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Pumping tests for construction dewatering in chalk

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ABSTRACT Well pumping tests, where one or more wells are pumped at a controlled rate for an extended period of time (usually several days), can be an effective method of obtaining data for the design of construction dewatering systems. Pumping tests in chalk present particular challenges, and the design of the test well and monitoring well array should take account of the hydrogeological setting of the chalk, which can include unconfined or confined aquifers, with or without overlying granular water-bearing deposits. Data from the pumping tests can be used to derive hydrogeological parameters, or can be used directly in dewatering design by the superposition of drawdown method. Where there is concern about potential impacts from groundwater lowering (e.g. settlement, changes in water chemistry, depletion of groundwater-dependent features) then relevant data from constant rate pumping phases can be useful in the assessment of the magnitude and distribution of impacts that might result from the dewatering system.

1 INTRODUCTION

Construction dewatering typically involves pumping groundwater from an array of wells or sumps in or around an excavation. The objective is to temporarily lower groundwater levels to allow excavation or tunnelling below original groundwater level in stable and workably dry conditions.

The design process for construction dewatering systems requires an adequate understanding of hydrogeological conditions that will affect construction. Potential environmental impacts will also need to be considered. The ground investigation should gather data on hydrogeological parameters, including permeability (hydraulic conductivity), which are used as inputs to the seepage analysis or groundwater numerical modelling used in design to determine *inter alia* the required dewatering pumping rates. Routinely, ground investigations will include: groundwater observations during drilling; installation and monitoring of piezometers; and, variable head permeability tests in boreholes and piezometers – Further details are given in Chapter 5 of CIRIA Report C750 (Preene *et al*. 2016).

On larger projects, or where hydrogeological conditions are complex, and/or where confidence is required in the seepage analysis, later phases of ground investigation often include a well pumping test. This paper will describe best practice in the design, execution and analysis of pumping tests for the specific purposes of construction dewatering in chalk.

2 GEOTECHNICAL INVESTIGATION IN CHALK

The Chalk Group is a significant aquifer in the UK, and is widely exploited for water supply. However, for construction projects below groundwater level, because of its diverse geotechnical and hydrogeological properties, chalk can be a very challenging material in which to work. The background to construction dewatering in chalk is described in detail by Preene and Roberts (2017). The more highly weathered, structureless forms of 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. Water strikes in percussion drilled boreholes in weathered structureless chalk can indicate low permeability 'putty' chalk acting as a confining layer to more permeable chalk below.

Conversely, 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 seepages to major inflows with associated risks of instability and inundation.

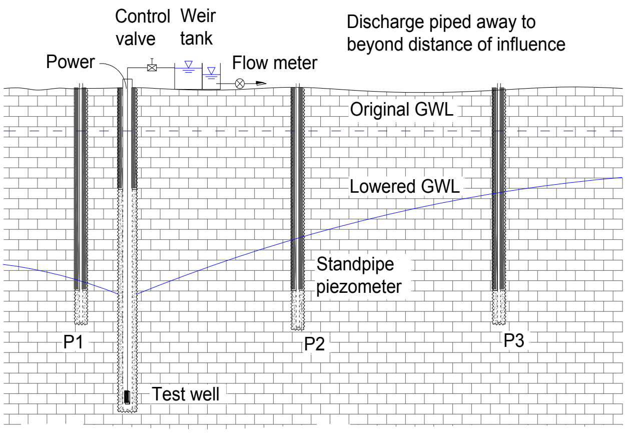


Figure 1. Schematic section through a single well pumping test (P1, P2, P3 are piezometers or monitoring wells).

Examination of samples, cores and borehole logs provides little quantitative information on hydrogeological parameters of a chalk aquifer. Experience suggests that anisotropic conditions, where the horizontal permeability is significantly greater than the vertical permeability, often predominate at construction project scale in chalk rock.

A range of in-situ borehole techniques are available to characterise hydrogeological conditions. Methods relevant to chalk include rising and falling head tests in boreholes and piezometers, or packer permeability tests in boreholes in stable chalk. The parameters derived are local and may be highly influenced by the presence or absence of fissures at the test horizon which may in any case be plugged with slurrified chalk during drilling.

Pumping tests are one of the most effective methods of obtaining project scale hydrogeological information. Groundwater is pumped at a controlled rate from a defined location (the test well) and the drawdown of groundwater level is observed in surrounding piezometers (Figure 1). Field methods are well defined and standards exist for such tests (e.g. BS ISO 14686:2003; BS EN ISO 22282-4:2012).

