

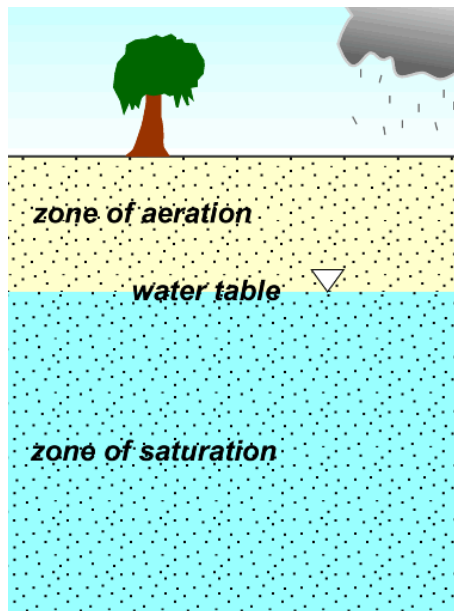
Lecture 8

Soil Water

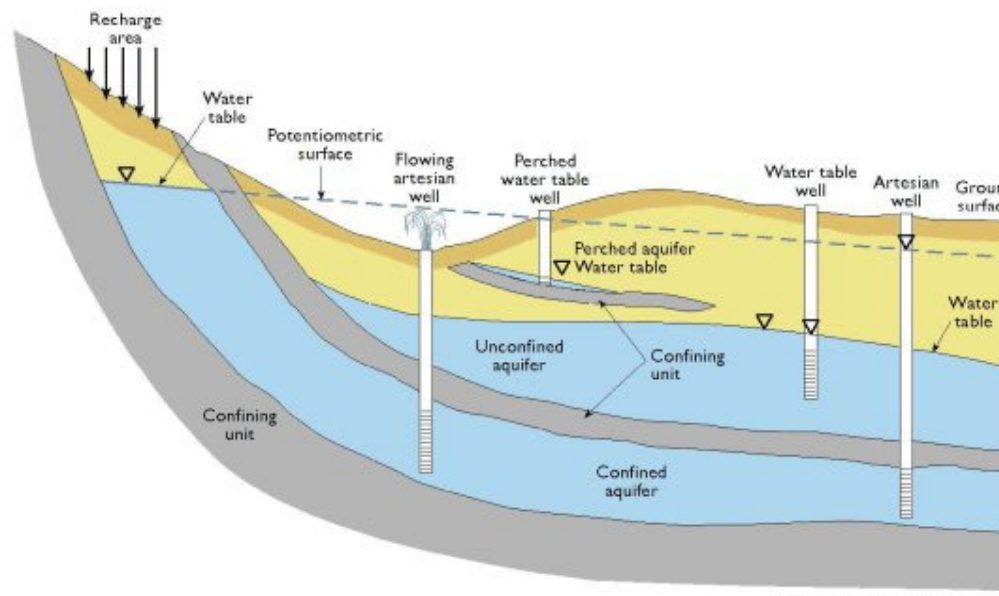
Text: Das, Chapter 7.

Subsurface water is found at all depths down to around 12,000 m below the Earth's surface. Below that depth, all voids are filled by the plastic flow of rocks under great pressure.

Soil mechanics is concerned with moisture much closer to the surface. In this region there are two zones, the *saturated zone* and the *unsaturated or aerated zone*.



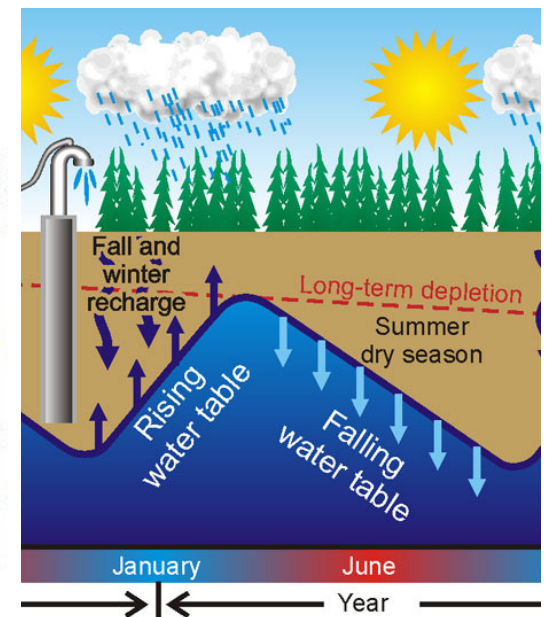
<http://myweb.cwpost.liu.edu/vdivener/notes/groundwater.htm>



<http://geosurvey.state.co.us/apps/wateratlas/downloads.asp>

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http://www.indywatersolutions.com/index_files/Page911.htm



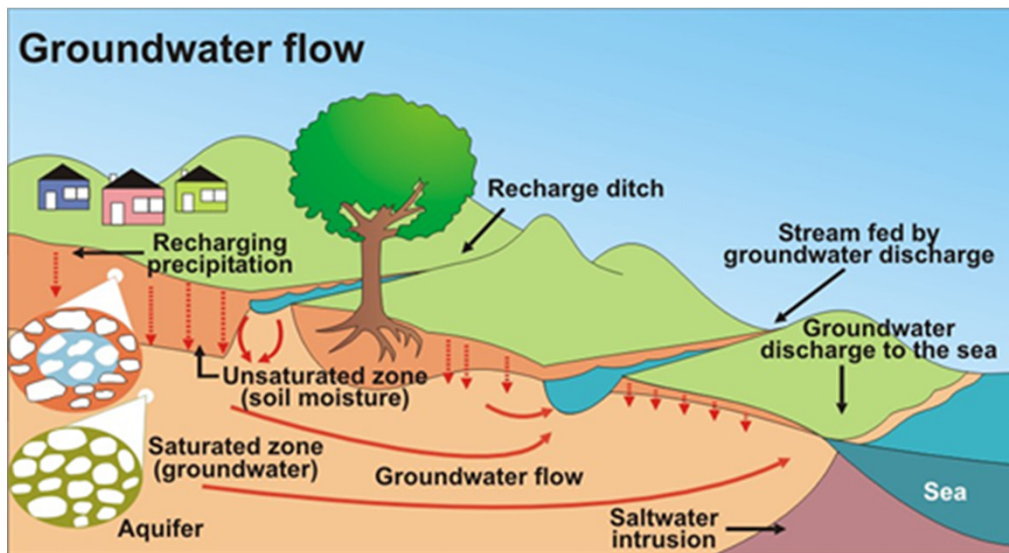
Saturated Zone: Ground Water

In the saturated zone, all the voids and fissures are filled with water under hydrostatic pressure, whereas above it the voids contain water and air.

The water table or phreatic surface divides the two zones. The water along this line is at atmospheric pressure.

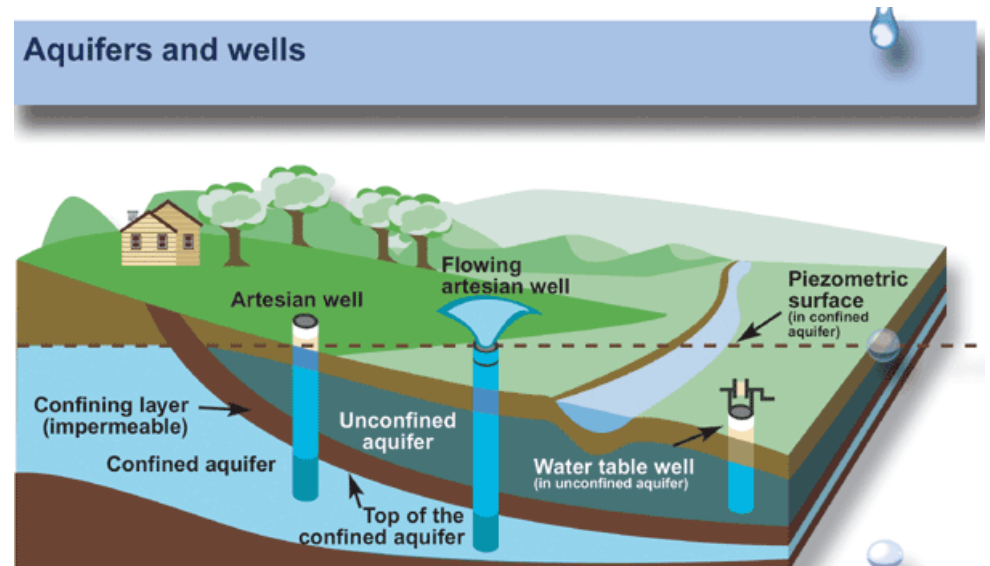
Generally if you dig a hole in the ground the water level in the hole defines the phreatic surface. The water table can vary seasonably with rainfall or with irrigation activity.

