessed for the older Chalk classification system (known as the Mundford grades: Wakeling, 1970) from Roberts and Preene (1990) and combines it with the more modern CIRIA classification (CIRIA grades).

Several points should be noted in relation to Table 1:

i. Structured Chalk, where bedding and jointing is present, should be expected to be 'water-bearing' (and can be termed an aquifer) with the associated risk of significant groundwater inflows, and will typically behave as rock in engineering terms.
ii. The less weathered structured Chalk (grade A) will tend to have widely spaced fissures, which will control groundwater inflow. Inflow to a given excavation or tunnel may therefore be erratic, depending on what fissures are encountered. Where significant fissures are encountered, inflows may be large. Conversely, if an excavation does not encounter open fissures, inflows may be modest.

iii. The more weathered structured Chalk (grades B and C) tends to have more closely spaced fissures and will also often be water-bearing. Moreover, the more closely spaced fissure networks mean that inflows may sometimes be more evenly distributed across an excavation, in a manner analogous to a coarse granular material such as a sand and gravel.

iv. There are two divisions of structureless Chalk grading: matrix dominated (Dm) and clast dominated (Dc). Spink (2002) indicates that Structureless Chalk behaves as a geotechnical soil, with Dm Chalk analogous to fine-grained soil (silts and clays) and Dc Chalk analogous to coarse-grained soil (sands and gravels). In permeability terms the distinction is not so clear. Structureless Chalk is generally of low permeability (10^{-7} to 10^{-9} m/s) but some Dc grades in harder Chalks can form highly permeable chalk bearings or frost shattered Chalk which can have permeability comparable to grades B and C Chalk.

In the same way that Spink (2002) highlights that determination of the Chalk grade should not be considered as a replacement for a full description of the Chalk, the permeability values in Table 1 are not intended to replace an appropriate hydrogeological investigation at a site where significant dewatering works are planned. The role of Table 1 is to identify potential order of magnitude ranges of permeability as an aid to initial selection of dewatering method and ground investigation strategy.

Potential Groundwater Conditions in Chalk

When developing a construction dewatering scheme in Chalk, it is essential to assess the potential presence of zones of higher permeability horizons (and conversely any zones of significantly lower permeability). This must be done on a site-by-site basis, using information from geological desk studies and intrusive ground investigations, among other techniques (see Chapter 9 of Lord *et al*., 2002). However, some general indicators of potential groundwater behaviour in Chalk are discussed below:

i. Chalk may form an unconfined or confined aquifer:
    a. In unconfined conditions the upper part of the Chalk may be unsaturated, and excavations into the Chalk above groundwater level may encounter little or no groundwater (Figure 2a).
    b. In confined conditions the entire thickness of the Chalk is saturated, and the piezometric level is above the top of the Chalk (Figure 2c)

ii. Overlying water-bearing deposits can be in hydraulic connection with the Chalk forming a combined aquifer (Figure 2b and 2c).

iii. It is generally accepted that overall distribution of permeability within the Chalk is strongly influenced by geological structure and surface topography. Higher permeabilities are associated with anticlines and river valleys, and lower values are expected in synclines and interfluves. The influence on permeability of river valleys and interfluves is known to be relevant, even where the Chalk is confined beneath very low permeability strata (e.g. the Palaeogene deposits of the London Basin) (Allen *et al*., 1997).

iv. In addition to structural features, the lithology and stratigraphy of the Chalk can also affect the distribution of permeability within structured Chalk.
    a. Bedding and flint bands can potentially form higher permeability zones. Harder layers (sometimes known as chalk hardgrounds or chalk rock), such as the Melbourn Rock or Totternhoe Stone can often form higher permeability zones. This is possibly because they fracture more cleanly due to their greater hardness (Price *et al*., 1993).
    b. Sheet flints and marl seams can form layers of lower permeability that can act as aquitards, restricting vertical groundwater flow. However, these lower permeability zones often create perched water tables, and thus more intensely weathered zones. The Chalk immediately above a marl seam can potentially be of higher permeability than elsewhere, but can also be a reservoir of perched water (Lord *et al*., 2002).

v. It is also generally accepted that significant permeable fissures are confined to the upper few tens of metres of the Chalk (50 m is commonly used as the maximum thickness of the permeable Chalk), in both confined and unconfined aquifer conditions. However, discrete widely-spaced permeable horizons may exist in the Chalk at greater depth, particularly associated with hardgrounds.

vi. In some unconfined Chalk aquifers zones several metres thick with significantly higher permeability may exist at or below current groundwater levels. These are associated with the zone of water table fluctuation under recent or historic (e.g. lower groundwater levels during the Quaternary period) environmental conditions. In these zones the concentration of groundwater flow has enlarged fissures and enhanced permeability,

vii. Structureless Chalk, which is the result of weathering, can have a key role on groundwater flow in the upper horizons of the Chalk.
    a. Structureless Chalk is often of significantly lower permeability than structured Chalk, as a result of the degradation and loss of the permeable bedding and fissures. Weathering can also significantly reduce its strength. This is reflected in the colloquial term ‘putty chalk’ sometimes used to describe relatively soft and low permeability structureless Chalk (Younger, 1989).
    b. The typically greater hardness of Northern Province Chalk, can result in the formation of rubbly ‘chalk bearings’ (a breccia-like deposit) in the upper horizons in the Chalk, as a result of periglacial weathering. Structureless Chalk in the form of chalk bearings can be of high permeability, which contrasts with the low permeability putty chalk often found in similar settings in the south of England (Gale and Rutter, 2006).

viii. In some hydrogeological conditions the Chalk can form karst systems. In these cases, long-term groundwater flow enlarges the fissures by solution to form a network of larger, and very permeable, conduits. Groundwater flow can be very rapid in such systems. Banks *et al*. (1996) report a tracer test that indicated groundwater flow velocities of more than 5,000 m/day between a sinkhole and spring in the Chalk in Berkshire, UK.

Three principal hydrogeological settings are relevant to potential construction dewatering problems in Chalk, as outlined below and in Figure 2.

Case A – Unconfined Chalk aquifer, no overlying high permeability stratum present (Figure 2a)
In this case the Chalk is not in hydraulic connection with an overlying permeable stratum. Where these aquifer conditions exist in the interfluves between river valleys the permeability may be relatively low. Conversely close to river valleys there is a likelihood of higher overall permeability. Structureless Chalk may be present in the upper horizons in some areas, as a result of weathering – in these cases an excavation may commence in structureless Chalk and then progress into structured grades at greater depths. As a result of the low fissure porosity groundwater levels may vary significantly (annual variations of several metres or more) between seasonal lows (in dry summers) and seasonal highs (in wet winters).

Case B – Unconfined Chalk aquifer, overlying high permeability stratum present (Figure 2b)
Here the Chalk is overlain directly by permeable stratum (typically River Terrace Deposits); an example of this might be several areas in the Thames Valley of England (Younger, 1989). The potential for high inflows is compounded by the typically higher permeability of the Chalk in river valleys where permeable gravels are often found. However, in some cases low permeability structureless Chalk (putty chalk) immediately below the gravels means there is only poor hydraulic connection between the Chalk and overlying strata (Younger, 1989). These conditions tend to be found in river valleys, and hence groundwater levels are often controlled by river levels.

Case C – Confined Chalk aquifer (Figure 2c)
Under these conditions the Chalk is overlain by very low permeability deposits (the confining layer) and the piezometric head is above the base of the confining layer; the confined Chalk aquifer beneath central London is a well-known example (Woods *et al*., 2004). In some cases there may be permeable granular deposits above the Chalk and below the confining layer (for example the Lower London Tertiary deposits in London). The Chalk is fully saturated and groundwater flow is controlled largely by structural features including bedding, marl seams and flint bands (particularly sheet flints). The overburden stress from the presence of the confining layer may act to reduce fissure openings and reduce permeability. Alternatively, structural features can result in zones of high permeability; this can include river valleys that are commonly associated with zones of high permeability, even below thick confining layers. The presence of low permeability confining beds means that the pre-construction groundwater regime may include vertical stratification of groundwater heads. This occurs in some parts of the London Basin where piezometric heads in the Chalk are much lower than in the overlying Lambeth Group and River Terrace deposits, as a result of historic high levels or abstraction from the Chalk (Environment Agency 2016).

Construction Dewatering Strategies in Chalk

The purpose of construction dewatering is to allow an open excavation, tunnel or cavern to be formed in workably dry and stable conditions. There are two objectives; firstly to prevent the excavation from flooding; secondly to ensure that the seepage gradients (and associated high groundwater pressures) do not result in instability which can be a problem in weaker grades of Chalk, including structureless Chalk.

Construction dewatering is a form of groundwater control using pumping to temporarily lower piezometric levels (Figure 3). This is typically achieved by pumping from an array of wells or sumps located in or around the excavation. Groundwater control can also be achieved by exclusion methods using cut-offs (Figure 4). Some form of groundwater pumping is often required to deal with the trapped groundwater within the cut-off, seepage beneath the cut-off, and any leakage inflow. A wide range of techniques is available for groundwater control by pumping or exclusion; further details are given in Cashman and Preene (2012) and Preene *et al*. (2016).

Table 2 presents summary data from construction dewatering projects in Chalk from published literature and the Authors' experience. The case histories are presented in date order. The majority of the case histories are in the Southern Province Chalk. This is probably the result of the greater number of deep infrastructure and construction projects in the South of England, relative to the north, rather than any geotechnical factors related to the properties of the Chalk in the different geological provinces. Groundwater control requirements (and the applicable methods) are strongly influenced by permeability, which, in the context of construction dewatering, can be broadly correlated to Chalk grade. Typical dewatering requirements in relation to Chalk grade are summarised in Table 3, which is an update of the original guidance in Roberts and Preene (1990).

