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Groundwater control: design and practice, second edition

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Summary

This publication provides information and guidance on pumping methods used to control groundwater as part of the temporary works for construction projects. Subjects covered include potential impact of groundwater on construction works, groundwater control techniques, safety, management and contractual matters, legal and environmental issues that arise when groundwater is pumped and discharged, site investigation requirements, and design methods for groundwater control schemes.

The guide explains the principles of groundwater control by pumping, and gives practical information for the effective and safe design, installation and operation of such works.

This revised publication was prepared under contract to CIRIA by Golder Associates (UK) Limited with support from WJ Groundwater Limited and the University of Southampton. The authors of the original guide (CIRIA C515) were M Preene, T O L Roberts, W Powrie, M R Dyer.

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Cover photograph courtesy Oliver Vincent

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Dr T O L Roberts	WJ Groundwater Limited

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Glossary

Analytical model	A simple mathematical model describing an aquifer and its boundary conditions.
Anisotropy	The condition in which one or more of the properties of an aquifer varies according to the direction of measurement.
Aquiclude	Soil or rock forming a stratum, group of strata or part of a stratum of very low permeability, which acts as a barrier to groundwater flow.
Aquifer	Soil or rock forming a stratum, group of strata or part of a stratum that is water-bearing (ie saturated and relatively permeable).
Aquitard	Soil or rock forming a stratum, group of strata or part of a stratum of intermediate to low permeability, which only yields very small groundwater flows.
Artificial recharge	Replenishment of groundwater artificially (via wells, pits or trenches) to reduce drawdowns external to a groundwater control system or as a means to dispose of the discharge. (Note that in the UK permission may be required from the regulator to allow artificial recharge, see Chapter 4).
Barrier boundary	An aquifer boundary that is not a source of water.
Base heave	Lifting of the floor of an excavation caused by unrelieved pore water pressures.
Biofouling	Clogging of wells, pumps or pipework as a result of bacterial growth.
Borehole	A hole drilled into the ground for any purpose, including site investigation boreholes. In groundwater terminology a borehole is often taken to mean a relatively small diameter well, which may or may not have a pump installed.
Capillary saturated zone	The zone that may exist above the phreatic surface in a fine-grained unconfined aquifer when the soil remains saturated at negative (ie less than atmospheric) pore water pressures.
Cavitation	The formation of vapour bubbles in water when the static pressure falls below the vapour pressure of water (which can occur inside certain types of pumps and ejectors). When the bubbles move to areas of higher pressure they may implode, causing shock waves that can damage the internal components of pumps and ejectors.
Cofferdam	A temporary retaining wall structure, which may also exclude lateral flows of groundwater and surface water from an excavation.
Confined aquifer	An aquifer overlain by a confining stratum of significantly lower permeability than the aquifer and where the piezometric level is above the base of the confining stratum (as a result the aquifer is saturated throughout). Also known as sub-artesian aquifer.
Consolidation settlements	Ground settlements resulting from a reduction in groundwater levels or piezometric level and the resulting increase in vertical effective stress.
Constant head test	A form of *in situ* permeability test carried out in boreholes or piezometers where water is added to or removed from the borehole. The

	water is maintained at a constant level and the flow rate into or out of the borehole is monitored.
Construction dewatering	Groundwater control.
Deepwell	A groundwater extraction well of sufficient dimensions to accept a submersible pump.
Deepwell pump	Slimline electric submersible pump designed to be used in deepwells. Also known as borehole pump.
Dipmeter	A portable device for measuring the depth to water in a borehole, well, piezometer or standpipe.
Discharge	The flow rate pumped by a groundwater control system.
Discharge permission	Permission from the regulatory authorities to allow water to be discharged from site.
Drawdown	The amount of lowering of the water table in an unconfined aquifer or of the piezometric level in a confined aquifer caused by a groundwater control system.
Ejector	A water jet pump which creates a vacuum by circulating clean water at high pressure through a nozzle and venturi arrangement located in a well. Also known as an eductor.
Electro-osmosis	A groundwater control method used in very low permeability soils where an electric potential difference is applied to the ground to induce groundwater flow.
Falling head test	A form of *in situ* permeability test carried out in boreholes or piezometers where water is added to raise the water level in the borehole, and the rate at which the water level falls is monitored.
Filter pack	Sand or gravel placed around a well screen to stabilise the aquifer and to act as a filter and to control movement of fine particles from the surrounding soil.
Formation level	The final dig level of an excavation.
Formation stabiliser	A coarse permeable filter gravel placed around a well screen in conditions when there is no requirement to act as a filter. The gravel acts as a permeable backfill to prevent aquifer material from collapsing against and distorting the well screen.
French drain	A gently sloping drain consisting of a perforated pipe with gravel surround.
Groundwater	Water contained within and flowing through the pores and fabric of soil and fissures in rock. In hydrogeological terminology, strictly refers to the water within the saturated aquifer or perched aquifers.
Groundwater control system	A system used to manipulate groundwater levels and flows usually to facilitate construction works. Schemes may involve use of wells, drains, sumps or cut-offs individually or in combination.
Hazen's formula	An empirical method that can be applied to particle size distributions to estimate approximate permeability values for samples of uniform sands.
Hydraulic gradient	The change in total hydraulic head between two points, divided by the length of flow path between the points.
Hydrogeology	The study of the interrelationships of the geology of soils and rock with groundwater. Also known as groundwater hydrology or, especially in the USA, as geohydrology.

