Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0114

Assessment of permeability for design of groundwater control systems

Évaluation de la perméabilité pour la conception de systèmes de contrôle des eaux souterraines

M. Preene
Preene Groundwater Consulting Limited, Wakefield, UK

W. Powrie
University of Southampton, Southampton, UK

ABSTRACT: Permeability is a fundamental input to the design of dewatering and groundwater control systems. Permeability datasets often show much greater variation (two to three orders of magnitude) than expected based on the anticipated soil or rock heterogeneity. Much of this variation may be due to permeability being assessed at differing scales by different methods. Groundwater control systems influence large volumes of the ground, and ideally require large-scale permeability values (as can be obtained from well pumping tests) for design. Small and very small scale permeability values are less useful as they may not include the effect of coarser fabric in soils and fracture networks in rock.

RÉSUMÉ: La perméabilité est un élément fondamental de la conception des systèmes de déshydratation et de contrôle des eaux souterraines. Les ensembles de données sur la perméabilité montrent souvent des variations beaucoup plus importantes (deux à trois ordres de grandeur) que prévu en fonction de l'hétérogénéité anticipée du sol ou du roc. Une grande partie de cette variation peut être due à l'évaluation de la perméabilité à différentes échelles par différentes méthodes. Les systèmes de contrôle des eaux souterraines influent sur de grands volumes de sol et nécessitent idéalement des valeurs de perméabilité à grande échelle (comme cela peut être obtenu à partir d'essais de pompage de puits) pour la conception. Les valeurs de perméabilité à petite et très petite échelle sont moins utiles car elles peuvent ne pas inclure l'effet du tissu plus grossier dans les sols et des réseaux de fractures dans les roches.

Keywords: dewatering; groundwater; permeability.

1 INTRODUCTION

Permeability (also known as hydraulic conductivity, coefficient of permeability or Darcy permeability) is a parameter used widely in geotechnical problems. It is of particular relevance to groundwater control and dewatering projects, where it has a dominant effect on groundwater pumping rates and seepage quantities into excavations below groundwater level.

Unfortunately, permeability is complex, both in concept and when applied in geotechnical design. Natural materials can have a very wide range of permeability values, and the factors controlling permeability are different in, say, a sedimentary sequence of glacial deposits, from those in a weathered and fractured rock.

Permeability is also difficult to assess by in-situ or laboratory methods, with many test procedures having significant limitations, and different methods assessing permeability at different scales.

Despite these challenges, it is essential that meaningful values of permeability are assessed in geotechnical design. This paper will address the background to permeability, particularly in relation to groundwater control systems. Different scales of permeability and available estimation methods will be discussed, including quantitative and non-quantitative approaches, and typical applications and potential limitations highlighted.

2 FUNDAMENTALS OF PERMEABILITY

In essence, permeability is a measure of the ease or otherwise with which a fluid passes through a porous medium. A complication is that the ease of flow is dependent not only on the nature of the porous media, but also on the properties of the permeating fluid. In other words, the permeability of a soil or rock to water is different from the permeability to another fluid, such as air or oil (the permeability parameter, independent of the fluid, is known as the intrinsic permeability of a material). Hydrogeology references highlight this by using the term ‘hydraulic conductivity’ to show that the permeability parameter used in this field is specific to water.

Civil and geotechnical engineers are also interested almost exclusively in the flow of water through soils and rocks and use the term “coefficient of permeability,” instead of hydraulic conductivity, which is given the symbol *k*. For convenience, *k* is generally referred to simply as ‘permeability’ and this terminology will be used in the current paper.

Permeability is typically applied in geotechnical engineering via solutions and models developed from Darcy’s law (Darcy, 1856). This relates the flow rate Q through a test volume of cross sectional area A, due to an hydraulic gradient i (the hydraulic gradient is created by the application of an excess head ΔH). Q is initially expressed in terms of the intrinsic permeability k_i and the properties of the permeating fluid (density ρ and dynamic viscosity μ):

$$Q = -\left(\frac{k_i \rho g}{\mu}\right) iA \tag{1}$$

where water is the permeating fluid, this becomes

$$Q = -kiA \tag{2}$$

where k is the permeability (hydraulic conductivity). The negative term is necessary in the equations because flow occurs down the hydraulic gradient – i.e. from high head to low head. Darcy’s law is typically illustrated by a laboratory seepage experiment (Figure 1), with hydraulic gradient expressed in terms of ΔH and flow path length *l* to give

$$Q = -k\frac{\Delta H}{l}A \tag{3}$$

Darcy’s law is predicated on laminar flow (termed Darcian flow) where, for a given geometry (for example a borehole test section), Q and ΔH have a linearly proportional relationship.