3 DESIGN OF PUMPING TESTS IN CHALK

3.1 Objectives of pumping tests

In the context of a ground investigation, a pumping test is probably the most expensive field test that directly informs the design of a dewatering system, and can provide high quality information. Unfortunately, pumping tests occasionally give inconclusive results, or results that do not adequately clarify the dewatering requirements. This is sometimes because the pumping test has not been designed appropriately to fulfil the designer's requirements.

There is no single template for the design and execution of a pumping test. A test for the purposes of assessing groundwater resources for water supply (as described in BS ISO 14686:2003) has different requirements to a test for the purposes of construction dewatering (see Preene and Roberts 1994). In addition to the ground conditions, the permanent and temporary works arrangements for the excavation or tunnel will influence the test design. The objectives for a pumping test intended to support construction dewatering design typically include:

1. Derivation of hydrogeological parameters including estimates of aquifer transmissivity, permeability and storage coefficients. These parameters are used as inputs to dewatering design calculations.
2. Well construction. Use of the same design and method of construction planned for the dewatering wells should confirm well yields and highlight any concerns with the well specification.

3. Assessment of wider hydrogeological conditions. Monitoring data from pumping tests can be analysed to discern aquifer boundary conditions, hydraulic connections between strata and potential impacts on water dependent features (springs, wetlands, nearby water supply wells, etc.).
4. Secondary objectives. The test may provide data gathering opportunities not available in the earlier phases of ground investigation. For example, the water samples from continuous pumping of a well may be more representative of groundwater chemistry than samples taken from piezometers or boreholes.

Note that careful selection of the test location can significantly reduce the marginal cost of a pumping test if the test well and piezometer array can later form part of the main works dewatering scheme.

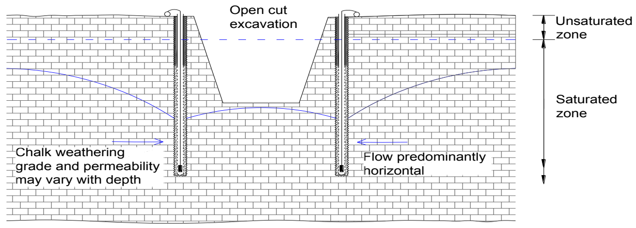
3.2 Hydrogeological conditions in chalk

Preene and Roberts (2017) identify that, in terms of assessing construction dewatering requirements, there are three significant hydrogeological settings (Figure 2). Chalk may form an unconfined or confined aquifer. In unconfined conditions the upper part of the chalk aquifer may be unsaturated, and excavations into the chalk above groundwater level may encounter little or no groundwater (Figure 2(a)). Overlying water-bearing deposits can be in hydraulic connection with the chalk forming a combined unconfined aquifer (Figure 2(b)). When chalk acts as a confined aquifer, the entire thickness of the chalk is saturated, and the piezometric level is above the top of the chalk (Figure 2(c)); overlying water-bearing deposits can be in hydraulic connection with the chalk; the potential connection will be influenced by the presence and vertical permeability of any structureless chalk at the interface between strata.

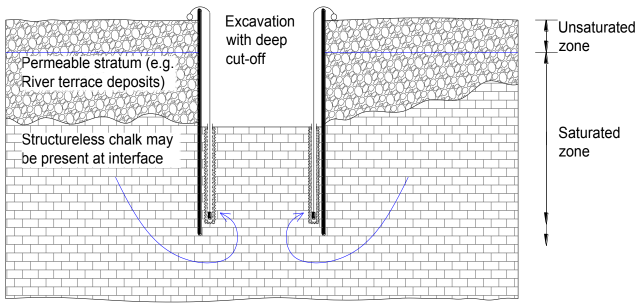
3.3 Influence of partial cut-offs

Where an open cut excavation (i.e. without low permeability cut-off walls) is made in an unconfined chalk aquifer, Figure 2(a), inflow is predominantly controlled by the horizontal permeability of the chalk. If a relatively deep cut-off wall is installed to target a higher permeability horizon and effectively cut it off, then flow to a dewatering system is controlled by the vertical permeability at or below the toe of the wall. However, if the cut-off wall penetrates to only a few metres below excavation level, then horizontal permeability will still be the controlling factor on dewatering flow rate. This is because the dewatering wells, even if installed internally, are likely to be required to extend to at least 6m to 10 m below the excavation level.