Abbreviations and acronyms

AGS	Association of Geotechnical and Geoenvironmental Specialists
AMF	Automatic mains failure
CDM	Construction (Design and Management) Regulations
bgl	Below ground level
BDA	British Drilling Association
DoE	Department of the Environment
EA	Environment Agency
EU	European Union
GBR	General Binding Rules
gwl	Groundwater level
HDPE	High density polyethylene
HIA	Hydrogeological impact appraisal
HSE	Health and Safety Executive
ICE	Institution of Civil Engineers
IChemE	Institution of Chemical Engineers
i.d.	Internal diameter
JCT	Joint Contracts Tribunal
LNAPL	Light non-aqueous phase liquid
NEC	New Engineering Contract
NIEA	Northern Ireland Environment Agency
NRW	Natural Resources Wales
o.d.	Outside diameter
PC	Personal computer
PCA	Permitted Controlled Activity
PSD	Particle size distribution
PVC	Polyvinyl chloride
SEPA	Scottish Environment Protection Agency
SPT	Standard penetration test
SPZ	Source protection zone
TBM	Tunnel boring machine
VWT	Vibrating wire transducer
WFD	Water Framework Directive

Notation

A	Area
a	Length of groundwater control system
B	Partial penetration factor for wells
b	Width of equivalent slot;
	Width of groundwater control system
	Half width of cofferdam
C	Calibration factor
c_{hv}	Coefficient of consolidation for vertical compression of soil under horizontal drainage
c_v	Coefficient of consolidation of soil
D	Thickness of confined aquifer
	Thickness of compressible layer
D_{10}	Sieve aperture through which 10 per cent of a soil sample will pass
D_{15}	Sieve aperture through which 15 per cent of a soil sample will pass
D_{40}	Sieve aperture through which 40 per cent of a soil sample will pass
D_{50}	Sieve aperture through which 50 per cent of a soil sample will pass
D_{60}	Sieve aperture through which 60 per cent of a soil sample will pass
D_{85}	Sieve aperture through which 85 per cent of a soil sample will pass
d	Depth to water table
	Depth of excavation in cofferdam
	Drainage path length
E	Young’s modulus of soil
$E'o$	Stiffness of soil in one-dimensional compression
G	Shape factor for flow to rectangular equivalent wells in confined aquifers
	Shear modulus of soil
H	Initial groundwater head
	Excess head in rising and falling head tests
	Applied head in packer test
H_c	Excess head in constant head test
H_o	Initial head in rising and falling head tests
h	Total hydraulic head
	Groundwater head
	Height of water over weir
h_n	Seepage head into a cofferdam
h_w	Groundwater head in a pumped well or slot
$(H-h)$	Drawdown
$(H-h_w)$	Drawdown in a pumped well or slot
i	Hydraulic gradient
i_{crit}	Critical seepage gradient for excavations
i_{max}	Maximum hydraulic gradient at entry to a well
k	Coefficient of permeability