Where it breaks the ground surface, swamps, lakes and springs occur.



Environment Canada

http://www.atsdr.cdc.gov/sites/oakridge/contaminated_groundwater.html



Source: Environment Canada.

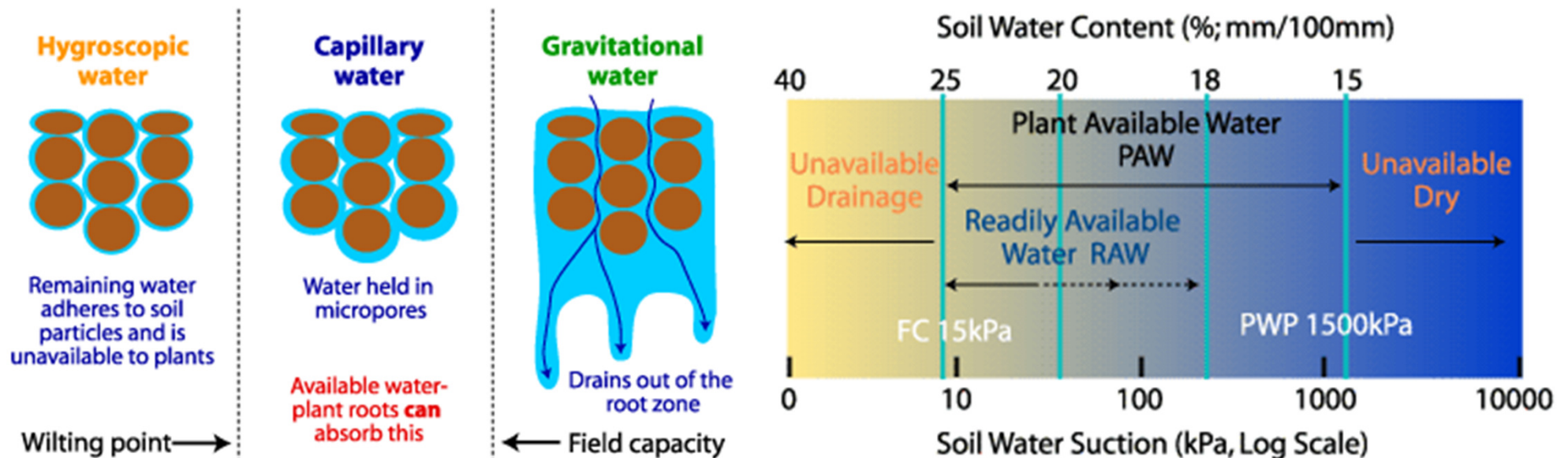
<http://ga.water.usgs.gov/edu/earthgw/aquifer.html>

Unsaturated Zone: Soil Water

In the unsaturated zone, water is bound to soil particles by a variety of physical and electrochemical forces. It takes energy to extract this water.

Conditions in the aerated zone depend on climate and biology, particularly recent rainfall, temperature and humidity and the growth activity of plants.

Depending on the degree of saturation, water may be held predominantly by hygroscopic interaction with soil minerals, or by the capillary action of free surfaces, or as both static and dynamic storage within the void spaces.

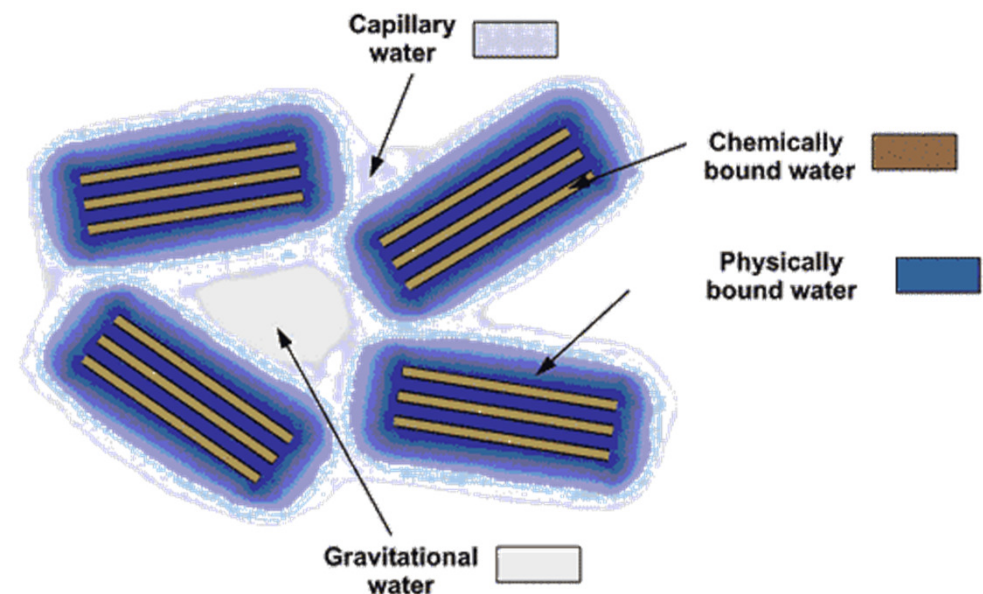
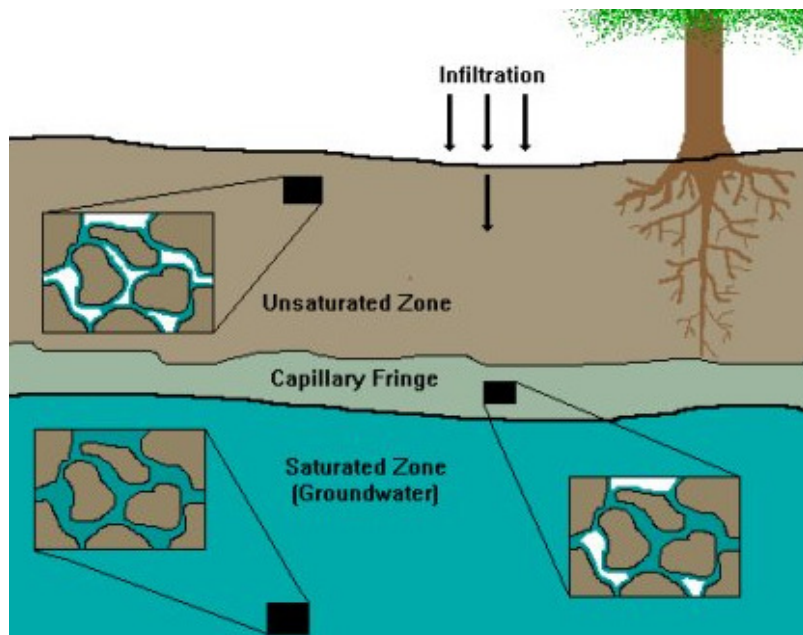


Capillary Water

Soil water at useful engineering levels of saturation is mainly bound by capillary forces. Higher levels of saturation are too wet, lower levels too dry.