Construction Dewatering in Grade A Structured Chalk

In relation to groundwater flow to excavations and dewatering systems, grade A structured Chalk can be treated as fissured rock, where the principal challenge to excavation is water management and removal, and groundwater-induced instability is not a major concern. Groundwater inflow into excavations in grade A Chalk is likely to be concentrated in fissures and discontinuities. Inflows can potentially be large; dealing with high flow rates can be challenging in shaft and tunnel excavations where space is limited. Example case histories from the literature in Table 2 include the Brighton and Hove Stormwater Tunnel and Croydon.

Dewatering is typically carried out by sump pumping to remove the water that enters the excavation. In some cases it may be appropriate to consider installing relief wells to intercept fissures around or in advance of the excavation. It has been suggested (Mortimore, 2012) that where groundwater inflow is associated with steeply dipping or sub-vertical joints, relief wells drilled at an angle to the vertical may have an increased chance of intercepting the permeable features.

Construction Dewatering in Grade B and C Structured Chalk

Roberts and Preene (1990) suggested that these materials might be considered, in relation to dewatering, to behave analogous to sandy gravels in that they have significant permeability and may become unstable even under the modest hydraulic gradients of groundwater inflow into the excavation. Due to the relatively high permeability, groundwater inflows may be substantial. Example case histories from the literature in Table 2 include the Port Solent Lock Structure, Mewsbrook STW and Chatham Yacht Lock.

The most appropriate approach in these conditions is 'pre-drainage' using arrays of pumped wells to lower groundwater levels in advance of excavation (Figure 3). This avoids the risk of seepage gradients and high pore water pressures causing instability. For relatively shallow excavations (less than 4 to 6 m below groundwater level) wellpoint dewatering could be considered. For deeper excavations, deep wells with submersible pumps is typically a suitable method, and is also widely used for shallow excavations.

Lower permeability layers (such as marl seams or flint beds) can impede the vertical drainage of groundwater allowing groundwater seepage to track sub-horizontally along these layers and enter the excavation as 'overbleed seepage'. Localised sump pumping with French drains may be used to intercept this 'nuisance water' from within the excavation.

Construction Dewatering in Structureless Chalk

Structureless Chalk can form poorly draining low permeability layers that can influence hydraulic connections with other strata, or can form highly permeable layers with the potential to allow high rates of inflow to an excavation.

Grade Dc Chalk (clast dominated structureless Chalk)

The clast-dominated grades of structureless Chalk are predominantly comprised of Chalk fragments of sand size or larger; comminuted chalk may be present in some or all of the interstices between the larger Chalk fragments. Materials with large proportions of comminuted chalk (Spink, 2002, indicates that grade Dc Chalk can contain up to 35% comminuted material) are likely to have a relatively low permeability and be comparable to Grade Dm Chalk in terms of dewatering behavior.

If the chalk fragments are predominantly gravel sizes, and the interstices relatively free of fine particles, then the permeability could be similar to the upper end (1×10^{-3} m/s) of the range for grade B and C Chalk. This may be described as chalk bearings (usually associated with the Northern Province Chalk), brecciated Chalk or frost shattered Chalk. Pre-drainage methods such as deep wells or wellpoints are most appropriate for high permeability grade Dc Chalk. Sump pumping is not normally suitable, due to the risk of instability caused by groundwater inflow.

Grade Dm Chalk (matrix dominated structureless Chalk)
The general expectation is that Dm grade Chalk will be of relatively low permeability because of the high proportion of silt and sand size fragments of comminuted chalk present in the interstices between the larger Chalk fragments. The resulting material is effectively an aquitard.

In terms of dewatering behavior, the grade Dm Chalk can be considered to be analogous to a silt or clay; gravity drainage by pumping from wells or sumps is likely to have little effect on draining the material.

A potential risk when excavating in low permeability structured Chalk, is instability of the base of the excavation (termed 'hydraulic failure') due to high groundwater pressures in more permeable Chalk below the base of the excavation. This type of instability can be avoided or mitigated by installing pumped wells or relief wells into more permeable Chalk at depth, to reduce groundwater pressures acting on the base of the structureless Chalk (Figure 5 and the Salisbury case history in Table 2).

Hydraulic Failure of Excavations in Strata Overlying Permeable Chalk
Where permeable Chalk is overlain by low permeability strata (such as in the London Basin where low permeability clays overlie the Chalk and the sands of the Thanet Sand and Lambeth Group, or in northern England where the Chalk is overlain by Glacial Till) the risk of hydraulic failure of the base of excavations must be considered (Figure 6). Where hydraulic failure of the base of an excavation is a concern, basal stability can be improved by the use of pumped wells or relief wells, to depressurise the permeable Chalk at depth. This reduces the destabilizing action of the groundwater pressures in the Chalk. Example case histories from the literature in Table 2 include Shoreham Harbour, Cleethorpes, South Humber Bank Station and the Crossrail Limmo shaft.

Indirect Dewatering of Other Strata
In many areas the Chalk is overlain by, and in direct hydraulic connection with, an overlying permeable stratum, see Figures 2b, 2c, 7 and 8. In these situations the interaction between the strata needs to be taken into account, and where possible exploited to advantage, when planning a dewatering scheme. Two examples are given below.

In London the Chalk is generally overlain by the Thanet Sand; together they form a confined aquifer below the London Clay and Lambeth Group. The Thanet Sand is a dense uniform fine sand with markedly different hydraulic characteristics to the Chalk below. Fine well screens and filters are required to prevent fines abstraction when pumping from the Thanet Sand which typically constrains well yields to less than 1 or 2 l/s. In contrast the, typically structured, Chalk below can be targeted with unlined boreholes, often developed by acidisation, to give order of magnitude greater potential yields. As a result it was realised in the early 1990s that an effective strategy for depressurising or dewatering the Thanet Sand is by underdrainage by pumping from the Chalk below, see Figure 7. Relatively few, high capacity, Chalk wells may be needed which can impact a wide area. Most of the London area Case C projects listed in Table 2 were exploiting this strategy.

On occasions the drawdown in the Thanet Sand has been found to be less than in the Chalk below. This is almost certainly due to a combination of a lower permeability horizon at the Thanet Sand/Chalk interface (increased fines in the Thanet Sand or grade Dm weathered Chalk) plus some horizontal flow or recharge to the Thanet Sand (perhaps from a Drift Filled Hollow). Supplementary wells or wellpoints which directly target the Thanet Sand are required to resolve this situation. The higher flows and wide area impact of Chalk dewatering carries potential risks which are considered further below. This has led to an alternative strategy using Thanet Sand wells to achieve a target drawdown which has the benefit of reduced abstraction flow and limited area of influence. Careful consideration needs to be given to recharge from the Chalk below which may constrain the drawdown which can be achieved and result in the potential for rapid recovery in groundwater levels in the event of an interruption to the pumping system.

Where more permeable River Terrace Deposits overlie the Chalk underdrainage is only effective in conjunction with a cut-off to the Chalk, see Figure 8. The top of the Chalk may be weathered structureless or structured grade C or B to some depth so that internal dewatering wells, with the area enclosed by the cut-off walls, are required to control upward seepage flows and avoid the risk of base instability. The internal pumping will lead to some external drawdown. Diversion of pumped dewatering flows to external recharge wells screened in the River Terrace Deposits has been used as an effective method of controlling external drawdowns and avoiding any consequent settlement risks. The Brooks Development at Winchester, CTRL Thames Tunnel North Side, the DLR WAX Portal, and the Crossrail portals at North Woolwich and Plumstead given in Table 2 all exploited this strategy.

The examples given above serve to demonstrate that when planning a dewatering scheme, particularly in Chalk, the wider geological setting must be considered.

Use of Cut-off Walls and Low Permeability Barriers

Low permeability cut-off walls (e.g. secant piles, sheet-piles or diaphragm walls) are a commonly used method of excluding groundwater from an excavation. The efficacy of cut-off walls in Chalk is often constrained by the apparent lack of a significant very low permeability strata or beds within the Chalk into which cut-off walls can be ‘toed into’ to form a classic complete groundwater exclusion system as shown in Figure 4.

Despite this, low permeability cut-off walls are frequently used as part of the groundwater control strategy in Chalk. They can be used to exclude groundwater from overlying permeable strata (such as River Terrace Deposits), or from highly permeable zones where they exist at shallow depth within the Chalk (Figure 8). While this will not fully exclude groundwater from an excavation, it can significantly reduce the potential rates of groundwater inflow. There are numerous examples of this approach in the case histories in Table 2 including Gallions Pumping Station, the Brooks Retail Development in Winchester and the Lee Tunnel Overflow Shaft.

Ground treatment by fissure grouting has proved effective in controlling groundwater flows in structured Chalk particular for tunnels and headings. Grouting in structureless Chalk is unlikely to be effective in these typically shallow, weak and more soil-like deposits. In these soils freeze walls generated by artificial ground freezing would be a more effective, although potentially costly, strategy (Harris, 1995).

Potential Risks with Groundwater Control in Chalk

The key construction risks relating to hydraulic failure of the base of excavations, instability and potential for high flows from local fissures have already been highlighted. Other risks which are not specific to Chalk such as surface settlement due to underdrainage of soft soils have also been mentioned together with artificial recharge as a possible mitigation measure. Newman *et al*. (2013) has highlighted the particular issue of deoxygenated gas occurrences in the Lambeth Group. This appears to be related to historic pumping from the Chalk for water supply that has led to under-drainage in some areas.