1 Groundwater in construction

1.1 INTRODUCTION AND USER GUIDE

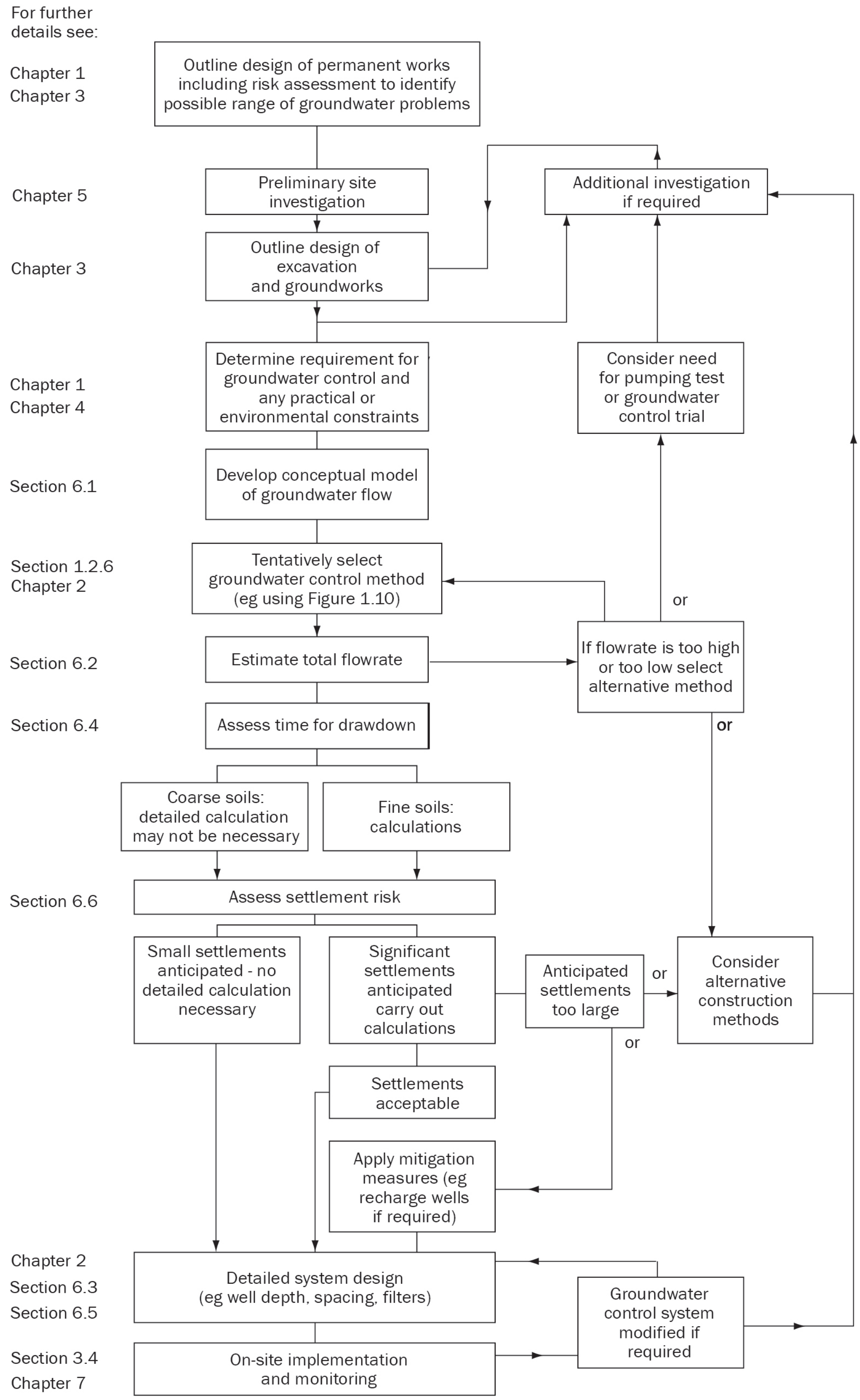


Figure 1.1 Principal stages in the analysis and design of groundwater control systems

Whenever an excavation is made below the natural water table, there is a risk that it will become unstable or flood unless steps are taken to control the groundwater in the surrounding soil (see Figure 1.2). Groundwater may be controlled by installing a physical barrier to exclude groundwater from the excavation, or by pumping groundwater from specially installed wells in order to lower artificially the water table in the vicinity of the excavation, or by a combination of the two techniques. Often, the use of a pumped well system, either alone or in combination with a physical barrier, will be the most economical and convenient approach. The appropriate type of pumped well system to use depends primarily on the nature of the ground and the depth of the excavation.

This guide explains the design and operation of groundwater control systems involving pumping from wells. It is divided into the following chapters:

Chapter 1: technical principles of groundwater flow and control

Chapter 2: commonly used methods of groundwater control

Chapter 3: management of pumped well groundwater control systems

Chapter 4: environmental considerations

Chapter 5: site investigation

Chapter 6: methods of analysis and design

Chapter 7: case studies.

The number of excavations where no consideration need be given to the potential effects of groundwater is very small. Thus the design, installation and operation of a groundwater control system – and obtaining the necessary site investigation data – should be viewed as an integral part of the overall works.

1.1.1 Users

The guidance given in this report is intended for use by those concerned with the design, specification, installation, operation, monitoring or management of pumped well groundwater control systems. As such it is intended to be accessible at a number of levels as:

- background information for project managers, resident engineers, site agents and others who encounter groundwater control systems during the course of their work and need to be able to discuss particular aspects with specialist groundwater contractors or consultants
- an introduction to the subject for geotechnical engineers with little or no previous experience of groundwater control
- a reference or source book for more experienced geotechnical engineers.

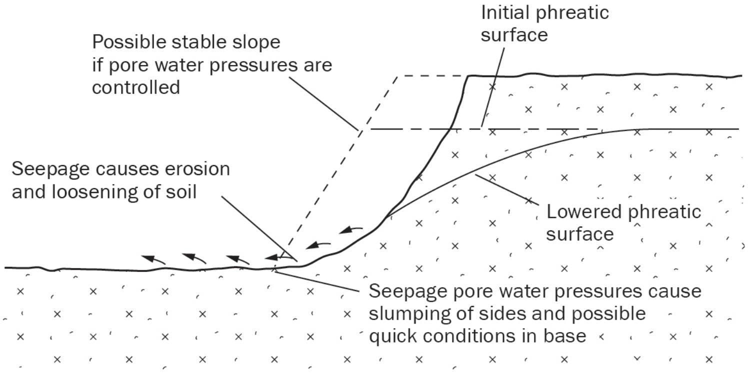
Technical details and case histories are presented in boxes, separately from the main text. The report is divided into sections and sub-sections. A feature to help the reader is the extensive cross-referencing between sections (highlighted in the left hand margins). Figure 1.1 shows a flow diagram of the principal stages in analysis and design of groundwater control systems, and the corresponding sections of this guide.