The capillary fringe occurs due to surface tension in the void spaces above the water table. The smaller the particle size, and hence voids, the higher the capillary fringe will be.

Water in the capillary zone is held at a negative or suction pressure. In clays, molecular forces hold moisture even more tightly than capillary forces can exert. In silt soils the capillary fringe may exceed 2 m in depth.



Soil Water Potential

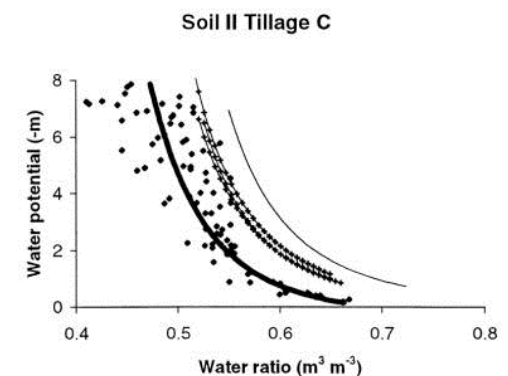
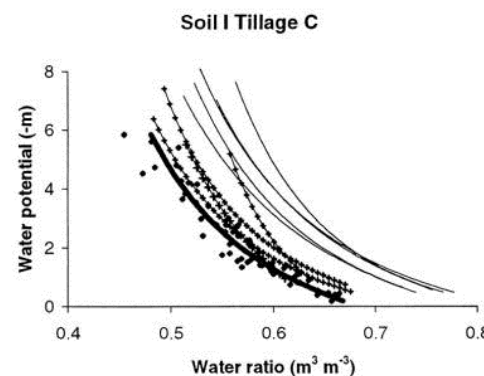
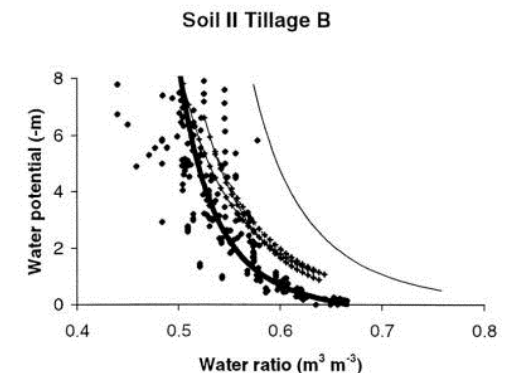
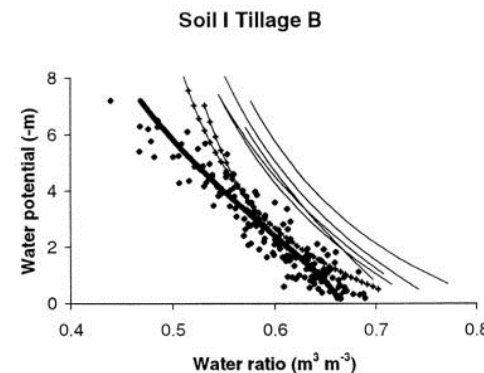
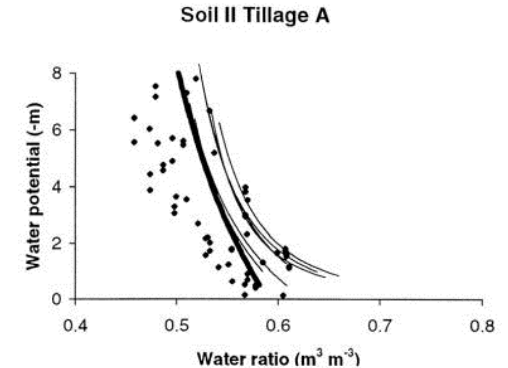
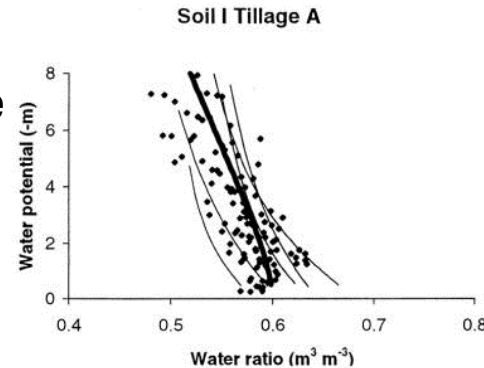
Water potential is similar to Bernoulli's principle in fluid mechanics.

Potential is measured in terms of total head (H), which is energy per weight of water. In soil there is effectively zero velocity head, but the head due to capillary and osmotic forces can be very large.

Soil water potential consists of three components: the *matric potential* h due to capillary forces, the *osmotic potential* o due to ions dissolved in the water, and the more familiar *gravitational potential* z due to elevation or depth.

In unsaturated soils, the matric potential is the largest. In saturated soils, h is close to zero while z is large.

$$H = h + o + z$$



Potential Tensionometry

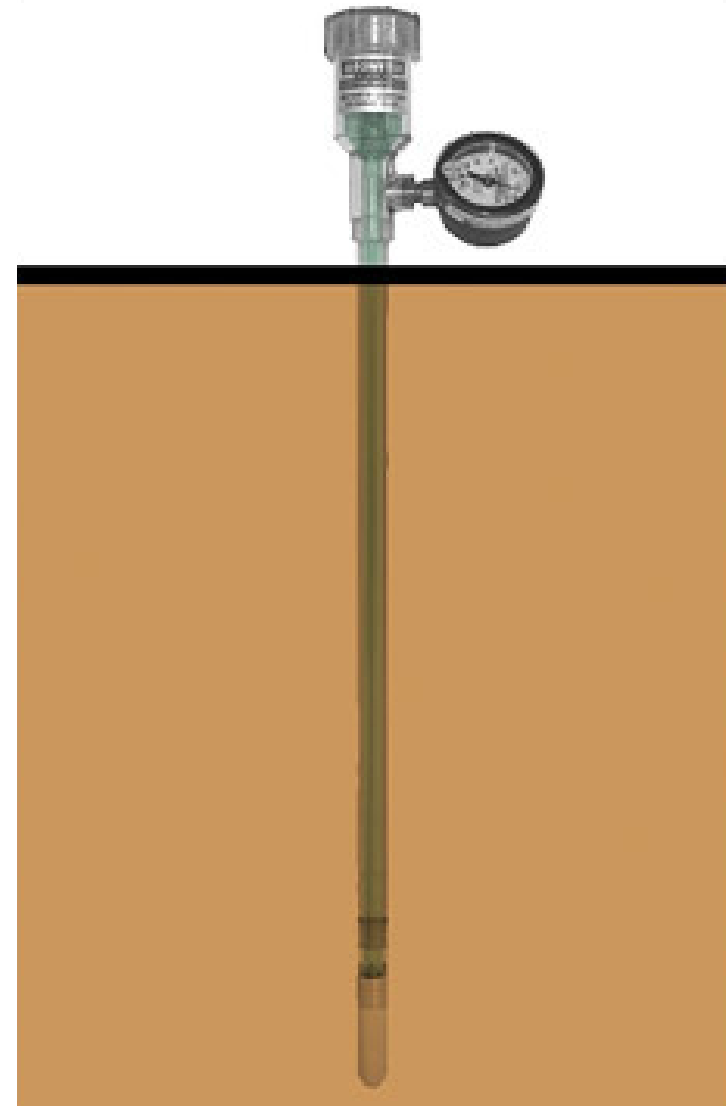
Water potential can be measured in the field by a *Tensionometer*.

A tensiometer consists of a vacuum gauge connected by a tube to a porous ceramic tip.

The tube is filled with water and is normally transparent (made of plexiglass) so the water level within it can easily be seen. The ceramic tip is permeable, and the water in the tube saturates it.

The tip is placed in contact with the soil in the root zone. Because the soil is normally not saturated, water is drawn from the tip into the soil.