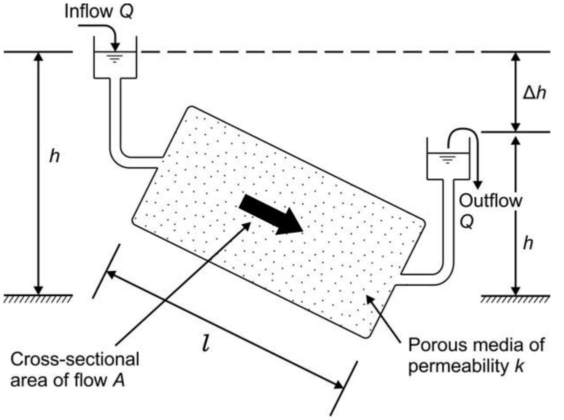

Figure 1: Darcy’s Experiment

At higher Reynolds Numbers (essentially at higher hydraulic gradients), flow becomes turbulent or non-Darcian and there is no longer a linear relationship between Q and ΔH. It is generally accepted that, for the range of hydraulic gradients encountered in most geotechnical problems, then Darcian flow will dominate. However, in rock where more open fractures are present, and if hydraulic gradients are high, non-Darcian (turbulent) flow will occur, and Q will increase under-proportionally with ΔH as energy is lost to turbulence. An example of a case where non-Darcian flow may occur is packer permeability tests in rock with very open fractures (Preene, 2018). In most other geotechnical problems, hydraulic gradients are low enough to ensure Darcian flow conditions prevail. The discussion in the remainder of this paper is based on the presumption of Darcian flow, which is the underlying assumption in most methods of analysis and modelling used for the design of groundwater control systems.

3 PERMEABILITY IN GEOTECHNICAL ENGINEERING

The permeability of a given soil may vary with void ratio, but the key governing factor is the size of the interconnected pores. In a granular soil, it is generally accepted that the permeability varies roughly as the square of the typical void or grain size (Hazen, 1892); hence the 5–6 orders of magnitude range of grain sizes between boulders (>200 mm) and clay (< 2 μm) leads to a 10–12 orders of magnitude variation in permeability. No other engineering material property, not even the variation in strength or stiffness between a soft clay and a hard steel, exhibits such a range.

In addition to its large potential range, permeability is likely to be anisotropic. In soils groundwater flow is generally easier in the horizontal direction than the vertical. Even if there is no obvious layering in a deposit, the ratio of horizontal to vertical permeabilities of a soil is likely to be in the order of ten, owing to the orientation of grains on deposition. In an horizontally laminated or structured deposit the permeability ratio may be 2–3 orders of magnitude. Some geomaterials (e.g. fractured rock, or an old clay fill embankment) exhibit a dual porosity / permeability structure, with rapid flow through fractures / joints and much slower flow in the intact material in between.

These factors make determining permeability difficult, especially on a large scale meaningful to civil engineering construction. This is especially important in construction dewatering, where permeability is a key parameter controlling the abstraction flowrate required for a given drawdown of the groundwater level or reduction in pore water pressures. The problem is compounded further by the fact the permeability, together with the drawdown, will govern the applicability and ultimately the success of a given method of pumped groundwater control, in accordance with Figure 2.

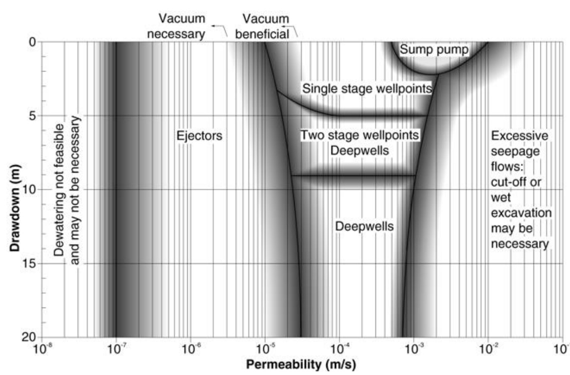

Figure 2. Range of application of pumped well groundwater control techniques (from Preene et al., 2016; reproduced courtesy of CIRIA: www.ciria.org)

4 ASSESSMENT OF PERMEABILITY IN PRACTICE

The mathematics of Darcian flow are simple, as shown by Equation 3 and Figure 1. However, using these methods to estimate permeability during site investigations is fraught with problems and uncertainties.