1.1.2 Limitations

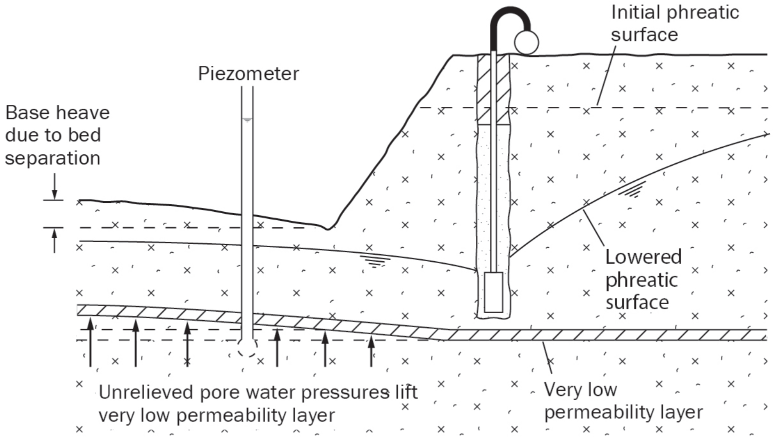
The guide is a comprehensive, up-to-date guide to the design and operation of pumped well groundwater control systems, but it is not intended to be a 'do-it-yourself' manual on dewatering for the novice. Success in ground engineering usually depends on the application of engineering judgement, which in turn requires not only a thorough understanding of the principles involved, but also a measure of experience. This guide is not a substitute for professional advice: if in doubt, consult an expert.

The guide does not cover exclusion methods of groundwater control, except to list them and indicate where further information may be found.

a) Slumping of side slopes caused by seepage into an excavation in fine sands



b) Instability of side slopes



c) Instability of base due to unrelieved pore water pressures

Figure 1.2 Groundwater-induced instability of excavation (from Preene and Powrie, 1994)

1.2 OBJECTIVES AND OVERVIEW OF GROUNDWATER CONTROL

1.2.1 Groundwater in the environment

The total volume of water on the earth is large, but finite. Most of it is in constant motion, in what is known as the hydrological cycle (Figure 1.3). Some of the water, which falls on the land as precipitation (rain, hail, sleet or snow) runs off into surface streams, rivers and ponds. Some evaporates directly, and the remainder infiltrates into the ground. A proportion of the water that infiltrates into the ground is taken up by plants through their roots, and the rest moves generally downward through the near-surface zone until it reaches the groundwater level or water table. The study of groundwater is encompassed by the field of hydrogeology. Further guidance can be found in Freeze and Cherry (1979), Price (1996) Fetter (2014), Brassington (2006) and Younger (2007).

The guidance given in this report is primarily aimed at construction projects where excavations are to be made in soil – uncemented deposits of mineral (and occasionally organic) particles such as gravel, sand, silt and clay. The soil particles are in contact with each other, but with voids in between them. These voids are known as soil pores, and flow of groundwater in soil is predominantly through the soil pores. Many of the techniques described in this report are also relevant to excavations in rock – deposits formed from mineral grains or crystals cemented together. Typically in rock the flow of groundwater will be predominantly through fissures or fractures, although intergranular flow can occur in some rock types, and in weathered rock.

Water contained in the soil pores (and within fissures and fractures in rock) is known as groundwater. Below the water table, the soil pores are full of water, and the soil is saturated. Above the water table, the soil pores will generally contain both air and water.

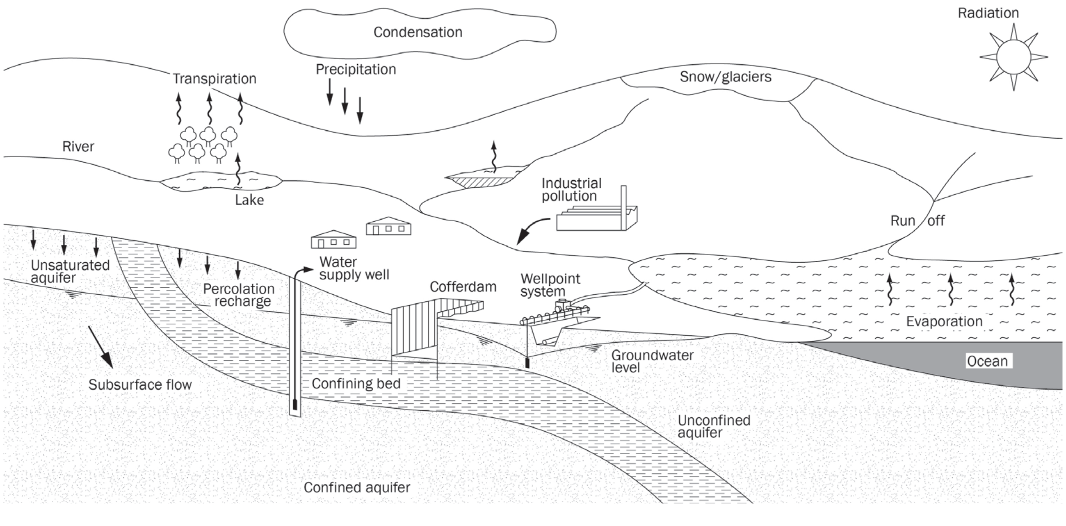


Figure 1.3 The hydrological cycle

The balance between the air and water in the zone of soil or rock above the water table is influenced by the pore size or fracture opening. In coarse-grained soils, the voids may contain significant quantities of air, and the soil or rock above the water table will often be unsaturated. Fine-grained materials can retain water in the voids by capillary action, remaining saturated for some height above the water table. The zone of unsaturated soil or rock near the surface is known as the vadose zone.