Groundwater pumped from wells, sumps or excavations in Chalk may contain entrained chalk particles giving a ‘milky’ appearance. The risk of entrainment is greater for excavations in structureless Chalk particular for sump pumping. Discharge from pumped wells generally runs clear, free of suspended solids, within a few hours of the start of pumping. Discharge from sumps or open excavations will not ‘clean up’ if there is continued disturbance from excavations or plant movements. The Chalk particles are silt or clay sized and the on-site water storage requirements for effective treatment by sedimentation are not generally viable where flows are more than a few litres per second. This can be a key driver in the choice of dewatering strategy in Chalk where discharge is to be to surface waters; wells are sometimes chosen in preference to sump pumping in order to avoid the need for on-site treatment prior to discharge.

The Chalk is England’s most important aquifer and is widely exploited for both public and private water supplies. Public water supplies have defined Source Protection Zones within which potentially polluting activities are curtailed. In some areas the Chalk aquifer is already being over exploited leading to potential for reduction in groundwater dependent stream and river flows, damage to groundwater dependent habitats and, in coastal areas, the potential for saline intrusion. In such areas further abstraction may be constrained via the Environment Agency’s Catchment Abstraction Management

Strategies. As a result when developing a strategy for groundwater control in the Chalk careful attention must be paid to potential environmental impacts which might arise particularly due to any external drawdown. Regulatory permissions will be needed for groundwater abstraction, recharge or discharge to surface waters. These will require an assessment of the potential for adverse environmental impacts together with any mitigation measures required such as monitoring, artificial recharge and provision for cut-off walls. Often a full assessment of these issues will require relevant site investigation information which is considered below.

Recommendations for Site Investigation

The compelling arguments for sufficient and relevant site investigations for construction works will not be rehearsed in this paper. The aim here is to identify the particular requirements relevant to works that require groundwater control in Chalk, under the following key headings:

Desk study

Before undertaking any intrusive investigation a desk study is essential. This should assess the project information already available and other relevant information available in the public domain, such as information from the records of the British Geological Survey. This would include or be followed by a walk-over survey to identify relevant visible features together with discussion with other stakeholders which should include the Environment Agency. Only following this can consideration be given to the purpose and design of an intrusive ground investigation.

Intrusive ground investigation

In general a minimum two phase intrusive investigation will be needed, typically involving boreholes, trial pits and associated in-situ testing (see Section 9 of Lord et al. 2002, for further guidance). The first phase will be focused on establishing the general geological profile, strata descriptions and laboratory testing of samples. This is also a good opportunity to install a network of standpipe piezometers together with a program of groundwater level monitoring and laboratory analysis of groundwater samples to establish baseline data.

Investigation of the permeability of the relevant strata will then form a key element of the second or follow-on investigation phase.

Assessment of permeability

Options for assessing permeability in Chalk are summarised in Table 4; this shows that a well pumping test or groundwater control trial is essential in order to obtain a useful assessment of the prevailing hydrogeological conditions in a Chalk aquifer. The pumping test should be designed to address specific questions raised by the first phase of the intrusive ground investigation and the intended construction methodology.

The design and interpretation of pumping tests in Chalk can be particularly difficult where a cut-off wall is planned to be installed for the main works but will not, of course, be present at the site investigation stage. As a result pumping test results may be dominated by one or more high permeability horizons that will be cut-off for the main works. An abstraction recharge trial, involving both abstraction and recharge wells (Roberts and Holmes 2011) combined with numerical modelling can go some way to addressing this shortcoming. Test pumping following cut-off installation and prior to excavation (Bellhouse *et al*. 2015) is an alternative option where program and the availability of contingency measures, allows.

Well pumping tests
Chalk wells installed in structured grade A Chalk can generally be constructed unlined (i.e. with no well screen). This is common practice for chalk wells in the confined Chalk aquifer in London and elsewhere. It is also common practice to develop such chalk wells by injection of concentrated hydrochloric acid which dissolves the drilling slurry, cleaning the bore and opening up blocked fissures (Banks *et al*., 1993).

A well pumping test should typically involve continuous pumping from a well (of similar design to the proposed dewatering wells) for between 3 and 7 days, while monitoring pumped flow rate and groundwater levels in the pumped well and in an array of monitoring wells at various distances from the pumped well. The pumping rate should be sufficiently large to generate a significant drawdown in the Chalk outside of the well; ideally the drawdown should be at least 10 per cent of the required drawdown for the proposed dewatering scheme. Samples should also be taken from the pumped water and tested to determine the groundwater chemistry. Further advice on pumping tests is given in Preene and Roberts (1994).

Geophysical logging of wells
Where wells are constructed unlined, with no well screen, borehole geophysics can be used to investigate the variation of Chalk properties with depth within the well. Possible geophysical techniques include: CCTV surveys and optical televiewers, caliper logs, fluid temperature logs, fluid conductivity logs and flow logs. Logging of fluid temperature, conductivity and flow can also be undertaken under pumped conditions, to assess conditions while water is being drawn into the well; this can make it easier to identify preferential flow horizons. An assessment of such geophyscial information can provide a useful indication of the productive horizons in the well which may assist in selecting target cut-off toe levels.

Conclusion
Excavations below groundwater level in the relatively soft fissured limestone of the Chalk can present challenging conditions for construction and tunnelling projects. For an excavation of given depth and geometry, the potential groundwater inflows will be controlled by the hydrogeological setting and the degree of weathering of the Chalk. A diverse range of groundwater problems can affect excavations, from groundwater-

induced instability in structureless Chalk or highly weathered structured Chalk. Conversely, less weathered structured Chalk may act like massive fissured rock, where large water inflows can occur along pre-existing bedding planes, fissures and other geological features such as sheet flints.

A range of construction dewatering techniques is potentially available to control groundwater for excavations in Chalk. Groundwater control requirements, and the construction dewatering techniques that are applicable, are strongly influenced by permeability, which can be related indirectly to weathering grade of Chalk. Table 3 of this paper presents guidance on dewatering methods to be used in different grades of Chalk; this is an update of previous guidance in Roberts and Preene (1990). This guidance should not be considered as a replacement for an appropriate hydrogeological investigation (and subsequent dewatering design) on sites where significant dewatering works are planned. In particular, a well pumping test or dewatering trial can be an important part of assessing the prevailing hydrogeological conditions that will affect a construction dewatering system in Chalk.

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Table 1: Approximate permeability ranges for Chalk weathering grades

CIRIA grade	**Mundford grade**	**Chalk type**[1]	**Approximate permeability range (m/s)**
A	I and II	Structured with bedding and/or jointing	Erratic because of presence of fissures
B and C	III and IV	Structured with bedding and/or jointing	10^{-5} to 10^{-3}
Dc	V and VI	Structureless, clast dominated	10^{-7} to 10^{-9} in relatively soft Chalk 10^{-5} to 10^{-3} in relatively harder Chalk, where they form chalk bearings or frost shattered Chalk
Dm	V and VI	Structureless, matrix dominated	10^{-7} to 10^{-9}

Notes: [1] After Spink (2002).

Table 2: Case histories of construction dewatering in Chalk

Location	Date	Chalk Province	Chalk lithology	Hydro-geological Setting[1]	Primary Chalk type being dewatered[2]	Primary Chalk grade being dewatered[3]	Reported permeability of Chalk	Excavation Type	Dewatering Method	Drawdown of piezometric level in Chalk	Dewatering flow rates	Source
Lock Structure, Shoreham Harbour, Sussex	Mid 1950s	Southern	Confined aquifer. Alluvial deposits comprising clay present immediately above Upper Chalk	Case C	Structured	ND	ND	Open excavation within a sheet-piled cofferdam	A grid of relief wells (at 6 m centres) into the Chalk in the base of the excavation. High groundwater pressures remained between the relief wells, and some localised heave of the clay in the base of the excavation	Approximately 10 m	ND	Ridehalgh (1958)
Thames Cable Tunnel (North Shaft), Tilbury, East London	1967-68	Southern	Confined aquifer. River gravels present immediately above Upper Chalk, gravels possibly in hydraulic connection with River Thames. Upper 9 m of Chalk of high permeability, permeability reduced significantly at depths greater than 15 m below top of the Chalk. During shaft sinking the upper 6 m of the Chalk was indicated to be completely disintegrated	Case C	Structured	ND	1×10^{-3} to 4×10^{-6} m/s in upper zones of Chalk, from in-situ permeability tests; 2×10^{-5} to 2×10^{-6} m/s below 15 m from top of Chalk, from Lugeon tests	Open excavation for shaft construction within a sheet-piled cofferdam	9 pumped deep wells, of maximum depth of 33 m. Due to high inflows form localised zones in the Chalk, deep well pumping was augmented significantly by sump pumping. Three recharge wells were installed to reduce the risk of settlement caused by lowering of groundwater levels in soft alluvial deposits overlying the River Gravels	Approximately 49 m	265 l/s from the dewatering wells	Haswell (1969); Cashman (1970)
Thames Barrier, East London	1974-80	Southern	Upper Chalk overlain by Thanet Sand in some areas and by Alluvium in others. A 0.5 to 1.5 m thick layer of clay (Bullhead Beds) was present at the Chalk/Thanet Sand interface	Case B	Structured	ND	ND	Several open excavations within individual cofferdams within the River Thames	Pressure relief wells (typically 20 per cofferdam) extending to 10 m below the tremie concrete plug in the base of the excavation. Some relief wells were acidised to improve yields	Up to approximately 22 m	ND	Grice and Hepplewhite (1983)
Gallions Pumping Station, Beckton, East London	1975-78	Southern	Chalk overlain by River Gravels and Thanet Sand. River gravels possibly in connection with River Thames. A 1.5 m thick layer of glauconitic clay and possibly some putty Chalk was present between Thanet Sand and Chalk, providing a degree of hydraulic separation	Case B	Structured	ND	8×10^{-5} m/s from well pumping test	Open excavation within diaphragm walls	6 pumped deep wells, some sealed into Chalk, some pumping from overlying gravels and Thanet Sand as well as from the Chalk	Approximately 12.5 m	Chalk well test pumped at 50 l/s in short term. When dewatering was initiated with six pumped wells in Chalk and Thanet Sand, total flow rate was 54 l/s	Townsend and Greeves (1979)
New Telephone Exchange, Salisbury, Wiltshire	1976	Southern	Valley Gravels over Upper Chalk. Upper 2 to 4 m of Chalk is soliflucted Chalk, underlain by Mundford grade V to III Chalk	Case B	Structured	Mundford V improving to III with depth	Soliflucted Chalk: 4×10^{-8} m/s from laboratory tests. Structured Chalk: 2×10^{-5} m/s from well pumping test	Open excavation within cofferdam	Sump pumping initially used in structureless Chalk. Geotechnical problems meant dewatering was suspended. Excavation base slab was cast underwater and then depressurised by pumped deep wells and relief wells in underlying structured Chalk	Approximately 5 m	ND	Burland, Hancock and May (1983)