Quantitative methods to assess permeability typically measure Q and ΔH, but, particlarly with in-situ methods the flow geometry (area A and flow path l) may be poorly known and subject to a number of assumptions, that vary from method to method. Different test and analysis methods may give significantly different permeability values for the same zone of soil or rock.

Ex-situ methods of permeability estimation enable the flow geometry to be well defined (e.g. in a laboratory permeameter), but have the disadvantage that the disturbance from extracting, handling and preparing a sample can significally affect its permeability.

In-situ test methods also suffer from the problem that the act of forming a test borehole can create a disturbed zone around the borehole, with altered permeability. The permeability measured can be strongly influenced by this 'skin effect' around the test borehole, and the calculated values may not be respresentative of the host soil or rock.

Preene & Powrie (1993) reviewed permeability data available for 30 groundwater control projects in fine-grained soils (typically sands and silts). It was not unusual for a project to have reported permeability ranging over two orders of magnitude in a given stratum. Several projects reported permeability ranging over four orders of magnitude. The study concluded that much of the reported variation was probably due to limitations in the test and assessment methods leading to erroneous results, rather than such wide variability in actual soil properties.

5 THE EFFECT OF SCALE ON PERMEABILITY ASSESSMENTS

Considering Darcy's law via Figure 1 it is apparent that permeability cannot be meaningfully associated with a single 'point'. Rather it is an average value associated with a particular volume through which flow is occurring. Numerous studies have shown that, in hetrogenous materials, measured values of permeability will vary with the scale of the test – in effect with the size of the volume of soil or rock within which water flow is induced.

Rowe (1972) addressed this from a geotechnical testing perspective (for laboratory testing of consolidation properties). This study identified that larger diameter samples gave higher values of permeability because there was a greater likelihood of permeable fabric being captured in such samples.

Other studies such as Chapuis (2013) addressed scale effects in hydrogeological testing. Typically, well pumping tests give higher permeability values than borehole tests, because a well pumping test will influence a much greater volume of a stratum and is more likely to connect with preferential flow paths. Examples of preferential flow paths include coarser beds in soils (where intergranualar flow dominates) or permeable fracture networks in rock.

Figure 3 is a schematic illustration of scale in permeability testing. Test zones show the volume of material significantly hydraulically influenced – either ex-situ (in the laboratory) or in-situ.

At very small (laboratory test) and small (borehole test) scale the test location may or may not intercept significant numbers of preferential flow paths. Tests at these scales tend to have a large scatter between maximum and minmum values, and may be biased toward lower values, as they do not fully hydraulically interact with the wider network of permeable fabric or fractures.

At the large and very large scale the zone affected is more likely to be a representative average of the host soil or rock, including any permeable pathways. Typically, these scale of tests will produce higher values of permeability than small and very small scale tests.

Dewatering and groundwater control systems tend to interact with very significant volumes of the ground, and the most useful permeability estimates are large and very large scale. Unfortunately, such data are often not available.