The pressure of the water in the soil voids at any point is termed the pore water pressure. The pore water pressure is measured relative to atmospheric pressure (ie a pore water pressure of 100 kPa means 100 kPa above atmospheric pressure). The pore water pressure is important because it affects not only the direction and speed of groundwater flow, but also the stability of the soil around or below an excavation (see Sections 1.2.4 and 1.2.5).

In fissured rock the same principles apply, but most of the groundwater that can move freely is contained in the fissures rather than in pores in the intact lumps of rock.

Excavations below the groundwater level are vulnerable to instability, erosion and flooding from the effects of groundwater (Figure 1.2), surface water and, in extreme cases, precipitation. This report is concerned with the protection of excavations below the water table from the effects of groundwater alone, and of groundwater and surface water acting in combination (eg where a stream or river acts as a source of recharge to the groundwater). This guide does not deal with the preventive measures used to protect excavations from the direct effects of surface water or precipitation.

1.2.2 Aquifers, aquicludes and aquitards

See also

1.2.4	Permeability
Box 6.3	Aquifers

Water can flow much more readily through the pores in coarse-grained soils (eg gravels and coarse sands) and fissures in rocks than through the pores in fine-grained soils (eg silts and clays). The ease with which water can flow through the pores of a soil or rock is expressed in terms of the permeability or hydraulic conductivity (Section 1.2.4).

Soils and rocks of high permeability whose voids are full of water are termed aquifers, while soils and rocks of such low permeability that they act as a seal are termed aquicludes. Strata of intermediate permeability, relative to aquifers and aquicludes, and which allow water to flow through them but only slowly, are termed aquitards. Usually, pumped well systems are used to control groundwater during temporary works in soils that are either aquifers or aquitards.

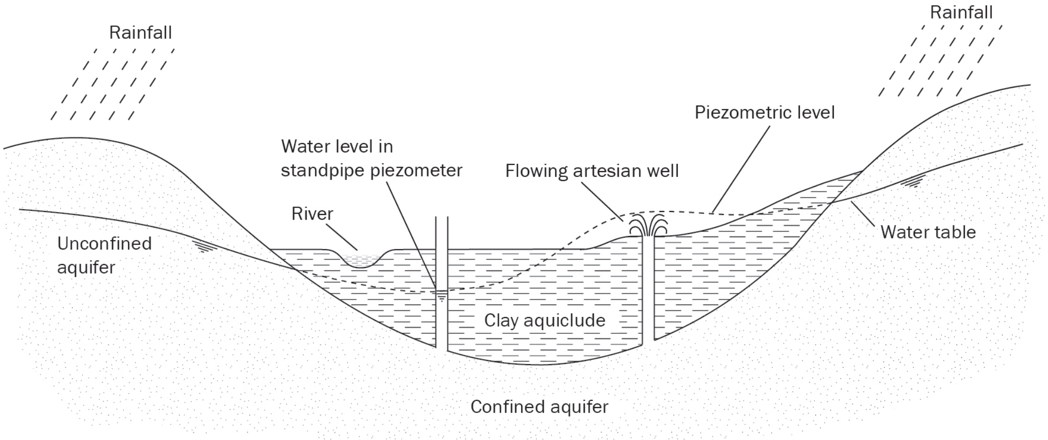
If the upper surface of an aquifer is exposed to the atmosphere, the aquifer is known as an unconfined or water table aquifer. If, on the other hand, the aquifer is fully saturated and overlain by a comparatively impermeable stratum or aquitard, the aquifer is described as confined. These terms are illustrated in Box 1.1 (see also Box 6.3).

1.2.3 Natural pore water pressures in the ground

The natural pore water pressures in the ground at a site depend on the ground conditions and the natural groundwater flow regime. The water table (or phreatic surface) may be defined as the level at which the pore water pressure (measured relative to atmospheric pressure) is zero. If the groundwater is at rest (or flowing horizontally through a uniform aquifer), the pore water pressures will be hydrostatic (Box 1.2).