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Pumping Station, Costessey, Norfolk	1986-87	Transitional	Gravels over Upper Chalk. Upper 6 m of Chalk was structureless (Mundford grade VI to V) with grade IV to II structured Chalk below	Case B	Structured	Mundford IV to II	1 x 10^{-9} to 2 x 10^{-9} m/s from rising head tests in structureless Chalk; 1 x 10^{-7} to 3 x 10^{-7} m/s from falling head tests in Structureless Chalk; 5 x 10^{-5} m/s back-analysed from the dewatering system flow rate	Open excavation within sheet-piled cofferdam	6 pumped deep wells, of depths 25 to 35 m.	5 m	Total flow rate 86l/s. One well yielded 33 l/s, but this well may have had a poor casing seal and received water from the overlying gravels. Average flow rate from other wells was approximately 11 /s	Bracegirdle, Mair and Daynes (1990)
Port Solent Lock Structure, Portsmouth, Hampshire	1987	Southern	Upper Chalk overlain by thin layer of Made Ground and Alluvium. Approximately the upper 8 m of Chalk was structureless (Mundford grade VI to V), with structured Chalk below	Case A	Structured	Mundford IV to III	1 x 10^{-4} m/s from well pumping test; 1 x 10^{-4} m/s back-analysed from dewatering system flow rate	Open excavation within cofferdam	10 pumped deep wells, of 17 m depth	9 m	65 l/s total dewatering flow; most of flow came from 3 of the 10 wells	Roberts and Preene (1990)
Mewsbrook STW, Littlehampton, Sussex	1987	Southern	Sand and clay over structured Chalk (Mundford grade IV to III)	Case A	Structured	Mundford IV to III	6 x 10^{-4} m/s from well pumping test; 7 x 10^{-4} m/s back-analysed from dewatering system flow rate	Open excavation within cofferdam	8 pumped deep wells, of 15 m depth	6 m	70 l/s total dewatering flow rate. Yield from individual wells varied considerabely	Roberts and Preene (1990)
Chatham Dock Yacht Lock, Chatham, Kent	1988	Southern	Confined Chalk aquifer. River Gravels present immediately above Upper Chalk. Upper 2 m of Chalk was structureless (Mundford grade VI to V) with grade IV to III structured Chalk below	Case C	Structured	Mundford IV to III	1 x 10^{-4} m/s back-analysed from dewatering system flow rate	Reconstruction of an existing dock structure	9 pumped deep wells, of 26.5 m depth	8 m	75 l/s total dewatering flow rate	Roberts and Preene (1990)

Table 2: Case histories of construction dewatering in Chalk

Location	Date	Chalk Province	Chalk lithology	Hydro-geological Setting[1]	Primary Chalk type being dewatered[2]	Primary Chalk grade being dewatered[3]	Reported permeability of Chalk	Excavation Type	Dewatering Method	Drawdown of piezometric level in Chalk	Dewatering flow rates	Source
The Brooks Retail Development, Winchester, Hampshire	1989-1990	Southern	Upper Chalk overlain by River Gravels, Structureless Chalk believed to be present at the top of Chalk, but may not form a continuous layer	Case B	Structured	Mundford IV to III	8.0×10^{-8} to 1.2×10^{-4} m/s from rising head tests (14 tests); 1.2×10^{-5} to 1.0×10^{-5} m/s from falling head tests (2 tests); 1×10^{-4} to 3×10^{-4} m/s from well pumping test (test may have been affected by leakage into well from overlying River Gravels); Dewatering design based on 5×10^{-5} m/s	Open excavation within diaphragm walls	18 pumped deep wells, of 20 m depth, located inside diaphragm walls that penetrated through the River Gravels into the top of the Chalk. An artificial recharge system was deployed outside the diaphragm walls to maintain groundwater levels in the River Gravels	7.5 m	Pumped flow rate from dewatering system was 100 l/s; Flow from dewatering wells was noted to vary significantly from well to well; 56 l/s of the pumped dewatering water was recharged back to the river gravels (outside of the diaphragm walls)	Powrie and Roberts (1995)
Limehouse Link Services Building, East London	1990-92	Southern	Confined Chalk aquifer. Thanet Sand present immediately above Chalk	Case C	Structured	ND	ND	Open excavation within diaphragm walls (Services Building)	5 pumped deep wells. Pumping from Chalk achieved significant depressurisation effect in Thanet Sand	10 m	Total flow rate approximately 30 /s	Boardman (1993); Withers (1996)
Black Rock, Brighton and Hove Stormwater Tunnel	1993	Southern	Seaford Chalk Formation, overlain by Beach Deposits	Case B	Structured	Shaft predominantly sunk through Mundford grades III to II	Borehole packer tests in the range 2×10^{-8} to 1×10^{-5} m/s	Shaft excavation	Sump pumping	ND	Groundwater inflow locations were attributed to sub-horizontal features, including bedding joints and sheet flints	Mortimore (2012)

Table 2: Case histories of construction dewatering in Chalk												
Location	**Date**	**Chalk Province**	**Chalk lithology**	**Hydro-geological Setting[1]**	**Primary Chalk type being dewatered[2]**	**Primary Chalk grade being dewatered[3]**	**Reported permeability of Chalk**	**Excavation Type**	**Dewatering Method**	**Drawdown of piezometric level in Chalk**	**Dewatering flow rates**	**Source**
Madeira B Shaft, Brighton and Hove Stormwater Tunnel	1993	Southern	Seaford Chalk Formation, overlain by Beach Deposits	Case B	Structured	Shaft predominantly sunk through Mundford grades III to II	ND	Shaft excavation	Sump pumping. In response to high rates of groundwater inflow, the shaft was flooded and inflows reduced by ground treatment in the form of grouting was then used	ND	At a depth of approximately 14 m total inflow to the shaft was more than 18 l/s from open (20 mm) sub-horizontal joints. At a depth of 16 m total inflow was of the order of 190 l/s, attributed to open joints associated with a sub-horizontal flint band. Some of the water inflow may have been associated with a poorly sealed site investigation borehole	Mortimore (2012)

Table 2: Case histories of construction dewatering in Chalk

Location	Date	Chalk Province	Chalk lithology	Hydro-geological Setting[1]	Primary Chalk type being dewatered[2]	Primary Chalk grade being dewatered[3]	Reported permeability of Chalk	Excavation Type	Dewatering Method	Drawdown of piezometric level in Chalk	Dewatering flow rates	Source
Norfolk Shaft, Brighton and Hove Stormwater Tunnel	1993	Southern	Seaford Chalk Formation, overlain by Beach Deposits	Case B	Structured	Shaft predominantly sunk through Mundford grades III to II (based on original site investigation logging). Subsequent analysis indicated Chalk was CIRIA grade C	Borehole packer tests in the range 8 x 10^{-6} to 1 x 10^{-5} m/s	Shaft excavation	Sump pumping. In response to high rates of groundwater inflow, ground treatment in the form of grouting was then used	ND	At a depth of approximately 27 m total inflow to the shaft was 3 l/s from a small number of minor faults. With only a further 1 to 2 m of digging the inflow to the shaft had increased to 100 l/s, with inflows attributed to open sub-vertical joints, open bedding plane fractures along a marl seam and a poorly sealed site investigation borehole. Groundwater inflows increased to 126 l/s associated with an influx of water and brown sediment, possibly from a cavity in the Chalk filled with Quaternary sediment	Mortimore (2012)

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Hove Street Shaft, Brighton and Hove Stormwater Tunnel	1993	Southern	Newhaven Chalk Formation, overlain by Beach Deposits	Case B	Structured	Shaft predominantly sunk through Mundford grades III to II (based on original site investigation logging). Subsequent analysis indicated Chalk was CIRIA grade C	ND	Shaft excavation	Sump pumping	ND	At a depth of approximately 27 m total inflow to the shaft was 3 l/s	Mortimore (2012)
Cleethorpes, Lincolnshire	1993	Northern	Confined aquifer. Glacial deposits comprising clay till present immediately above Flamborough Chalk Formation.	Case C	Structureless (probably Chalk bearings) and structured Chalk	ND	ND	Shaft excavation	Shaft base was located in the Glacial clay above the Chalk. No deep depressurisation was carried out, and the base of the shaft failed. Subsequently, 8 pumped deep wells where installed into the Chalk to allow construction to be completed	Approximately 20 m	Approximately 95 l/s	Author records
Medway Crossing, Chatham, Kent	1993-96	Southern	Confined Chalk aquifer. River Gravels present immediately above Upper Chalk. Upper 2 to 5 m of Chalk was structureless (Mundford grade VI to V) with grade VI to III structured Chalk below	Case C	Structured	Mundford grade III to IV	10^{-7} to 10^{-9} m/s in structureless Chalk (Mundford grade V/VI) estimated from in-situ and laboratory tests; 10^{-3} to 10^{-5} m/s in structured Chalk (Mundford grade III/IV) estimated from in-situ and laboratory tests; 9×10^{-4} m/s back-analysed from dewatering system flow rate	Large casting basin and portal excavation	40 pumped deep wells, of maximum 30 m depth	Approximately 14 m	Peak flow rate of approximately 400 l/s	Leiper, Roberts and Russell (2000); author records
North Woolwich Pumping Station, East London	1995	Southern	Unconfined Chalk aquifer over lain by River Terrace Deposits (sand/gravel)	Case B	Structured	ND	1.5×10^{-4} m/s from pumping test	Cofferdam for pumping station	14 internal deepwells and 6 external recharge wells	Approximately 9 m	110 l/s abstraction, recharge up to 20 l/s	Author records