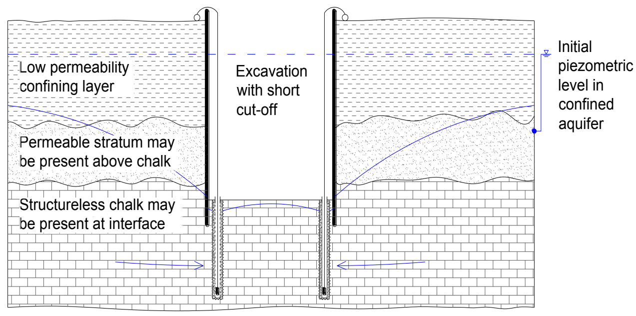
For the hydrogeological conditions shown in Figure 2(b) inflows to a shallow open cut excavation (i.e. with no low permeability cut-off wall) in the overlying gravels would be controlled by the permeability of the gravels.



(a) Unconfined chalk aquifer, no overlying high-permeability stratum present (open cut excavation shown, predominantly horizontal flow)



(b) Unconfined chalk aquifer, overlying high-permeability stratum present (excavation with deep cut-off shown, significant vertical flow component)



(c) Confined chalk aquifer (excavation with short cut-off shown, predominantly horizontal flow) Drawdown causes aquifer to become locally unconfined near dewatering system

Figure 2. Principal chalk hydrogeological settings relevant to construction dewatering problems, showing interaction between cut-off depth and flow orientation.

Conversely, if a low permeability cut-off is installed down to the top of the chalk, inflow would typically be governed by the horizontal permeability of the chalk. If the cut-off is extended deeper the vertical permeability of the chalk will become increasingly important.

Where a partial cut-off is present which reaches below the internal well depth (as depicted in Figure 2(b), then the seepage analysis is dependent on several factors; the horizontal permeability of the chalk below the cut-off toe; the vertical permeability of the chalk above the cut-off toe; and the individual yields of dewatering wells installed to the proposed target internal well depth.

A further complication is that where permeability varies with depth, due to chalk weathering as in Figure 2(a), or due to the existence of an overlying stratum, Figure 2(b) or (c), then the pumping test response will usually be dominated by the most permeable horizon present. If the intention is to install a cut-off through the high permeability horizon then data from a fully screened, test well, installed before the cut-off is constructed, may be of limited value.

3.4 Design of test well and monitoring well array

Effective pumping tests in chalk require that the pumping well and the array of piezometers be designed appropriately for the hydrogeological conditions (Table 1). The strength and stability of the chalk (as described by the CIRIA grades, see Spink (2002)) must also be considered, as this influences well design:

- Grade A structured chalk typically allows stable boreholes to be formed, where the lower sections of wells are left unlined as an open hole (i.e. with no well screen). This is common practice for wells in the confined chalk aquifer in London and elsewhere (Charalambous *et al*., 2013). It is also common to develop such wells by injection of concentrated hydrochloric acid, which dissolves the drilling slurry, and cleans the bore, opening blocked fissures (Banks *et al*. 1993).
- In more weathered grades of chalk (structured grades B and C, and structureless grade D) boreholes are more likely to be unstable and slotted well screens are typically installed to keep the bore open. Well development by acidisation is rarely carried out, and airlift pumping is commonly used to develop wells.

Test wells screened across geological boundaries should generally be avoided because of difficulties in interpretation of the data plus the potential contamination risk associated with aquifer cross connections.

The design of the piezometer array should also be appropriate to the hydrogeological setting. Where there is an overlying permeable stratum (Figure 2(b) and 2(c)), it is usually necessary to have separate piezometers with response zones targeted at the chalk and the overlying stratum.

The screened zone for the test well needs to target the appropriate horizon. Where a partial cut-off is planned this may be the chalk below the cut-off.

Well design must also consider the presence of any groundwater contamination. In some settings, particularly unconfined conditions, legacy contamination can exist from former land use. Groundwater may be contaminated in permeable strata overlying the chalk (e.g. River Terrace Deposits) where present, in the chalk or in both strata. In such conditions, piezometers should have short response zones and grout seals to reduce the risk of forming a pathway for contamination to migrate vertically. Where contamination is present, the test programme needs careful design to avoid unnecessarily mobilising contamination. Also, the need for treatment of pumped water prior to disposal should be considered.

Table 1: Typical pumping test well design for dewatering design in chalk

Hydrogeology	Typical pumping test well construction	Typical well development
Unconfined chalk aquifer, no overlying permeable stratum (Fig 2(a))	Plain well liner above groundwater level, slotted well screen below. Formation stabilizer filter gravel around screen, grout seal above	Airlift development is common. Wells rarely acidised
Unconfined chalk aquifer, with overlying permeable stratum (Fig 2(b))	**Well screened in chalk only*:** Plain well liner to extend short distance (3 to 5 m) below top of chalk, grouted into place, with slotted well screen below. Formation stabilizer filter gravel around screen, grout seal above	Airlift development is common. Wells rarely acidised
Confined chalk aquifer (Fig 2(c))	**Well screened in chalk only*:** Plain well liner to extend short distance (3 to 5 m) below top of chalk, grouted into place. Well is completed as open hole below well liner.	Wells commonly acidised

Note: *Where permeable strata are present above the chalk, test wells can be installed with the well screen and filter gravel through both strata, with grout seals above. However, pumping tests in such hybrid wells can be difficult to usefully analyse for dewatering design purposes.