Box 1.1 Non-hydrostatic groundwater conditions

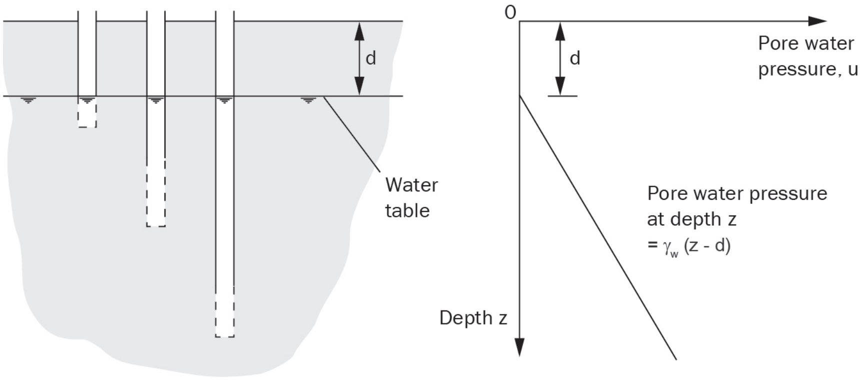
An aquifer overlain by a clay soil in a river valley is shown below. The aquifer extends beyond the edges of the clay, up into the surrounding hills. In the valley where the aquifer is overlain by the clay the aquifer is confined; in the hills where its surface is exposed to the atmosphere the aquifer is unconfined. The pore water pressures in the aquifer where it is confined in the valley can be high, because the pore water can flow relatively easily through the aquifer from the high hills while the clay acts as a seal. A standpipe driven through the clay may indicate a water level or piezometric level in the aquifer which is above the ground surface in the valley. If the standpipe is not tall enough it will overflow, bringing water from the aquifer to the surface. At the ground surface, the pore water pressure is zero. At the base of the clay layer, the pore water pressure is equal to the unit weight of water γ_w multiplied by the height to which the water rises in the standpipe (assuming that it is tall enough to prevent overflowing). The pore water pressures in the aquiclude are greater than they would be if the groundwater conditions were hydrostatic below a water table at the ground surface. Groundwater flows upward through the clay, but probably not more quickly than it can evaporate from the ground surface.



Cross-section through confined and unconfined aquifers with flowing artesian groundwater conditions

Box 1.2 Hydrostatic groundwater conditions

If the groundwater is at rest (or flowing horizontally through a single, uniform stratum), the pore water pressures will be hydrostatic below the water table; ie at a depth *z*, the pore water pressure (in kPa) will be equal to the unit weight of water γ_w (in kN/m^3) multiplied by the depth below the water table ($z-d$) (in m). In the vicinity of an excavation where pumping is being carried out or where there is a significant vertical flow of groundwater, the increase in pore water pressure with depth will not in general be hydrostatic.



Hydrostatic pore water pressure distribution

Non-hydrostatic conditions are usually associated with significant vertical groundwater flow. One example of this is when the pore water pressure in a confined aquifer is high enough to cause water to flow very slowly upward through the overlying aquiclude (Box 1.1). If a well is drilled through the aquiclude to the underlying aquifer, the well will overflow. Such a well is known as a flowing artesian well, and the conditions that cause it are termed artesian or flowing artesian.

In an unconfined aquifer, the pore water pressures above the water table can be negative, rather than positive. There is, however, a limit to the negative pore water pressure a soil can sustain without drawing in air (at atmospheric pressure) through any surface which is exposed to the atmosphere. This limiting negative pore water pressure is known as the air entry value, and increases as the soil pore size decreases. The consequence is that coarse soils above the water table (at which the pore water pressure is zero) will tend to be unsaturated, with very little water retained in the pores by capillary action. Fine-grained soils (ie silts and clays) may remain saturated for several metres above the water table, with pore water pressures continuing to decrease until the air entry value is reached (Figure 1.4).

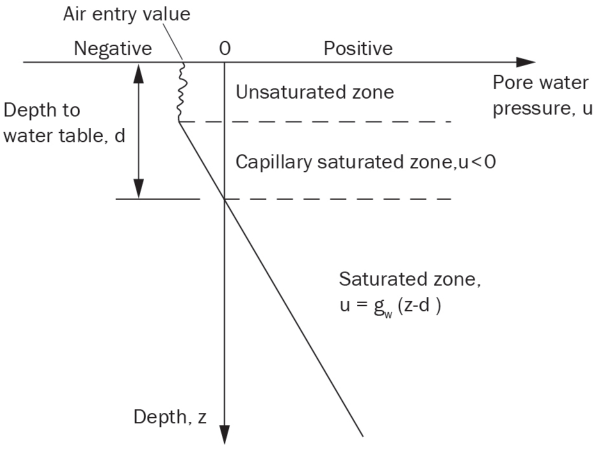


Figure 1.4 Pore water pressures in a fine-grained soil above the water table (groundwater at rest) (after Bolton, 1991)

1.2.4 Groundwater flow and permeability

If the pore water is at rest, the distribution of pore water pressure must be hydrostatic (Box 1.2). Conversely, any localised change in pore water pressure from the hydrostatic value will cause water to flow through the voids between the soil particles. Groundwater flow is driven by a difference in the total hydraulic head, which may be defined as the height to which water rises in a pipe, inserted with its tip at the point where the head is to be measured (Box 1.3). The total hydraulic head may be measured from any convenient datum, but once the datum level has been chosen for a particular situation, it should not be changed. The total hydraulic head is also known as the total head or the hydraulic potential.

In 1836 Robert Stephenson used pumped wells to lower groundwater levels, to enable the construction of the Kilsby tunnel on the London to Birmingham railway, in Northamptonshire (Preene, 2004). Stephenson observed that on pumping from one well, the water levels in adjacent wells dropped. He also recognised that the head difference between the wells was, for a given rate of pumping, an indication of the ease with which water could flow through the soil. In 1856 Henri Darcy, on the basis of a series of experiments carried out at Dijon in France, proposed what is now known as Darcy's Law, which describes the flow of groundwater through saturated soil (Box 1.3).