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Tunnel Portal, Bransholme, Hull	Mid 1990s	Northern	Confined aquifer. Alluvial deposits comprising clays present immediately above Flamborough Chalk Formation. Upper sections of Chalk are weathered, and probably form chalk bearings	Case C	Structureless (probably chalk bearings) and Structured Chalk	ND	ND	Open excavation within cofferdam	13 pumped deep wells of 25 m depth. A portion of the dewatering flow rate was directed to recharge wells located 750 m distant from the dewatering system	Approximately 15 m	Approximately 150 l/s	Author records
South Humber Bank Power Station, Stallingborough	1995	Northern	Confined aquifer. Alluvial deposits comprising clays and silts present immediately above Flamborough Chalk Formation. Upper sections of Chalk are weathered, and probably form chalk bearings	Case C	Structureless (probably chalk bearings) and Structured Chalk	ND	ND	Open excavation within cofferdam	13 pumped deep wells of 35 m depth, and 6 relief wells of 29 m depth. Groundwater levels recovered very rapidly when pumping from the deep wells was interrupted; the objective of the relief wells base to prevent the base of the excavation blowing if the pumped dewatering wells stopped	Approximately 18 m	Approximately 120 l/s	Author records

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Jubilee Line Extension, Durands Wharf Shaft, East London	Mid 1990s	Southern	Confined aquifer. Thanet Sand present immediately above Upper Chalk	Case C	Structured	ND	Jubilee Line Extension project pumping tests report at range of permeability of 6 x 10^{-6} to 9 x 10^{-5} m/s at Canada Water and Canary Wharf Sites	Shaft excavation	8 pumped deep wells, penetrating 30 m in the Chalk. Objective of dewatering was to underdrain the overlying Thanet Sand	15 m from initial 8 well system	23 l/s for 15 m drawdown. Dewatering was not fully effective due to low permeability zones at the base of the Thanet Sand and/or in upper zones of Chalk	Linney and Withers (1998)
Jubilee Line Extension, Canary Wharf Station, East London	Mid 1990s	Southern	Confined aquifer. Thanet Sand present immediately above Upper Chalk	Case C	Structured	ND	Jubilee Line Extension project pumping tests report at range of permeability of 6 x 10^{-6} to 9 x 10^{-5} m/s at Canada Water and Canary Wharf Sites	Large cofferdam for station box	10 pumped deep wells, penetrating 30 m in the Chalk. Objective of dewatering was to underdrain the overlying Thanet Sand	21 m	Initial flow rate approximately 100 l/s, reducing to 35-40 l/s when steady state conditions were achieved	Linney and Withers (1998)
Jubilee Line Extension, Preston Road Shaft, East London	Mid 1990s	Southern	Confined aquifer. Thanet Sand present immediately above Upper Chalk	Case C	Structured	ND	Jubilee Line Extension project pumping tests report at range of permeability of 6 x 10^{-6} to 9 x 10^{-5} m/s at Canada Water and Canary Wharf Sites	Shaft excavation	10 pumped deep wells, penetrating 30 m in the Chalk. Objective of dewatering was to underdrain the overlying Thanet Sand	24 m	Peak flow rate of 230 l/s	Linney and Withers (1998)
Jubilee Line Extension, Culling Road Shaft, East London	Mid 1990s	Southern	Confined aquifer. Thanet Sand present immediately above Upper Chalk	Case C	Structured	ND	ND	Shaft excavation	4 pumped deep wells	2.5 m	ND	Withers (1996)
Jubilee Line Extension, Canada Water Station, East London	Mid 1990s	Southern	Confined aquifer. Thanet Sand present immediately above Upper Chalk	Case C	Structured	ND	ND	Large cofferdam for station box	8 pumped deep wells	10.5 m	39 l/s	Withers (1996)

Table 2: Case histories of construction dewatering in Chalk

Location	Date	Chalk Province	Chalk lithology	Hydro-geological Setting[1]	Primary Chalk type being dewatered[2]	Primary Chalk grade being dewatered[3]	Reported permeability of Chalk	Excavation Type	Dewatering Method	Drawdown of piezometric level in Chalk	Dewatering flow rates	Source
Jubilee Line Extension, Downtown Road Shaft, East London	Mid 1990s	Southern	Confined aquifer. Thanet Sand present immediately above Upper Chalk	Case C	Structured	ND	ND	Shaft excavation	6 pumped deep wells	4 m	33 l/s	Withers (1996)
Jubilee Line Extension, Pioneer Wharf Shaft, East London	Mid 1990s	Southern	Confined aquifer. Thanet Sand present immediately above Upper Chalk	Case C	Structured	ND	ND	Shaft excavation	6 pumped deep wells	8 m	ND	Withers (1996)
Hull Wastewater Flow Transfer Tunnel, Shaft T4, Kingston upon Hull	1998	Northern	Confined aquifer. Alluvial deposits (associated with the channel of the River Hull) comprising sands and gravels present immediately above Burnham Chalk Formation. Upper sections of Chalk are weathered, and probably form Chalk bearings	Case C	Structureless (probably chalk bearings) and Structured Chalk	ND	ND	Shaft excavation	8 pumped deep wells, of 45 m depth	8 m	115 l/s	Author records
CTRL Stratford Station (Temporary Dewatering), East London	Early 2000s	Southern	Confined aquifer. Upper Chalk overlain by Thanet Sand. A 0.1 to 0.2 m thick layer of clay (Bullhead Beds) was present at the Chalk/Thanet Sand interface	Case C	Structured	ND	ND	Large cofferdam for station box	22 pumped deep wells, penetrating 30 m in the Chalk. A 23rd well was also drilled but was rejected as it pumped high levels of suspended sand in the water	17 m	Peak flow rate of 220 l/s	Whitaker (2004)
CTRL Running Tunnels, East London	Early 2000s	Southern	Confined aquifer. Upper Chalk overlain by Thanet Sand.	Case C	Structured	ND	ND	Tunnel construction. Depressurisation pumping for shaft sinking and cross-passage construction. Groundwater depressurisation also had benefits for tunnel construction using tunnel boring machines (TBMs).	An array of widely spaced dewatering wells, along the tunnel route. Typically extending 60 m into the Chalk, with a total depth of around 100 m	ND	Peak flow rate of approximately 580 l/s from the group of dewatering wells associated with the tunnel construction	Hamilton, Riches, Realey and Thomas (2008)

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Location	Date	Chalk Province	Chalk lithology	Hydro-geological Setting[1]	Primary Chalk type being dewatered[2]	Primary Chalk grade being dewatered[3]	Reported permeability of Chalk	Excavation Type	Dewatering Method	Drawdown of piezometric level in Chalk	Dewatering flow rates	Source
CTRL Thames Tunnel, North Side, West Thurrock, Essex	Early 2000s	Southern	Confined aquifer. River Gravels present immediately above Upper Chalk, gravels possibly in hydraulic connection with River Thames. The upper 1 to 2 m of Chalk were structureless	Case C	Structured	CIRIA grade B and grade C, improving to A3 to A1 with depth	4×10^{-4} m/s for CIRIA grade B Chalk from well pumping tests; 1×10^{-5} to 2×10^{-5} for CIRIA grade A Chalk from well pumping tests	Large cofferdam for tunnel portal	Pumped deep wells, located within the diaphragm wall forming the portal cofferdam. An array of recharge wells was installed to reduce the risk of settlement caused by lowering of groundwater levels in soft alluvial deposits overlying the River Gravels	18 m	Peak dewatering flow rates 110 to 140 l/s. Recharge system flow rates 60 to 140 l/s	Roberts and Holmes (2011)
CTRL Thames Tunnel, South Side, Swanscombe, Kent	Early 2000s	Southern	Confined aquifer. River Gravels present immediately above Upper Chalk, gravels possibly in hydraulic connection with River Thames.	Case C	Structured	CIRIA grade B2 and B3; CIRIA grade C4 to C5 may have been associated with zones where dewatering flow rates were high	2×10^{-6} to 1×10^{-4} m/s from borehole packer tests; Numerical modelling to back-analyse the dewatering system implied that a high permeability zone of the order of 3×10^{-2} to 7×10^{-2} m/s may have existed in the Chalk in part of the excavation	Large cofferdam for tunnel portal	44 pumped deep wells, located within the diaphragm wall forming the portal cofferdam.	18 m	Peak dewatering flow rate approximately 600 l/s. Flow rates were unevenly distributed along the alignment of the portal structure	Bevan, Powrie and Roberts (2011)