3.5 Types of pumping test programme

A pumping test typically comprises a sequence of test phases, each intended to provide different information. Different projects and different hydrogeological conditions require different test programmes, comprising test phases selected from Table 2, which is based on the authors' experience.

Often the constant rate pumping test phase is most relevant to the design of dewatering systems. This typically involves using a borehole submersible pump to abstract from a test well for between 2 and 7 days; longer tests are sometimes carried out, especially where environmental impacts are of concern. The pumping rate should be large enough to generate significant drawdown in the chalk outside the well. Ideally, at the end of the test drawdown in piezometers in the target horizon at between 10 to 30 m from the pumped well should be of the order of 10% of the required drawdown for the proposed dewatering scheme.

Table 2: Characteristics of different phases of pumping tests

Test type	Typical duration	Outline of typical test and test objective
Equipment test	15–60 min	Short period of continuous pumping. Objective is to confirm pumps, pipework, etc. are functioning, and to inform setting of pumping rates for later phases.
Yield test	1–8 h	Well pumped at nominal constant rate. Objective is to estimate well yield.
Step test	8–12 h	Well pumped in step-wise fashion with increasing flow rates (typically 60 to 100 min per step). Objective is to estimate well performance, including well yield.
Constant rate pumping test	2–28 d	Well pumped at nominal constant rate. Objective is to assess drawdown in aquifer over a wide area and allow derivation of hydrogeological parameters and boundary conditions.
Pumping re-injection test	2–28 d	Water pumped from well(s) and re-injected to other well(s). Objectives are same as for constant rate test, plus estimating recharge well capacity and assessing interaction between abstraction and recharge wells.
Dewatering trial/pilot test	5–28 d	A group of wells, typically forming all or a sub-section of the proposed dewatering system is pumped. Objective is to investigate the effectiveness of the full system.
Cut-off wall pumping test	1–5 d	A well within the area enclosed by a cut-off wall is pumped. The objective is to investigate the effectiveness of the cut-off wall.

Note: min = minute; h = hour; d = day

The term 'constant rate' is a misnomer. If the borehole pump is not adjusted, the flow rate will tend to reduce slightly as the drawdown in the well changes the discharge head at the pump. In some cases, for example where the aquifer is bounded, and large drawdowns are generated, the pumped flow rate may reduce significantly. Where the test is for the purposes of construction dewatering design it is normal practice to allow the flow rate to reduce, and not to attempt to adjust the pump to keep flow rate constant.

Also, to gain the most useful data 'constant rate' pumping tests for dewatering schemes are generally carried out at the maximum achievable flow rate. The test well is commonly 'over pumped' with drawdown in the well at or close to pump intake. As a result, there may be a significant seepage face so that the water level in the pumped well often does not provide a useful guide to conditions in the aquifer outside the well.

Where artificial recharge of groundwater is planned, special test programmes involving re-injection of water are required. Typically, the test is started conventionally whereby water is pumped from well(s) and discharged to surface water. In later stages the water from the pumped well(s) is diverted to recharge well(s). This allows data to be gathered both on the capacity of the recharge wells, and the interaction between the pumping and recharge wells. A test using two pumping wells and three recharge wells is described by Roberts and Holmes (2011).

Short pumping test programmes (e.g. comprising yield tests or step tests only) are sometimes carried out where there are restrictions on the volumes of water that can be discharged from the test, or where hydrogeological conditions are already well characterised, but there is uncertainty over likely well yields. Short duration pumping tests can also be useful to assess the effectiveness of groundwater cut-off walls in shafts and cofferdams.

The basic monitoring requirements for pumping tests are to record the pumped flow rate (via flowmeters or V-notch weirs) and groundwater levels in the pumped well and piezometers (via manual readings or water level dataloggers).