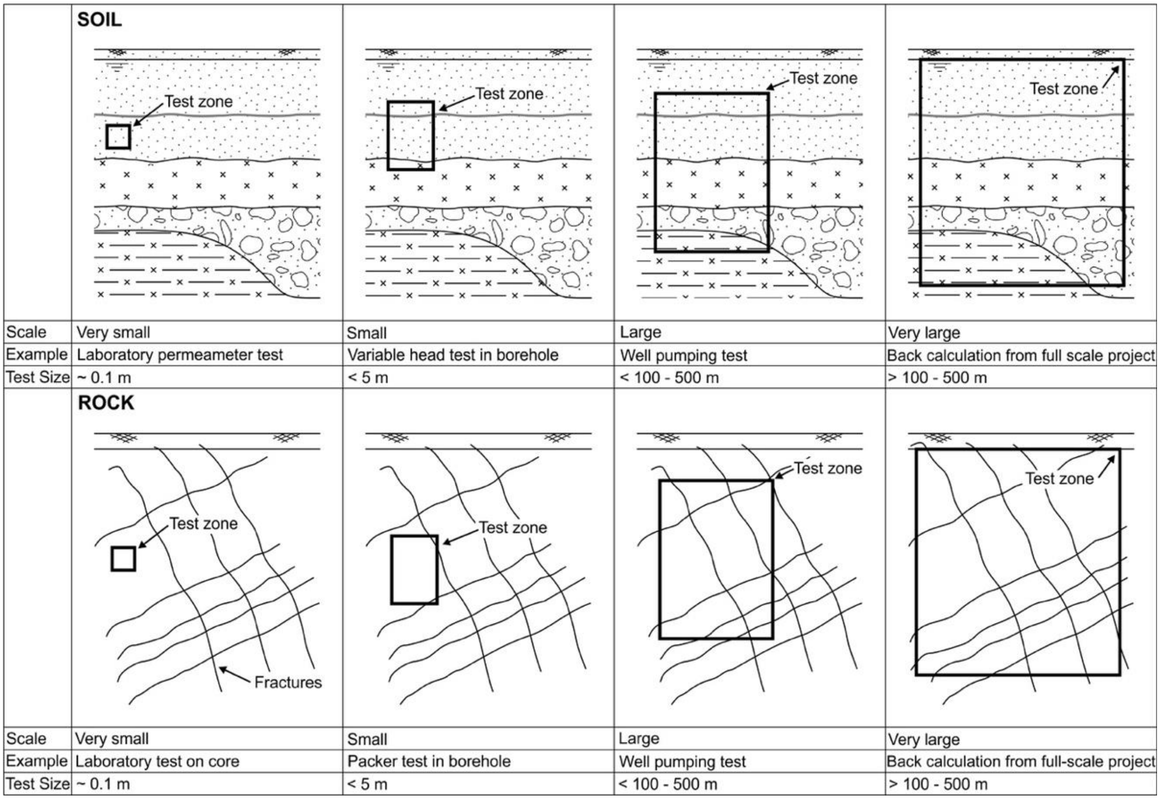

Figure 3: Scale effects on measurement of permeability in soil and rock

6 APPROACHES TO DETERMINING PERMEABILITY VALUES

A range of methods are available to assess permeability. These can be grouped as:

- Non-quantitative assessment methods
- Quantitative methods
  – empirical assessment
  – ex-situ methods
  – in-situ methods.

These methods are reviewed briefly below.

6.1 Non-quantitative assessment methods

The authors have observed a common shortcoming when assessing design values of permeability that there is a focus on quantative methods – ‘values’ of permeability from tests. As discussed earlier, many test methods have limitations, and may give different scales of permeability values. These results are often not adequately validated against non-quantiative methods.

A simple validation that is often overlooked is to assess the permeability values against published ranges based on classification of the soil or rock (such as Table 1 for soils). Such values must necessariliy be generic, but experience shows that there is a strong correlation between permeability and the nature (including stress state and weathering) of the soil or rock in question. Such correlations can be used to exclude unrepresentative test results from the permeability dataset. Other non-quantitative methods are sumarised in Table 2. Typically, these can be used to identify the presence of localised high permeability zones at specific depths in boreholes which may not be apparent from small scale tests or from large scale tests that report average permeability (for example from a well pumping test).

Table 1. Typical values of soil permeability (after Cashman and Preene, 2012)

Soil type	**Typical classification of permeability**	**Permeability (m/s)**
Clean gravels	high	> 1 x 10^{-3}
Clean sand and sand/gravel mixtures	high to moderate	1 x 10^{-3} to 5 x 10^{-4}
Fine and medium sands	moderate to low	5 x 10^{-4} to 1x 10^{-4}
Silty sands	low	1 x 10^{-4} to 1 x 10^{-6}
Sandy silts, very silty fine sands and laminated or mixed strata of silt/sand/clay	low to very low	1 x 10^{-5} to 1 x 10^{-8}
Fissured or laminated clays	very low	1 x 10^{-7} to 1 x 10^{-9}
Intact clays	practically impermeable	< 1 x 10^{-9}

Table 2. Potential non-quantitative indicators of relative values of permeability

Potential non-quantitative indicators	**Notes**
Water strike (inflow) records from boreholes	For drilling methods where added drilling fluids do not mask water inflows, can identify zones of relatively high permeability within borehole column.
Water levels at start and end of shift	For drilling methods that remove water (cable percussion and rotary air flush), changes in water level between start and end of shift can indicate water inflow/outflow.
Drilling fluid (flush) loss records, voids or tool drops in boreholes	Zones of where loss of drilling fluid is noted, or where voids are identified, can indicate permeable zones
Borehole geophysical fluid logging	Changes in gradient in fluid logs (temperature, specific conductivity, flowmeter logs) can indicate inflow zones in unlined boreholes (Roberts & Hartwell, 2018).