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Thames Water Ring Main Extension, Honor Oak Shaft, Southeast London	Mid 2000s	Southern	Confined Chalk aquifer. Thanet Sand present immediately above Seaford Chalk	Case C	Structured	CIRIA grade B2, B3, improving to A2 with depth	ND	Shaft excavation	3 pumped deep wells, of 90 m depth	Approximately 30 m	ND	Newman and Wong (2011)
Lee Valley Cable Tunnels: Carpenters Road shafts	2005	Southern	Confined Chalk aquifer. Thanet Sand present immediately above Upper Chalk	Case C	Structured	ND	ND	Two underpinned caisson shafts	8 pumped deep wells, of 70 m depth	Approximately 10 m	Approximately 38 l/s; 45% of the total flow from just one well	Author records
Lee Valley Cable Tunnels: East Way Shaft	2005	Southern	Confined Chalk aquifer. Thanet Sand present immediately above Upper Chalk	Case C	Structured	ND	ND	Underpinned caisson shaft	3 pumped deep wells, of 70 m depth	Approximately 11 m	Approximately 58 l/s	Author records
DLR WAX Royal Docks Portal	2005-06	Southern	Unconfined Chalk aquifer over lain by River Terrace Deposits (sand/gravel)	Case B	Structured	2 m undefined over Mundford grade III	1.2×10^{-4} m/s from pumping test	Railway tunnel portal with diaphragm wall support	13 internal pumped deep wells and 14 external recharge wells	Approximately 17 m	10 to 45 l/s abstraction, recharge flows up to 38 l/s	Author records
Croydon	2008	Southern	Upper Chalk	ND	Structured	ND	ND	Shaft excavation	Sump pumping (9 x 150 mm sump pumps and 2 x 250 mm sump pumps)	Approximately 11 m	Maximum flow rate 225 l/s. Vast majority of flow rate believed to be entering shaft via limited number of fissures	Hartwell (2015)
South East Berkshire	2009-10	Southern	Unconfined Chalk aquifer overlain by River Terrace Deposits (sand/gravel)	Case B	Structured	CIRIA grade D at top with grade C and B below	5×10^{-4} m/s from pumping test	Large cofferdam for basement excavation	40 internal pumped chalk wells plus 27 external gravel recharge wells	Approximately 6.5 m	160 l/s reducing to 120 l/s abstraction, 140 l/s reducing to 95 l/s recharged	Author records

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Location	Date	Chalk Province	Chalk lithology	Hydro-geological Setting[1]	Primary Chalk type being dewatered[2]	Primary Chalk grade being dewatered[3]	Reported permeability of Chalk	Excavation Type	Dewatering Method	Drawdown of piezometric level in Chalk	Dewatering flow rates	Source
Lee Tunnel Overflow Shaft, Beckton, East London	Early 2010s	Southern	Confined Chalk aquifer in area of signficant faulting. Thanet Sand present immediately above Seaford Chalk	Case C	Structured	CIRIA grade A2 to A3 at formation level	ND	Open excavation within very deep diaphragm walls (98 mbgl)	Sump pumping from relief wells	Approximately 65 m	Pump testing of relief wells inside the shaft gave flow rates of 1.3 l/s for approximately 66 m drawdown in adjacent relief wells	Bellhouse, Skipper and Sutherden (2015) and author records
Crossrail, Canary Wharf Station, East London	Early 2010s	Southern	Confined Chalk aquifer. Thanet Sand present immediately above Upper Chalk	Case C	Structured	ND	ND	Large cofferdam for station box	14 pumped deep wells into the Chalk	Approximately 20 m	Peak flow rate of approximately 175 l/s, reducing to 130 l/s when drawdown was achieved	Travers and Yeow (2014)
Crossrail Limmo Shafts, East London	2011-12	Southern	Confined Chalk aquifer. Thanet Sand present immediately above Chalk	Case C	Structured	ND	ND	Shaft enclosed within a diaphragm wall	7 pumped deep wells, of 107 m depth	24 m	160 l/s total flow rate from Chalk wells; additional 11 l/s from Thanet Sand wells	Roberts, Linde, Vincente and Holmes (2015)
Great Blakenham, Ipswich, Suffolk	2012	Transitional	Chalk overlain by River Gravels. Upper zones of the Chalk are highly weathered	Case B	Structureless	CIRIA grade Dm	ND	Open excavation within concrete secant pile wall cofferdam	Typically pumping from 1 deep well plus sump pumping	Approximately 10 m	2 l/s initially, reducing to 1 l/s	Bickley and Judge (2015); author records
Crossrail Woolwich Arsenal Station	2012	Southern	Confined Chalk aquifer. Thanet Sand present immediately above Upper Chalk	Case C	Structured	CIRIA grade A with some voids	Packer tests: 1 to 3 x 10^{-5} m/s. Pumping tests: 1.5 x 10^{-4} m/s	Large cofferdam for station box	32 internal pumped chalk deep wells	Approximately 12 m	10 l/s	Author records
Crossrail, Portal at Plumstead	2012-13	Southern	Upper Chalk overlain by 1 m of Thanet Sand with River Terrace Deposits above (sand/gravel)	Case B/C	Structured	CIRIA grade B4, B3 and A3	1.5 x 10^{-5} to 3 x 10^{-5} m/s from pumping test and numerical modelling	Railway tunnel portal with diaphragm wall support	39 internal pumped chalk and gravel deep wells plus 44 external gravel recharge wells	Approximately 15 m	65 to 85 l/s abstraction, 60 to 100 l/s recharged	Author records

Table 2: Case histories of construction dewatering in Chalk

Location	Date	Chalk Province	Chalk lithology	Hydro-geological Setting[1]	Primary Chalk type being dewatered[2]	Primary Chalk grade being dewatered[3]	Reported permeability of Chalk	Excavation Type	Dewatering Method	Drawdown of piezometric level in Chalk	Dewatering flow rates	Source
Shaft, Bridlington, Yorkshire	2012-13	Northern	Confined aquifer. Glacial deposits comprising Glacial Till and sands and gravels present immediately above Flamborough Chalk. Upper zones of Chalk are structureless, including possible Chalk Bearings	Case C	Structureless and Structured	CIRIA grade Dc and grade B	ND	Shaft excavation	Relief wells	Approximately 10 m, for final shaft construction	During shaft sinking, flow rates from relief gradually increased with depth to a maximum of 22l/s with the excavation approximately 5 m below groundwater level. Below this level flows increased dramatically with water rising up in the shaft by 3 m in 20 minutes.This implies a short-term inflow rate of 250 l/s, possibly from a fissure in the structured Chalk. Following the inflow, the shaft excavation was completed underwater and the base slab formed by tremie concrete	Author records
Crossrail, Connaught Tunnel, East London	2012-14	Southern	Confined Chalk aquifer. Thanet Sand present immediately above Upper Chalk (Thanet Sand thining across the site)	Case C	Structured	CIRIA grade B2 at top of chalk	1 x 10^{-8} to 1 x 10^{-4} m/s from borehole permeability tests	Modification and update of existing Victorian tunnel	6 pumped deep wells, of 70 m depth	Approximately 14 m	35 l/s	Author records

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Crossrail, Portal at North Woolwich	2013-14	Southern	Unconfined Chalk aquifer overlain by River Terrace Deposits (sand/gravel)	Case B	Structured	CIRIA grade Dc with grade C and B below	5×10^{-6} to 1×10^{-5} m/s from pumping test and numerical modelling	Railway tunnel portal with diaphragm wall support	41 internal pumped chalk and gravel deep wells plus 41 external gravel recharge wells	Approximately 14 m	70 to 100 l/s abstraction, 30 to 70 l/s recharged	Author records
Crossrail, Crosspassage 13, East London	2013-15	Southern	Confined Chalk aquifer. Thanet Sand present immediately above Upper Chalk	Case C	Structured	Mundford grade II	9×10^{-5} m/s from pumping test assuming 50 m aquifer thickness	Cross passage between TBM driven tunnels	6 pumped deep wells, of 90 m depth plus support from pumping at another site 1050 m away	Approximately 33 m	Maximum 225 l/s reducing to 175 l/s plus 80 l/s from site 1,050 m away	Author records
Crossrail, Crosspassage 11, East London	2014-15	Southern	Confined Chalk aquifer. Thanet Sand present immediately above Upper Chalk	Case C	Structured	CIRIA grade B3 at top of chalk	ND	Cross passage between TBM driven tunnels	4 pumped deep wells, of 80 m depth	Approximately 14 m	55 l/s	Author records

Notes

[1] Hydrogeological setting (see Figure 2)
Case A – Unconfined Chalk aquifer, no overlying high permeability stratum present (Figure 2a)
Case B – Unconfined Chalk aquifer, overlying high permeability stratum present (Figure 2b)
Case C – Confined Chalk aquifer (Figure 2c)
[2] The Chalk type from which water is being directly pumped by the dewatering system
[3] Mundford grades of Chalk are defined in Wakeling (1970); CIRIA grades of Chalk are defined in Lord *et al.* (2002)

ND = No data
CTRL = Channel Tunnel Rail Link (now known as HS1)