As water moves from the tube into the soil, a partial vacuum is created and measured by the gauge. This measurement is not a direct measurement of soil water content. Rather, it is a measurement of soil water tension



Saturated Zone: Hydrostatic Potential

In the saturated zone the soil water potential is dominated by gravity, ie water under ordinary hydrostatic pressure.

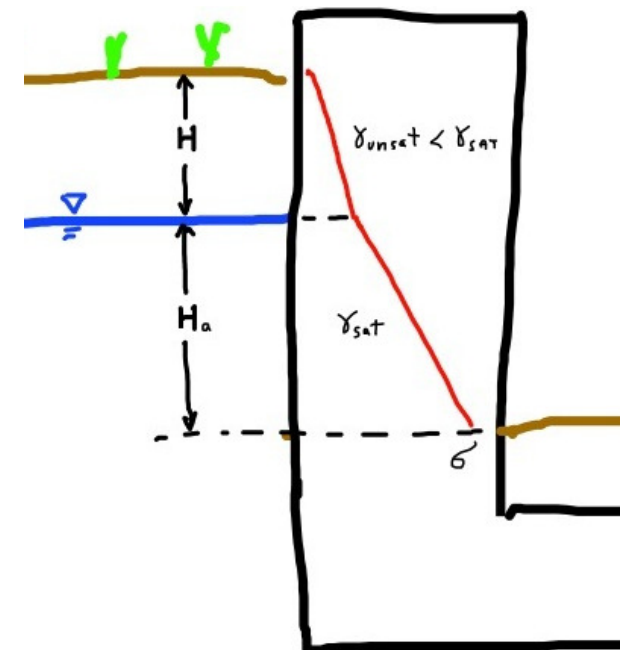
Pore water pressure in the saturated zone is the same as in a body of free water:

$$P = \rho g H_a = \gamma_w H_a$$

Where H_a is the depth below the water table. This pressure contributes to the total pressure σ exerted by the weights of saturated and unsaturated soil:

$$\sigma = \gamma_{unsat} H + \gamma_{sat} H_a$$

where H is the depth *above* the water table. γ_{sat} includes the density of soil and water. σ is thus the total pressure exerted on a supporting structure such as a retaining wall.



Saturated Zone: Effective Stress

As well as loads on supporting structures, it is often essential to know the pressure that a soil mass exerts on itself. This requires the idea of *effective stress*.

As with any submerged object, saturated soil particles are supported by buoyancy. The effective weight of each particle is reduced by its displaced volume of water:

$$W = \gamma_s V - \gamma_w V = (\gamma_s - \gamma_w) V$$

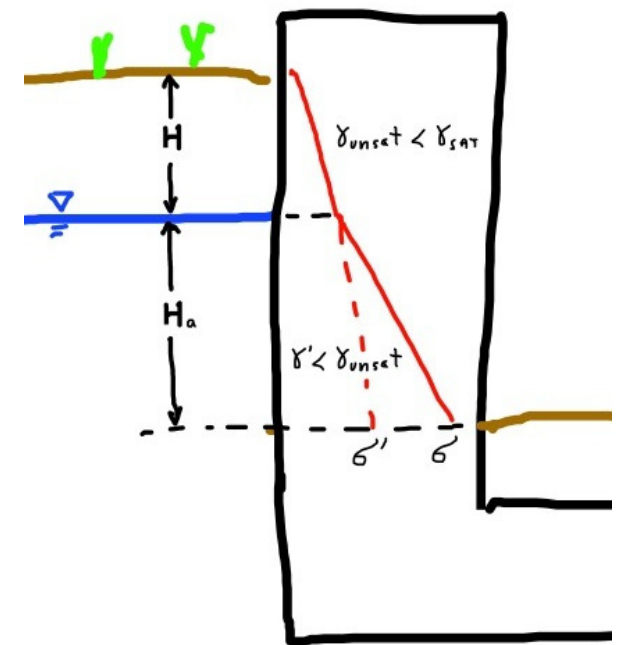
The effective pressure that soil particles exert on each other is thus reduced by the same factor:

$$\sigma' = \sigma - P = \gamma_{unsat} H + \gamma_{sat} H_a - \gamma_w H_a$$

$$= \gamma_{unsat} H + (\gamma_{sat} - \gamma_w) H_a$$

σ' is referred to as the *effective stress*. γ' is the *effective unit weight*.

Bearing pressures on the soil itself are determined by the effective stress, while structural pressures on any other element are given by the total stress σ .



Saturated Zone: Effective Stress

The bulk, saturated and effective unit weights of soil can be compared by the formulas developed in an earlier lecture:

Saturated soil:

$$\gamma_{sat} = \gamma_w \frac{G + e}{1 + e}$$

Unsaturated (bulk) soil:

$$\gamma_b = G \gamma_w \frac{1 + w}{1 + e} = \gamma_w \frac{G + Se}{1 + e} < \gamma_{sat} \text{ as } S < 1$$

Effective (buoyant) soil:

$$\begin{aligned} \gamma' &= \gamma_{sat} - \gamma_w = \gamma_w \left(\frac{G + e}{1 + e} - 1 \right) \\ &= \gamma_w \left(\frac{G - 1}{1 + e} \right) < \gamma_b \end{aligned}$$

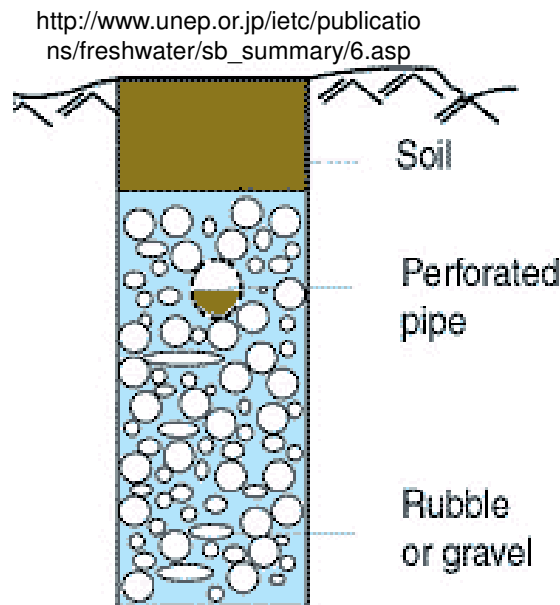
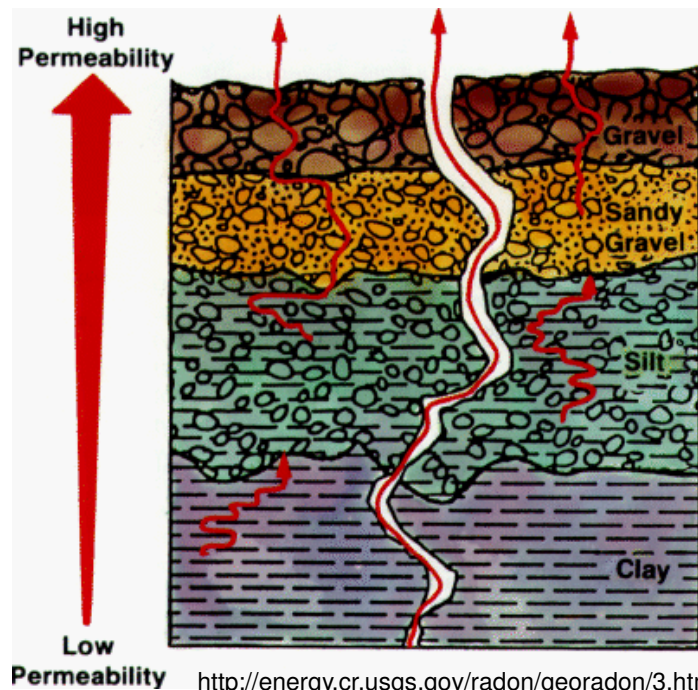
These formulas are used to calculate pressures of different kinds on structures and soil foundations. This is used not only in structural loading but in soil loading for consolidation and compaction, both of which depend on contact pressures between soil particles.