6.2 Quantitative assessment methods

Each method has limitations, and may estimate permeability values at different scales. Possible methods are summarised in Table 3, and the more commonly-used methods are disussed below.

6.2.1 Empirical correlations with PSD

A commonly applied type of empirical correlation is to relate permeability to the particle size distribution (PSD) of granular soil. Bricker & Bloomfield (2014) summarise the generic form of correlations between PSD and permeability as:

$$k = \left(\frac{\rho g}{\mu}\right) C f(n) d_e^2 \qquad (4)$$

where *C* is a sorting coefficient, *n* is porosity, *f*(*n*) is porosity function and d_e is effective grain size. Some formula, such as Hazen's rule (Hazen, 1892) conflate multiple aspects of the correlation to produce a simpler equation, requiring only limited input data. Other formula, such as Kozeny-Carman (Carrier, 2003) apply the separate aspects of Equation 4, and therefore require estimates of porosity and other aspects.

It is clear that different PSD correlations will produce different estimates of permeability for a given sample. Furthermore, the process of sampling and PSD testing may render the samples less representative of the in-situ conditions, introducing further error into the permeability estimates.

6.2.2 In-situ methods

Because of their low cost and relatively short duration (allowing multiple tests to be carried out in a site investigation programme) variable head tests in boreholes are a commonly used method for investigations in soils. Along with packer tests in boreholes, these tests only influence a small zone around the borehole, and can be significantly affected by any disturbed zone or clogging effects local to the borehole. Furthermore, as discussed by Black (2010) and Preene (2018), the methods of analysis must be carefully selected to avoid inappropriate interrpetation of test results.

Well pumping tests (where a borehole is pumped in a controlled manner for an extended period) can provide larger scale permeability values than borehole tests. Provided the test is designed with a sufficiently large pumping rate, this method is less affected by the disturbed zone around the borehole and influences a very large volume of ground, typically out to more than 100 m from the test well.

Table 3. Common methods for quantitative assessment of permeability

Method	Typical scale (Figure 3)	Characteristics and limitations	Example references
Empirical methods			
Particle size distribution (PSD) correlations	Very small	Elements of soil grading (PSD) curves are used in empirical correlations. Each correlation method (e.g. Hazen; Kozeny-Carman) has a limited range of PSDs to which it should be applied; use outside those ranges can result in gross errors. Samples may be unrepresentative because a) sampling and the PSD testing process results in homgenisation of samples, and loss of structure and fabric; and b) fine particles may be lost from the sample (typically flushed out into the borehole fluid).	Carrier (2003); Bricker & Bloomfield (2014)
Ex-situ methods			
Permeameter testing	Very small	Water flow is induced through a specimen of soil or rock. Sample size is limited to a few hundred millimetres. Disturbance (disruption of structure and fabric) and changes in stress state due to sampling means permeability values may not be representative.	Head & Epps (2011)
Oedometer testing	Very small	Similar to permeameter testing.	Head & Epps (2011)
In-situ methods			
Variable head tests in boreholes and standpipe piezometers	Small	Common method (also known as slug test) for testing discrete zones during borehole drilling, especially in soils. Falling head tests cause water to flow out of the borehole, and rising head tests induce inflow to the borehole. In high permeability strata water levels change rapidly during the test and the rate of change can be difficult to record manually (the problem can be overcome by the use of dataloggers). In low permeability soils a test may need to last several hours as excess heads slowly dissipate. The presence of a disturbed zone (caused by drilling) around the borehole or piezometer can result in unrepresentative responses. Different methods of analysis can give different values of permeability for the same test response.	Black (2010)
Packer tests in boreholes	Small	Widely used for testing of boreholes in fractured rock, typically by injecting water to induce flow out of a borehole. Produces an average permeability for the test section; it can be difficult to determine whether the permeability is associated with many distributed fissures, or a smaller number of discrete fissures.	Preene (2018)
Geophysical flowmeter logging	Small	Specialist technique that can be used in boreholes in fractured rock. A profile of vertical flow velocity within the borehole can be used to determine vertical variations in permeability.	Parker *et al.* (2010)
Well pumping tests	Large	Water is pumped from a well, monitoring pumped flow rate and drawdown in neighbouring monitoring wells. Provided that the pumped flow rate is sufficient to create a large drawdown in the strata around the well, and if pumping continues for an extended period (typically several days), a large volume of the ground can be influenced. The large-scale permeability values from this method are a good match for the needs of dewatering designers. May also provide information on hydraulic boundary conditions.	Preene & Roberts (1994)
Groundwater control trials	Large/Very large	Simular to well pumping tests, but typically pumping from multiple wells. Potentially affects even greater volumes of the ground.	Preene & Roberts (1994)
Back calculation from full scale projects	Very large	Pumping rate and groundwater level data are used to assess permeability from full-scale dewatering. Can only be applied during or after significant phases of a project are in progress, provided adequate monitoring is in place. Useful to refine designs for later phases.	Bevan *et al.* (2010)