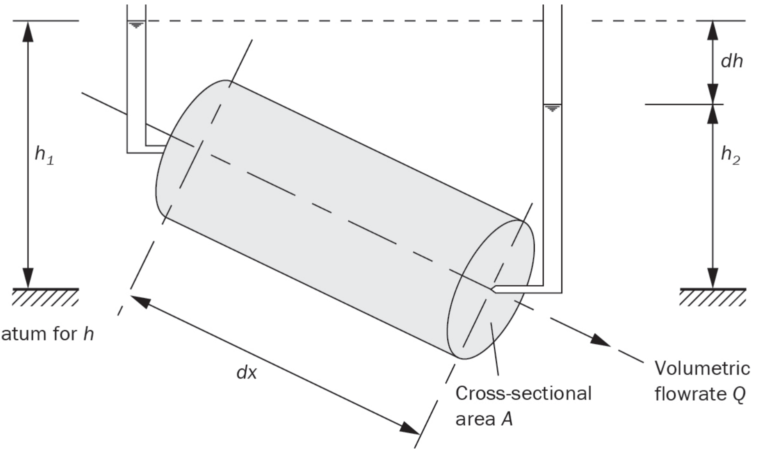
See also
5.3.5 Particle size analysis

The coefficient of permeability used in Darcy's Law is a measure of the ease with which water can flow through the voids between the soil particles, and depends on the properties of the permeant fluid as well as of the soil matrix. For uniform soils, Darcy's coefficient of permeability depends on a number of factors including the void size, the void ratio, the arrangement of particles and the viscosity of the pore fluid (which for water varies by a factor of about two between temperatures of 20°C and 60°C). These factors are discussed in detail by Loudon (1952). In a uniform soil the void size (which is related to particle size) is generally by far the most significant factor. Some empirical correlations between particle size and coefficient of permeability are given in Section 5.3.5.

In this report the term permeability, *k*, is used to mean the coefficient of permeability with water as the permeating fluid, as defined by Darcy's Law (the coefficient of permeability is sometimes also called the hydraulic conductivity).

Approximate permeability values for various types of soil are shown in Table 1.1. Note that the overall range is large and is reinforced by comparing the difference in permeability between gravels and clays (a factor of perhaps 10^{10}) with the difference in shear strength between high tensile steel and soft clay (about 10^5).

Box 1.3 Darcy's Law



Darcy's experiment

Darcy's Law is expressed mathematically as:

$$Q = Aki \tag{1.1}$$

where

Q (m^3/s) is the volumetric flow rate of water

A (m^2) is the cross-sectional area of flow

i is the rate of decrease of total hydraulic head (potential) h with distance in the direction of the flow (x), $-dh/dx$, termed the hydraulic gradient

k (m/s) is a soil parameter known as the coefficient of permeability or the saturated hydraulic conductivity

Note

The negative sign in the definition of the hydraulic gradient is mathematically necessary because the flow is always in the direction of decreasing head. If dh/dx is positive, the flow rate will be in the negative x direction. If dh/dx is negative, the flow rate will be in the positive x direction.

The main condition required for Darcy's Law to be valid is that groundwater flow should be laminar, rather than turbulent. In soils which have a particle size larger than a coarse gravel, groundwater velocities may be large enough for turbulent flow. In most other geotechnical applications, flow will be laminar. It is normally assumed that the soil is saturated. The permeability of an unsaturated or a partly saturated soil is an altogether different matter. Surface tension effects offer considerable resistance to flow, so that when a soil becomes unsaturated its permeability will fall by perhaps three orders of magnitude. These effects are discussed by McWhorter (1985).

See also

5.3	Permeability testing
6.1.3	Permeability selection

Many analytical methods assume that the ground can be assigned a single value of permeability, which is the same in all directions and does not vary from point to point. In reality, the permeability is likely to be different in the vertical and horizontal directions as a result of deposition-induced anisotropy or layering, and to vary significantly because of heterogeneities such as fissures, sand lenses etc (see Sections 5.3 and 6.1.3). The influence of soil fabric and structure on permeability is discussed by Rowe (1972). The permeability of a confined aquifer k is sometimes multiplied by the saturated thickness of the aquifer D to give a parameter known as the aquifer transmissivity, T.

Table 1.1 Permeabilities of typical soils

Indicative soil type	Degree of permeability	Permeability m/s
Clean gravels	High	$>1 \times 10^{-3}$
Sand and gravel mixtures	Medium	1×10^{-3} to 1×10^{-5}
Very fine sands, silty sands	Low	1×10^{-4} to 1×10^{-7}
Silt and interlaminated silt/sand/clays	Very low	1×10^{-6} to 1×10^{-9}
Intact clays	Practically impermeable	$<1 \times 10^{-9}$

1.2.5 Groundwater and stability

A saturated soil comprises two phases, the soil particles and the pore water. The strengths of these two phases, in terms of their ability to withstand shear stresses, are very different. The shear strength of water is negligible. The only form of stress that static water can sustain is an isotropic pressure, which is the same in all three principal directions. The soil skeleton, however, can resist shear – mainly because of interparticle friction. The frictional nature of the strength of the soil skeleton means that the higher the normal stress pushing the particles together, the greater the shear stress that can be applied before slip between particles starts to occur.