Permeability

Text: Das, 2010. Principles of Geotechnical Engineering Ch 7

Soils are permeable due to the existence of interconnected voids through which water can flow from points of high energy to points of low energy.

The study of the flow of water through permeable soil media is necessary for estimating the quantity of underground seepage under various hydraulic conditions, for investigating problems involving the pumping of water for underground construction, and for stability analysis of earth dams and earth retaining structures that are subject to seepage forces.



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<http://www.wrl.unsw.edu.au/site/2012/01/three-phd-research-scholarships-available/>

Groundwater Flow

Bernoulli equation and headloss

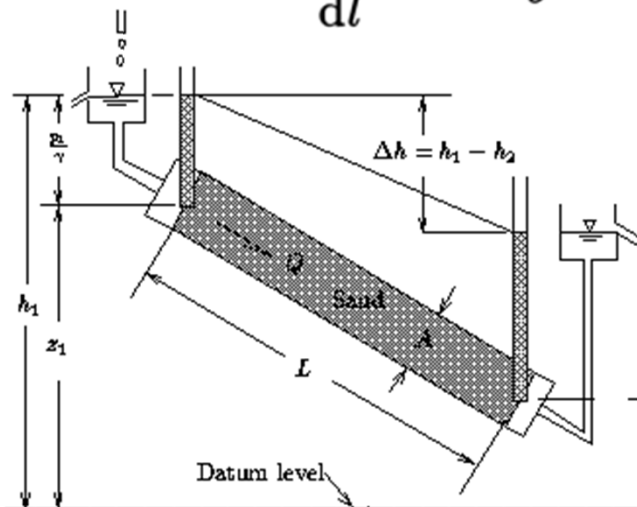
Bernoulli's equation is of limited use in groundwater flow. The total head is not constant, due to high friction losses in pores and capillary pathways.

However, a soil strata of constant porosity characteristics will show a constant rate of headloss or *hydraulic gradient*.

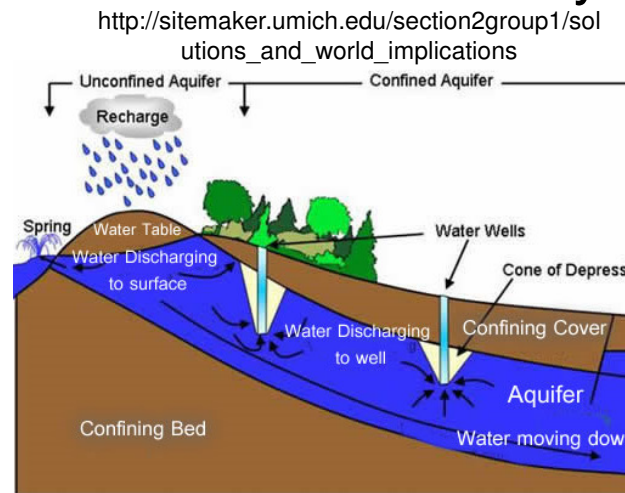
$$h = \frac{P}{\rho g} + Z = Z \text{ at the water table surface}$$

$$\frac{dh}{dl} = i \text{ hydraulic gradient}$$

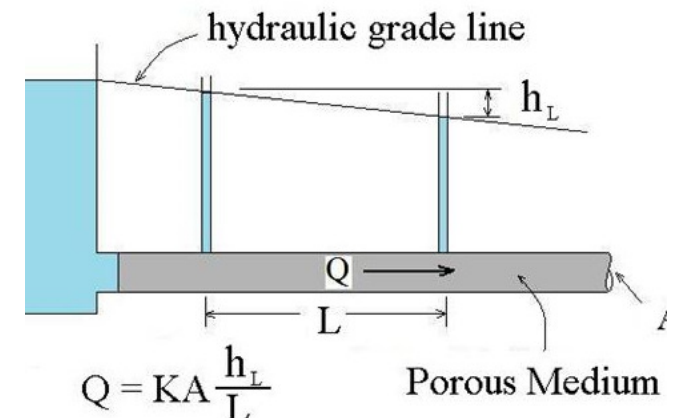
Measurement of variations in water table (eg by observation wells) enables measurement of the hydraulic gradient.



http://www.interpore.org.chopin.ch-meta.net/ref-mat_pub/agwh-course/agwh_darcy.html



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<http://www.brighthubengineering.com/hydraulics-civil-engineering/58490-darcys-law-for-modeling-groundwater-flow/>

Groundwater Flow

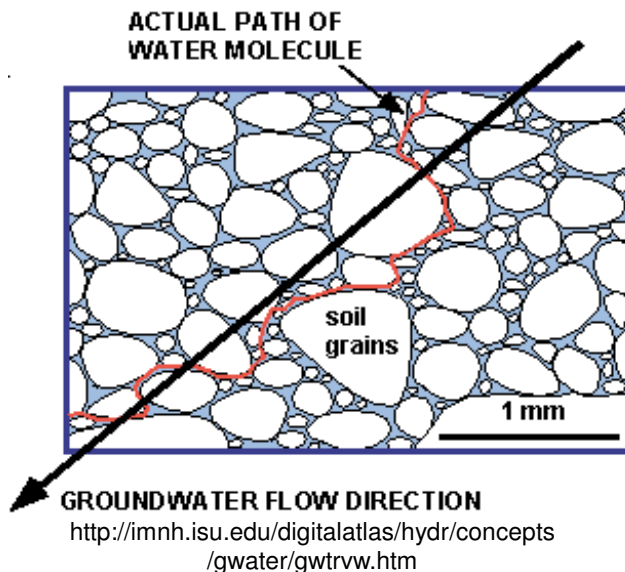
Darcy's Law

Still considering only soils with constant porosity characteristics, we can define the *hydraulic conductivity* k of a soil in terms of a constant hydraulic gradient i :

$$v = ki = -k \frac{dh}{dx}$$

The minus sign gives a +ve velocity for decreasing head, ie -ve hydraulic gradient.

v is the *discharge velocity*, defined as the average flow velocity in the direction of groundwater flow. This is less than actual flow velocities, which take long random pathways through the pore space while moving in any overall direction.



The discharge velocity is measured by the discharge and area across the flow:
 $v = Q/A$

The true or *seepage velocity* is related to the porosity and the discharge velocity: $v_s = v/n$

Groundwater Flow

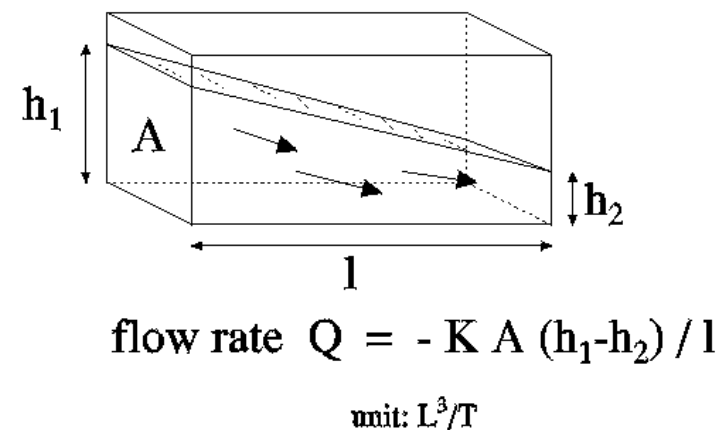
Darcy's Law

Given the hydraulic conductivity k (a property of each distinct soil stratum) and a known head difference H over a flow path length L , the flow rate through a unit area of soil can be estimated:

$$Q = kA \frac{H}{L} = k \frac{H}{L} \quad (\text{for } A = 1)$$

k has the units of velocity, since the hydraulic gradient is dimensionless. Hydraulic conductivity varies over a wide range for different soil types:

Soil Type	k cm/sec
Clean gravel	100-1.0
Coarse sand	1.0-0.01
Fine Sand	0.01-0.001
Silty clay	0.001-0.00001
Clay	<0.00001

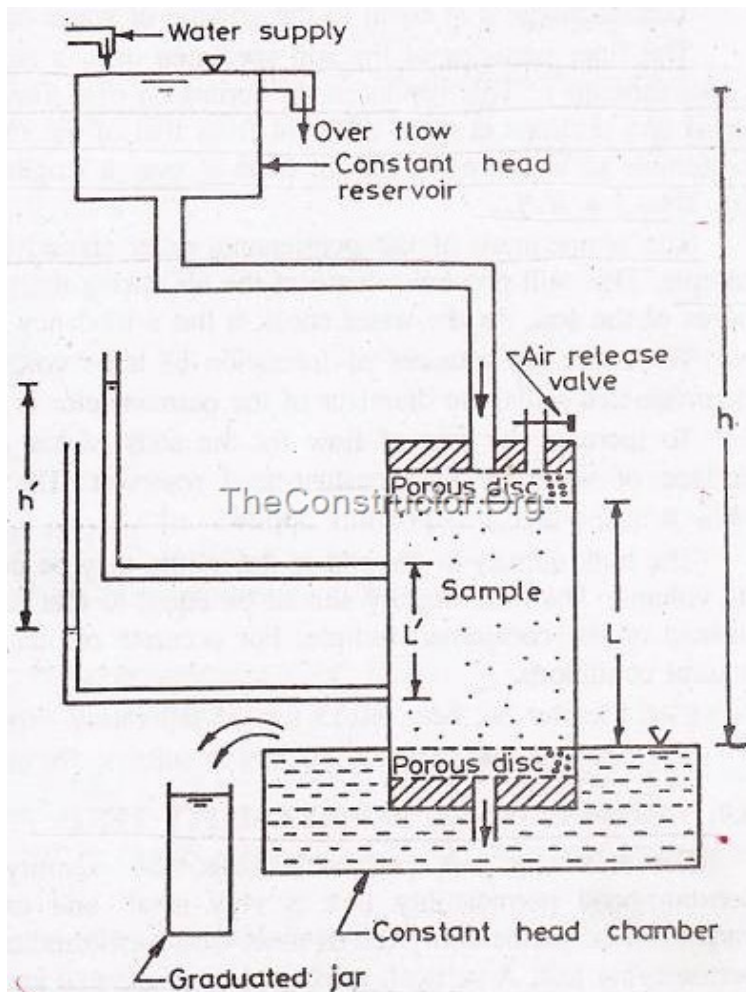


"The velocity of flow is proportional to the hydraulic gradient"

Hydraulic Conductivity

Constant Head Permeameter

Hydraulic conductivity is measured by direct tests of flow rate for an observed head loss over a known path length. If the head difference is kept constant the measurement is known as a *constant head permeameter* test.



1. Flow is established with constant head and flowrate.

2. A volume V of water is collected over a measured interval t

3. Flowrate $Q = V/t = Avt = A(k_i)t = Ak(h'/L')t$

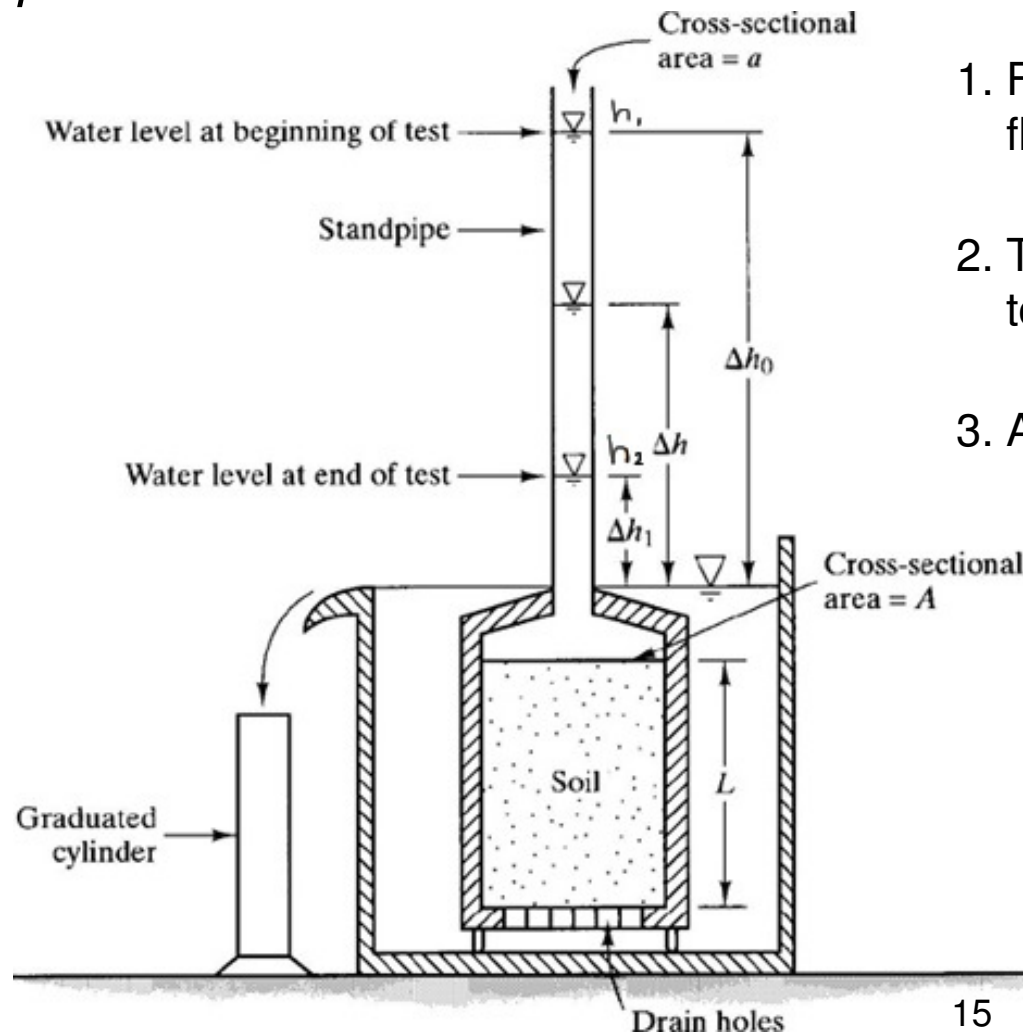
4. thus
$$k = \frac{VL'}{Ah't^2} = \frac{QL'}{Ah't}$$

A is the cross sectional area of the flow chamber

Hydraulic Conductivity

Falling Head Permeameter

An alternative arrangement tests for conductivity over a range of hydraulic gradients by allowing the head to fall as flow occurs, ie a *falling head permeameter* which drains over a finite interval:



1. Flow is established with constant head and flowrate.
2. The inflow is halted and the standpipe allowed to fall from h_1 to h_2 over time Δt .
3. At any time the flowrate Q is:

$$Q = a \frac{dh}{dt} = kA \frac{-\Delta h}{L}$$

$$\text{or } dt = \frac{aL}{Ak} \frac{-dh}{h}$$

the -ve sign accounts for the falling head

$$\text{integrating, } t = \frac{aL}{Ak} \ln \left(\frac{h_1}{h_2} \right)$$

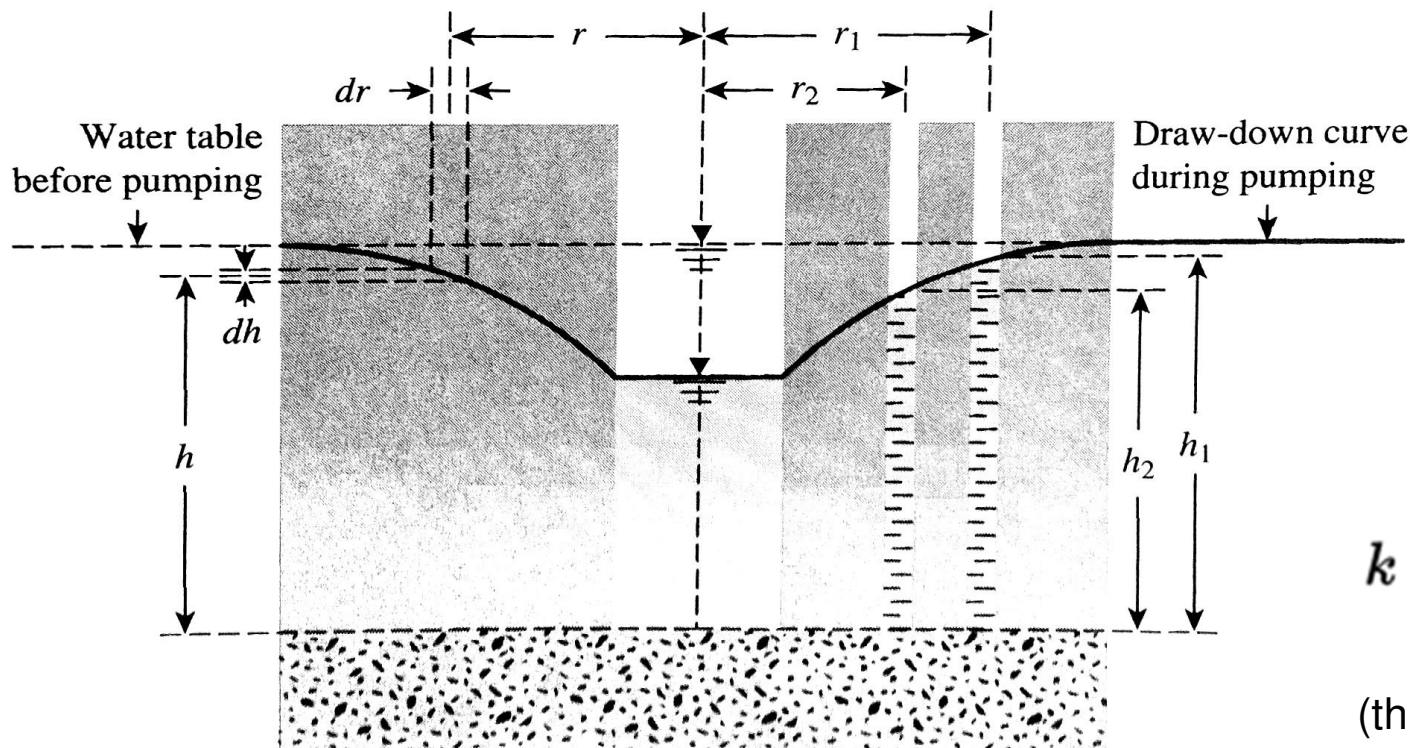
$$\text{or } k = \frac{aL}{At} \ln \left(\frac{h_1}{h_2} \right)$$

Hydraulic Conductivity

Pumping Test

It may be possible to test soil permeability directly in the field, with all local details of variability accounted for, by a pumping test.

This requires that the water table be accessible by pump wells:



 Impermeable layer
  Test well
  Observation wells

1. Pump flow is established with constant head and flowrate.

2. The head at two observation wells r_1 and r_2 are recorded.

3. The conductivity k is proportional to the flowrate:

$$k = \frac{Q \ln \left(\frac{r_1}{r_2} \right)}{\pi (h_1^2 - h_2^2)}$$

(this theory depends on aquifer stratification, see more examples in the text)

Hydraulic Conductivity

Ranges and indications of k

Soils can be classified to a limited extent by hydraulic conductivity. The classification system below uses pore size as a classification correlated with drainage and soil type. The range of suitable test methods is also indicated.

K (m/s)	1	10 ⁻²	10 ⁻⁴	10 ⁻⁶	10 ⁻⁸	10 ⁻¹⁰
Drainage	good		moderate	bad		
Classification	large	moderate	small	very small	impervious	
Soil type	gravel	clean sand		silt, clayey sand		clay
Direct test	pumping test					
		dipool sounding				
	constant head					
		falling head				(oedometer)
Indirect test					piezocone	
				oedometer		
Correlation	grainsize distribution / density			density	index of clay	

<http://geo.citg.tudelft.nl/~uffink/syllabusCT3320/part1/0a/0a.html>

A pumping test is conducted in the field using exploration well-drilling equipment or similar. Other indirect tests are available at the geotechnical specialist level.

Hydraulic Conductivity

Empirical and theoretical models

There are any number of models and theoretical estimates of k as a function of soil and water parameters such as porosity and viscosity.

These tend to be less than useful, as in practice individual soils do not match those parameterised in research. Conductivity is very sensitive to local details of soil formation.

This is not a problem however as a direct measurement of k is usually possible. Serious geotechnical work would not proceed without such tests.

$-\log K$ (cm/sec)	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11
Permeability	Pervious				Semipervious				Impervious					
Aquifer	Good				Poor				None					
Soil	Clean gravel	Clean sand or sand & gravel				Very fine sand, silt loess, loam, solonetz								
					Peat		Stratified clay		Unweathered clay					
Rocks					Oil rocks Sandstone				Good limestone dolomite		Breccia granite			

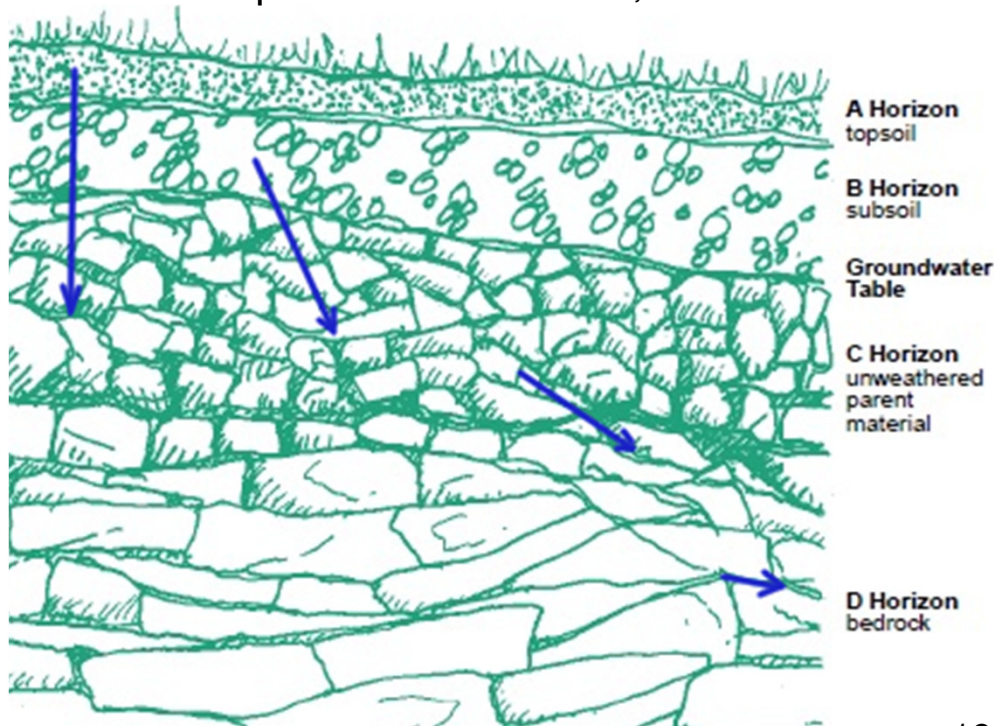
Hydraulic Conductivity

Homogeneity and Isotropy

A *homogenous* soil has a roughly constant value of hydraulic conductivity at all locations and depths in the profile and plan area of interest. This is very rare and cannot be assumed.