7 CONCLUSION

Permeability is a fundamental input to the design of dewatering and groundwater control systems. Designers are often faced with permeability datasets that contain very wide ranges of values (perhaps two to three orders of magnitude), with a much greater variation than expected based on the anticipated soil or rock heterogeneity.

While some of the observed variation in permeability values may arise from limitations in the permeability testing methods, much may be due to permeability being assessed at differing scales by different methods (Figure 3). Groundwater control systems influence large volumes of the ground, and ideally large-scale permeability values (as can be obtained from well pumping tests) should be used in design. Small and very small scale permeability values are less useful as they may not include the effect of more permeable pathways (coarser fabric in soils and fracture networks in rock).

Whatever the source of the permeability dataset, it is important that permeability values are validated against non-qualitative methods to exclude likely unrepresentative values.

8 REFERENCES

Bevan, M.A., Powrie, W. & Roberts, T.O.L. 2010. Influence of large-scale inhomogeneities on a construction dewatering system in chalk. Géotechnique **60**, 635–649.

Black, J.H. 2010. The practical reasons why slug tests (including falling and rising head tests) often yield the wrong value of hydraulic conductivity. *Quarterly Journal of Engineering Geology and Hydrogeology* **43**, 345–358.

Bricker, S.H. & Bloomfield, J.P. 2014. Controls on the basin-scale distribution of hydraulic conductivity of superficial deposits: a case study from the Thames Basin, UK. *Quarterly Journal of Engineering Geology and Hydrogeology* **47**, 223–236.

Carrier, W.D. 2003. Goodbye, Hazen; Hello, Kozeny‐Carman. *Journal of Geotechnical and Geoenvironmental Engineering* **129,** 1054–1056.

Cashman, P.M. & Preene, M. 2012. *Groundwater Lowering in Construction: A Practical Guide to Dewatering, 2nd edition*. CRC Press, Boca Raton.

Chapuis, R.P. 2013. Permeability scale effects in sandy aquifers: a few case studies. *Proceedings of the 18th International Conference on Soil Mechanics and Foundation Engineering, Paris, France*, 505–510.

Darcy, H. 1856. *Les Fontaines Publique de la Ville de Dijon*. Dalmont, Paris.

Hazen, A. 1892. *Physical properties of sands and gravels with reference to their use in filtration*. Report of the Massachusetts State Board of Health.

Head, K.H. & Epps, R.J. 2011. *Manual of Soil Laboratory Testing. Volume II: Permeability, Shear Strength and Compressibility Tests.* Whittles Publishing, Caithness, UK.

Parker, A.H., West, L.J., Odling, N.E. & Bown, R.T. 2010. A forward modeling approach for interpreting impeller flow logs. *Ground Water* **48**, 79–91.

Preene, M. 2018. Design and interpretation of packer permeability tests for geotechnical purposes. *Quarterly Journal of Engineering Geology and Hydrogeology*. doi.org/10.1144/qjegh2018-079.

Preene, M. & Powrie, W. 1993. Steady-state performance of construction dewatering systems in fine soils. *Géotechnique* **43** 191–206.

Preene, M. & 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.). Thomas Telford, London, 121–133.

Preene, M., Roberts, T.O.L. & Powrie, W. 2016. *Groundwater Control – Design and Practice, 2nd Edition.* Construction Industry Research and Information Association, CIRIA Report C750, London.

Roberts, T.O.L. & Hartwell, D.J. 2018. Chalk permeability. *Engineering in Chalk: Proceedings of the Chalk 2018 Conference* (Lawrence, J.A., Preene, M., Lawrence, U.L. & Buckley, R. (eds)). ICE Publishing, London 1–4.

Rowe, P W. 1972. The relevance of soil fabric to site investigation practice. *Géotechnique* **22**, 425–430.