Table 3: Typical dewatering methods in Chalk

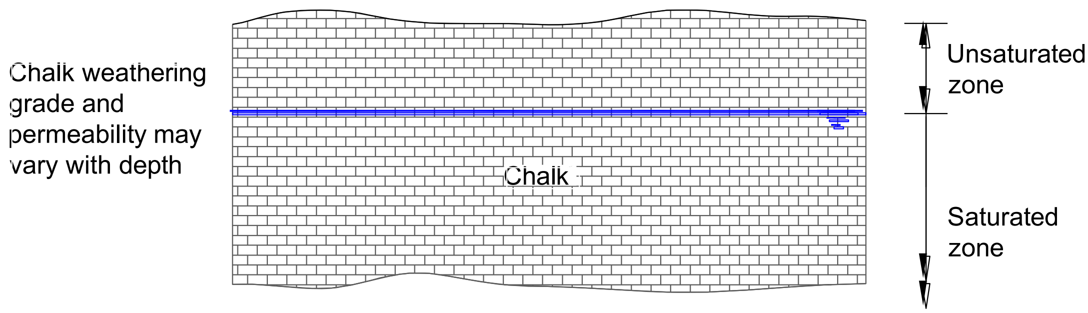
CIRIA grade	Chalk type[1]	Approximate permeability range (m/s)	Typical dewatering method
A	Structured with bedding and/or jointing	Erratic because of presence of fissures	Sump pumping (possibly in combination with relief wells)
B and C	Structured with bedding and/or jointing	10^{-5} to 10^{-3}	Deep wells (pumped by submersible pumps) or wellpoints
Dc	Structureless, clast dominated	10^{-7} to 10^{-9} in relatively soft chalks	Grade Dc Chalk in relatively soft Chalks may require similar methods to grade Dm Chalk
		10^{-5} to 10^{-3} in relatively harder Chalks, where they form chalk bearings or frost shattered Chalk	Grade Dc Chalk in relatively harder Chalks, including Chalk bearings and frost shattered Chalk, may require similar methods to grade B and C Chalk
Dm	Structureless, matrix dominated	10^{-7} to 10^{-9}	Gravity drainage unlikely to be effective; use underdrainage by pumping from more permeable Chalk beneath (including the use of relief wells)

Notes: [1] After Spink (2002).

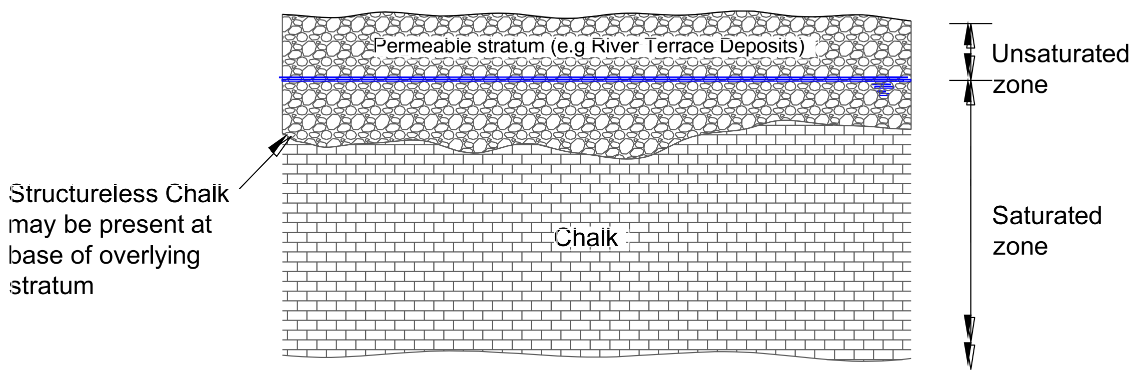
Table 4: Methods of estimating permeability in Chalk (after Preene *et al*., 2016)

Category	Method	Notes	Notes relevant to chalk
In situ (large scale)	Groundwater control trials	Generally only cost effective for large projects	Abstraction recharge trial appropriate if recharge is planned Test can be designed to investigate permeability profile
	Well pumping test	Can estimate permeability of a large volume of soil Can provide information on boundary conditions	Provides a good estimate of average horizontal mass permeability but limited information on vertical permeability or variation in permeability with depth
In situ (small scale)	Borehole tests: Falling/rising/constant head test, packer test	Tests only a small zone around piezometer Can be dramatically affected by soil disturbance (typically resulting in permeability being under estimated) Packer testing normally only carried out in rock	Results greatly influenced by presence or absence of fissuring at the test horizon Chalk fissures particularly susceptible to blockage by drilling debris Packer test equipment may constrain measurement of high permeability horizons (Hartwell 2015) Packer testing only feasible in stable structured chalk
	Piezometer test: Falling/rising/constant head test	Tests only a small zone around piezometer	Result may be constrained by installation specification of piezometers (use of fine screens can reduce the measured permeability)
Geophysical surveying of unlined wells	CCTV, optical televiewer, caliper. Fluid temperature, fluid conductivity and flow logs under unpumped and pumped conditions	Applicable in unlined wells in rock No quantitative measurement of permeability but can identify fissures and provide a useful indication of the level of productive horizons	Only feasible in stable structured chalk in unlined well Potentially useful addition to a pumping test especially when considering required cut-off depth

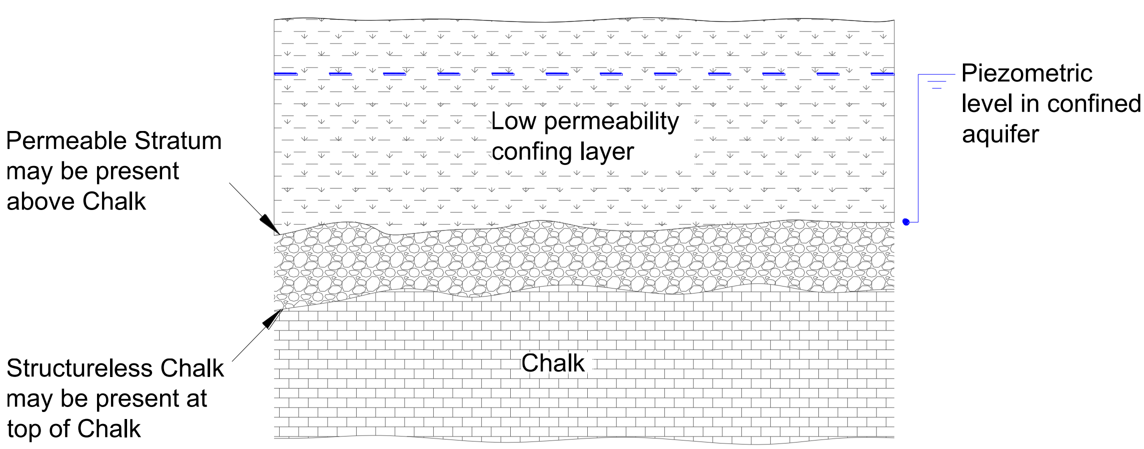
Figure 1: Distribution of Chalk in England (reproduced from Lord, J A, Clayton, C R I and Mortimore, R N (2002), *Engineering in Chalk*. CIRIA, C574, London (ISBN 0 86017 574 X) with kind permission of CIRIA www.ciria.org)



a) *Unconfined Chalk aquifer, no overlying high permeability stratum present*



b) *Unconfined Chalk aquifer, overlying high permeability stratum present*



c) *Confined Chalk aquifer*

Figure 2: Principal hydrogeological settings relevant to construction dewatering problems