Because the strengths of the soil skeleton and the pore water are so different, it is necessary to consider the stresses acting on each phase separately. This is achieved by applying the principle of effective stress proposed by Terzaghi in 1936 (Box 1.4).

Box 1.4 The principle of effective stress

The effective normal stress σ' is the stress carried by the soil skeleton (the soil particles), which controls the volume and strength of the soil. For saturated soils, the effective stress may be calculated from the total normal stress σ and the pore water pressure u by Terzaghi's equation:

$$\sigma' = \sigma - u \tag{1.2}$$

As the pore water cannot take shear, all shear stresses must be carried by the soil skeleton.

It is shown in the remainder of this section that pore water pressures have a crucial influence on the stability of the base and sides of an excavation.

Base stability

A common objective of groundwater control is to maintain the stability of the base and possibly the sides of an excavation. The base of an excavation in a uniform soil will become unstable if the pore water pressure is close to the vertical total stress (due to the weight of the soil), so that the vertical effective stress approaches zero. This condition is known as fluidisation or boiling – quicksand if it occurs over a large area; and piping if it occurs in localised channels.

By considering the forces acting on a block of soil which is on the verge of uplift, it can be shown (see Powrie, 2013) that fluidisation will occur in regions of upward flow in a soil of uniform permeability when the upward hydraulic gradient exceeds a critical value, i_{crit}:

$$i_{crit} = (\gamma_s - \gamma_w)/\gamma_w \tag{1.3}$$

where γ_s is the unit weight of the soil, and γ_w is the unit weight of water (Figure 1.8). For soils with $\gamma_s = 20$ kN/m$^3 \approx 2\gamma_w$, then $i_{crit} \approx 1$. The maximum upward hydraulic gradient below the floor of an excavation should not normally exceed i_{crit} .

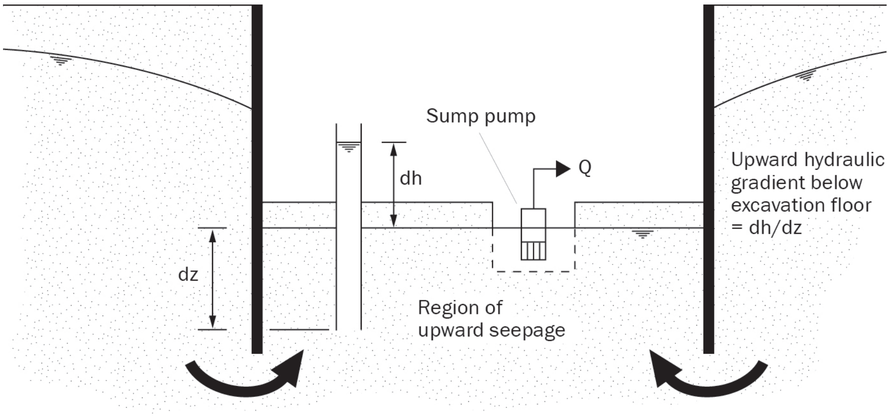


Figure 1.5 Upward hydraulic gradient for base instability: excavation in a uniform soil

See also
Box 5.1 Base heave

Basal failure or base heave may occur where an excavation is made into a stratum of low permeability soil overlying a confined aquifer (Figure 1.6). Instability is a risk when the upthrust (from the pore water pressure in the confined aquifer) on the base of a plug of the low permeability soil becomes equal to the weight of the soil plug, plus any shear stresses on its sides (see also Hartwell and Nisbet, 1987). A case history illustrating the conditions leading to, and the consequences of, the failure of the base of an excavation is given in Box 1.5 (see also Box 5.1). Instability can be avoided by reducing the pore water pressures in the confined aquifer.

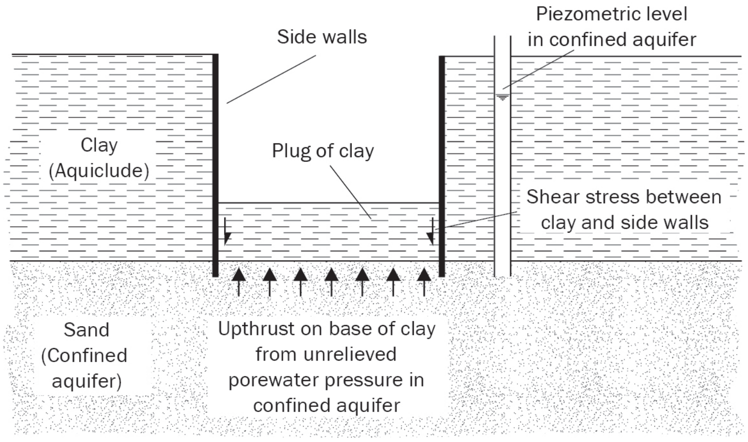


Figure 1.6 Base failure: excavation in a low permeability soil overlying a confined aquifer