The piezometer array should be appropriate for the hydrogeological setting. The piezometer array will typically include instruments in the range 5m up to 100m distant from the pumped well. In confined aquifers far field monitoring out to several hundred metres or more may be required to assess off-site effects. Some piezometers should also target any high permeability strata overlying the chalk. The rate of drawdown of groundwater levels occurs rapidly, immediately after pumping starts, and then gradually slows. Typically, very frequent readings are taken in early stages of pumping, becoming gradually less frequent – guidance is given in BS ISO 14686:2003 and BS EN ISO 22282-4:2012. In coastal and estuarine areas, groundwater levels may be tidal and groundwater level readings should be frequent throughout the pumping period (typically at 15 minute intervals) to record tidal variations.

Additional monitoring may include:

- Water quality sampling
- Downhole geophysical testing which can be particularly useful in unlined chalk wells where data collected under pumped conditions can help identify the major inflow horizons to the well.
- Monitoring of nearby groundwater dependent features (e.g. water supply wells, wetlands, springs, streams) that may be affected.

A fundamental requirement for a pumping test is the need to dispose of the pumped water. For most pumping tests in chalk the volume is too large to store on site. The water is typically discharged to surface watercourses or to sewer. When planning a pumping test, checks must be made that the disposal route has adequate capacity, and the necessary permissions must be obtained from the Environment Agency (discharge to watercourses or recharge) or from regional water companies (for discharge to sewers).

4 USE OF PUMPING TEST DATA

The most common use of the pumping test data (pumped flow rates and drawdown of groundwater levels) is parameter assessment using classical hydrogeological theory. The data are analysed either manually or using proprietary software, and the gradient of the curves is used to assess the hydrogeological parameters, see Kruseman and De Ridder (1994). Alternatively, the distance-drawdown relationships observed during the test can be applied directly to dewatering design by using the cumulative drawdown method (Preene and Roberts, 1994). This can avoid some of the complications which arise in the treatment of aquifer boundary conditions in the design process.

On projects where there are potential impacts from groundwater lowering (e.g. settlement, changes in water chemistry, depletion of groundwater-dependent features) then relevant data from the constant rate pumping phase can be useful in the assessment of the magnitude and distribution of impacts.

5 CONCLUSIONS

Well pumping tests are widely accepted as the most effective method of obtaining data for the design of construction dewatering systems. Pumping tests in chalk present particular challenges.

The design of the test well and monitoring well array should take account of the hydrogeological setting of the chalk, which can include unconfined or confined aquifers, with or without overlying granular water-bearing deposits. To gain the most useful data, pumping tests for dewatering design should be generally carried out at the maximum achievable flow, with the well 'over pumped' so that drawdown in the well is at or close to pump intake.

6 REFERENCES

Banks, D. Cosgrove, T. Harker, D, Howsam, P.J. and Thatcher J.P. 1993. Acidisation: borehole development and rehabilitation. *Quarterly Journal of Engineering Geology*, 26, 109–125.

BS EN ISO 22282-4:2012. *Geotechnical investigation and testing. Geohydraulic testing. Pumping tests*. British Standards Institution.

BS ISO 14686:2003. *Hydrometric determinations. Pumping tests for water wells. Considerations and guidelines for design, performance and use.* British Standards Institution.

Charalambous, A.N., Burnet, B.R and Jones, M.A. 2013. Aspects of water well design and construction in confined Chalk overlain by Basal Sands in the London Basin with particular reference to sand ingress. *Quarterly Journal of Engineering Geology and Hydrogeology* 46, 179-188.

Kruseman, G.P. and De Ridder, N.A. 1990. *Analysis and Evaluation of Pumping Test Data, 2nd edition*. Publication 47, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands (ISBN: 978-9-07075-420-4).

Preene, M. and Roberts, T.O.L. 1994. The application of pumping tests to the design of construction dewatering systems. *Groundwater Problems in Urban Areas* (Wilkinson, W.B. (ed)), Institution of Civil Engineers, Thomas Telford, London, 121–133.

Preene, M. and Roberts, T.O.L. 2017. Construction dewatering in Chalk. *Proceedings of the Institution of Civil Engineers, Geotechnical Engineering* 170, 367–390.

Preene, M. Roberts, T.O.L. and Powrie, W. 2016. *Groundwater Control – Design and Practice, 2nd edition*. Construction Industry Research and Information Association, London, UK, CIRIA Report C750.
Roberts, T.O.L. and Holmes, G. 2011. Case study of a dewatering and recharge system in weak Chalk rock. *Proceedings of the XV ECSMFGE, Geotechnics of Hard Soils – Weak Rocks* (Anagnostopoulos, A. Pachakis, M. Tsatsanifos, C.H. (eds)), IOS Press, Amsterdam, The Netherlands, 1461-1466
Spink, T.W. 2002. The CIRIA Chalk description and classification scheme. *Quarterly Journal of Engineering Geology and Hydrogeology* 35, 363–369.