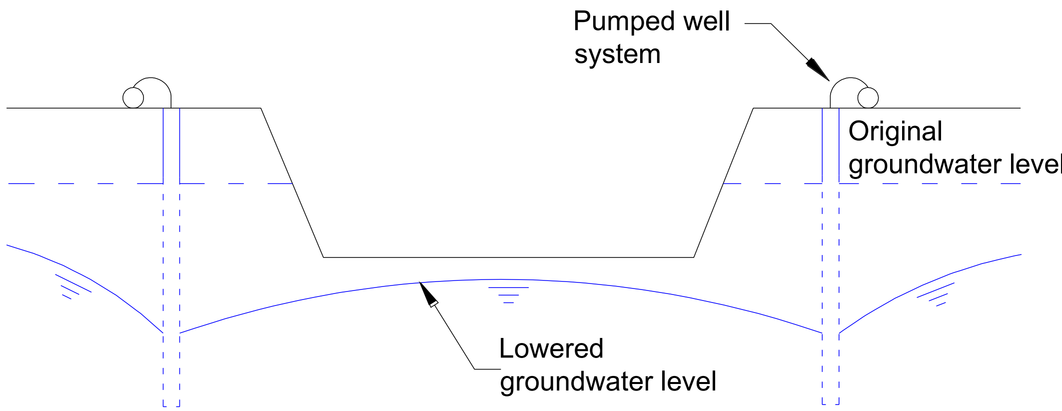


Figure 3: Groundwater control by pumping

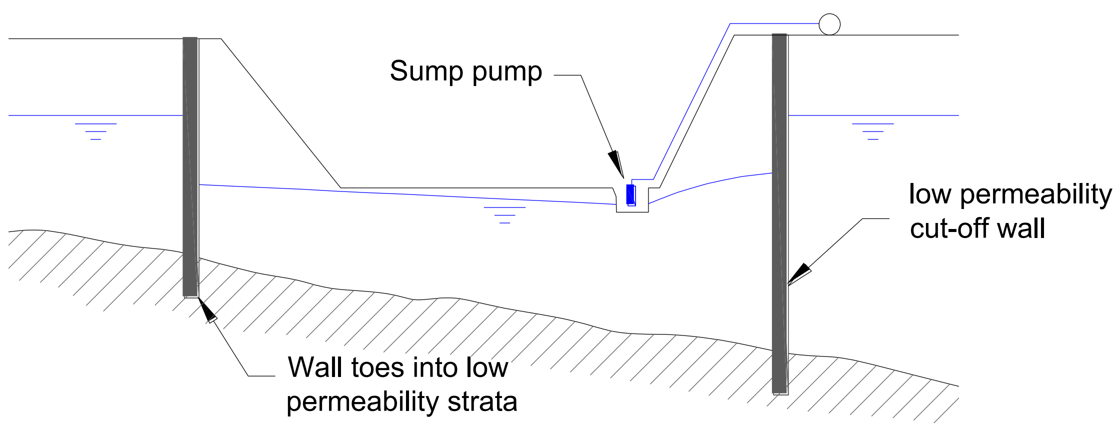


Figure 4: Groundwater control by exclusion using physical cut-offs

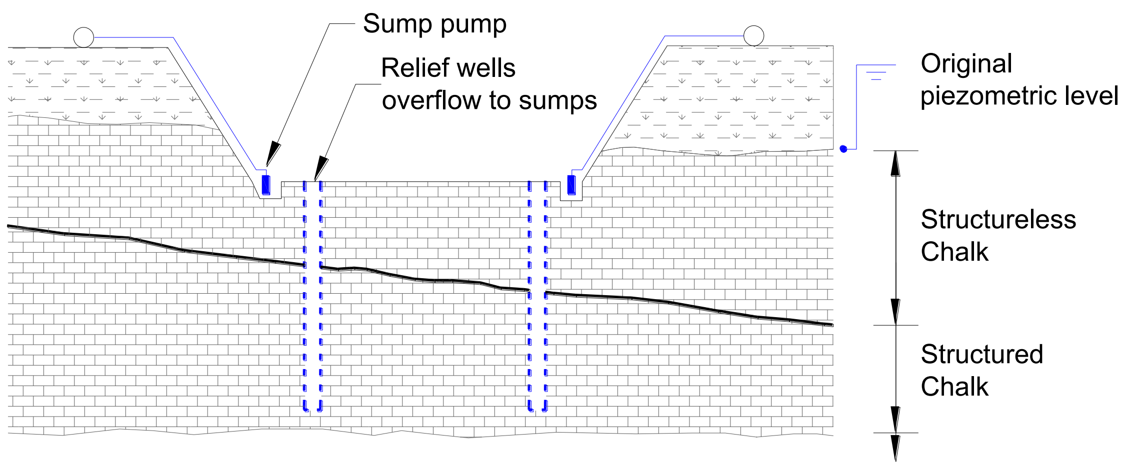


Figure 5: Relief wells used to depressurise structured Chalk beneath structureless Chalk

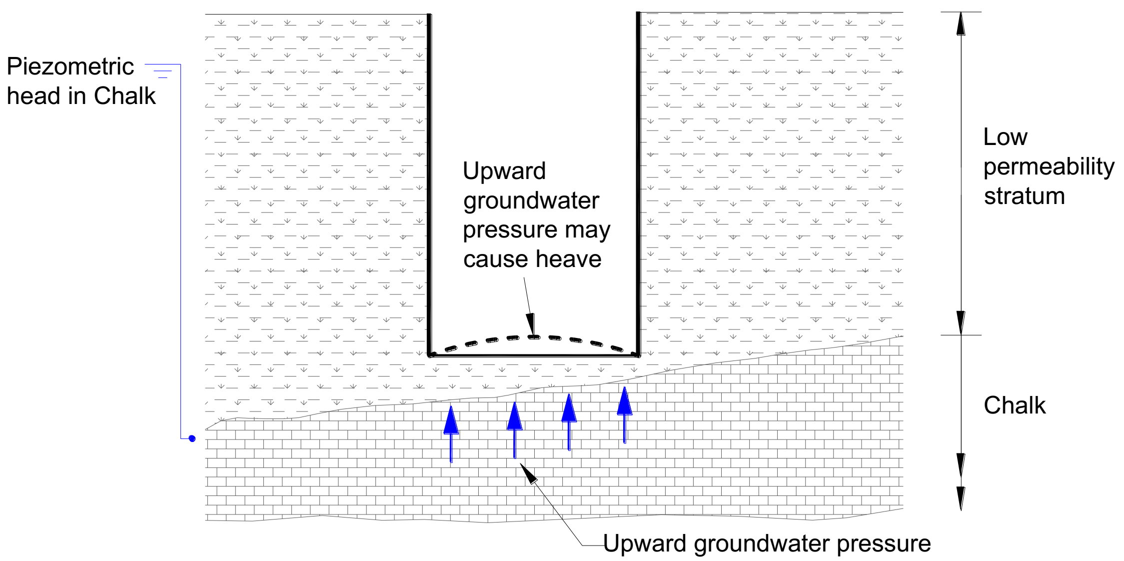


Figure 6: Risk of hydraulic failure of the base of excavations in strata overlying Chalk

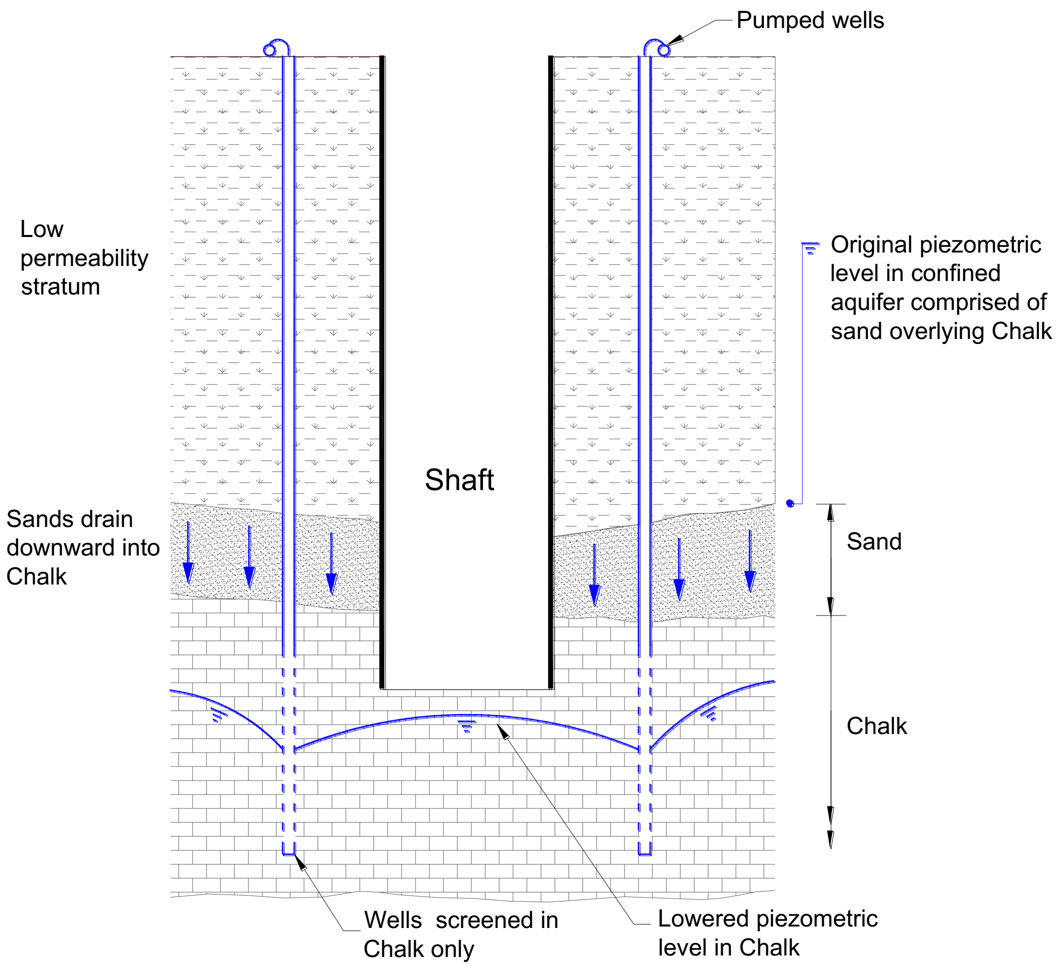


Figure 7: Pumping from Chalk used to indirectly dewater other strata

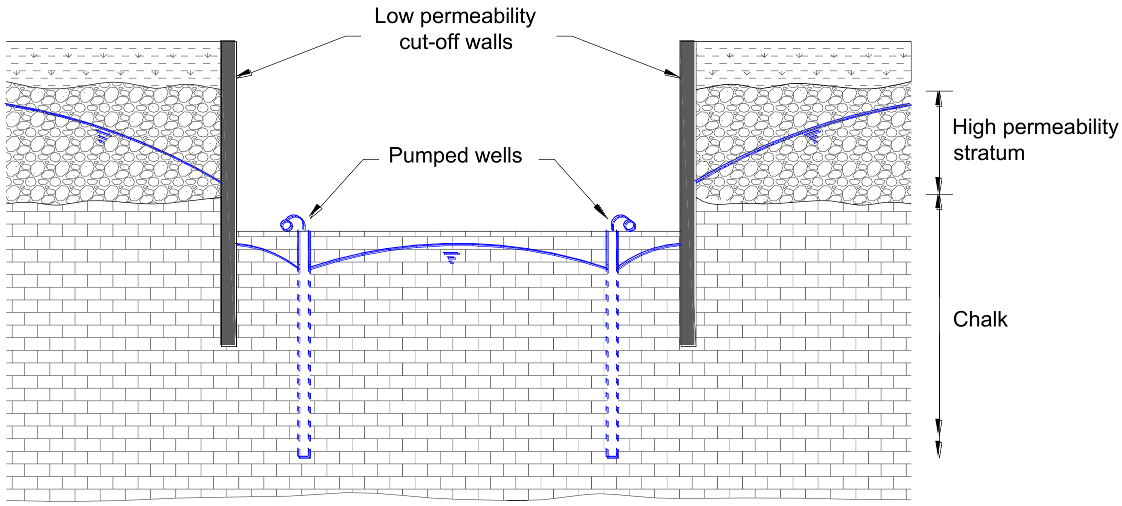


Figure 8: Low-permeability cut-off walls used to exclude groundwater from high permeability strata overlying Chalk