An *isotropic* soil has the same value of k in any direction from the point of measurement. This also is rare; most soils are anisotropic in horizontal and vertical directions due to orientations of structure.

Individual soil strata may be approximately homogenous, but drainage lines cross any number of strata at different depths. Over all strata, most soils are both *inhomogenous* and *anisotropic*.



Soil profile with typical stratified discharge velocity vectors. Conductivity decreases with depth as compaction and the proportion of native rock both increase.

Preferred flow directions vary from vertical to horizontal due to both the hydraulic gradient and the ratio of vertical to horizontal conductivity.

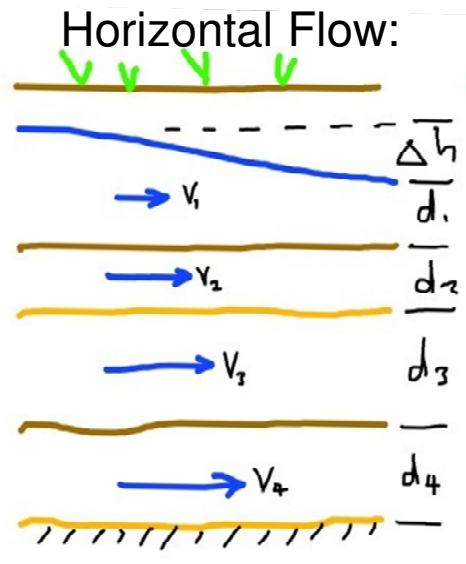
A Horizon soils have a dominant vertical flow due to vertical drying cracks and the vertical structure of macropores. C horizons tends to horizontal flow due to strata fracturing and the underlying impervious bedrock.

Hydraulic Conductivity

Anisotropic Soils

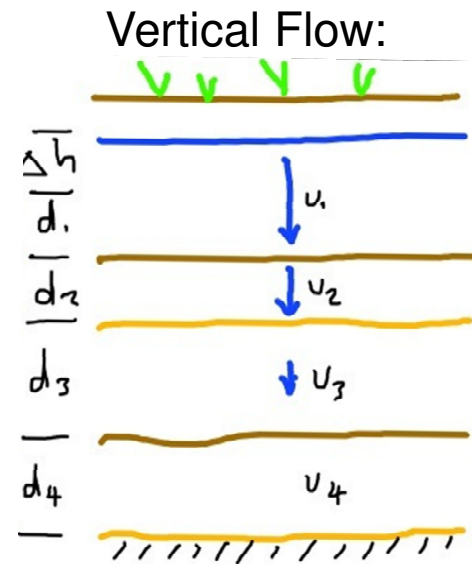
Calculations of flow across or along stratification layers can be simplified by combination formulas for *average* vertical and horizontal conductivities.

These weighted averages are analogous to electrical resistance in parallel or series. The average horizontal and vertical conductivities k_h and k_v can be estimated as:



$$Q = \sum Q_i = \sum k_i d_i \frac{dh}{dl} = k_h \frac{dh}{dl} \sum d_i$$

$$\text{so } k_h = \frac{\sum k_i d_i}{\sum d_i}$$



$$\Delta h = \sum \frac{v_i d_i}{k_i} = \frac{\bar{v}}{k_v} \sum d_i$$

$$\text{but } \bar{v} = \sum \frac{v_i d_i}{d_i} \text{ so } k_v = \frac{\sum d_i}{\sum \frac{d_i}{k_i}}$$

Hydraulic Conductivity

Example

A soil profile has the following strata:

$$d_A = 400 \text{ mm} \quad k_{hA} = 0.004 \text{ cm/s} \quad k_{vA} = 0.009 \text{ cm/s}$$

$$d_B = 700 \text{ mm} \quad k_{hB} = 0.007 \text{ cm/s} \quad k_{vB} = 0.005 \text{ cm/s}$$

$$d_C = 900 \text{ mm} \quad k_{hC} = 0.009 \text{ cm/s} \quad k_{vC} = 0.001 \text{ cm/s}$$

Calculate average horizontal and vertical hydraulic conductivities.

$$k_h = \frac{\sum k_i d_i}{\sum d_i}$$

$$k_v = \frac{\sum d_i}{\sum (d_i / k_i)}$$



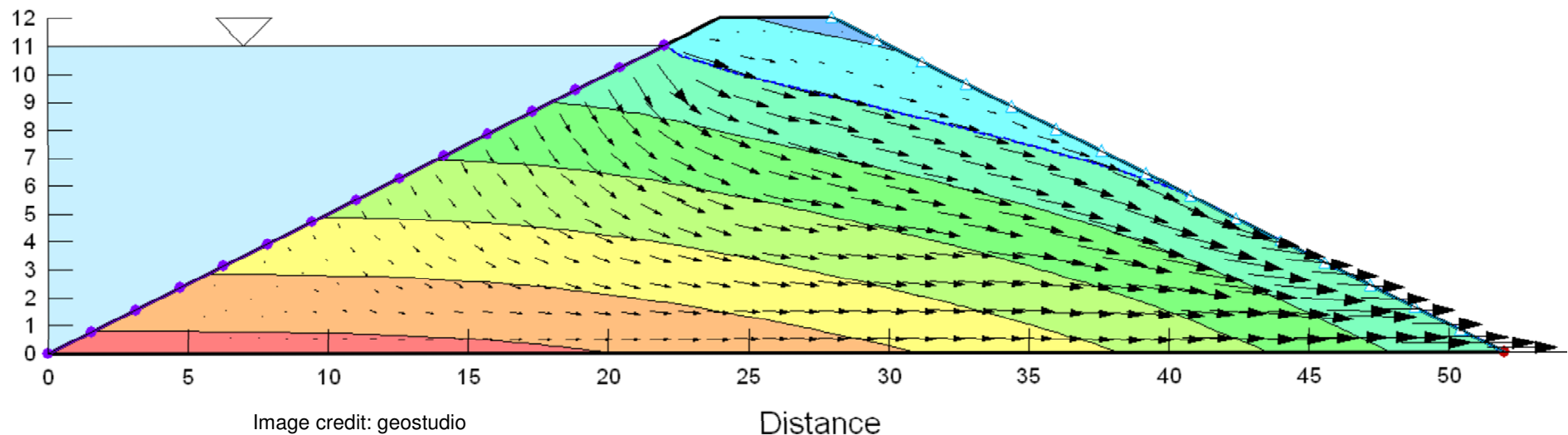
Hydraulic Conductivity

Computer Programs

Hydraulic conductivity design and analysis gets much more complex than this.

Modern geotechnical engineering makes heavy use of computer power to analyse even routine flow paths for stability.

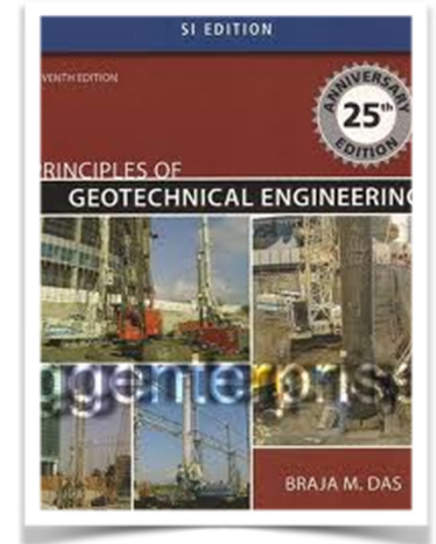
ENGT350 will make use of the student edition of Geoslope; reasonably advanced geotechnical software for seepage, slope stability and other problems.



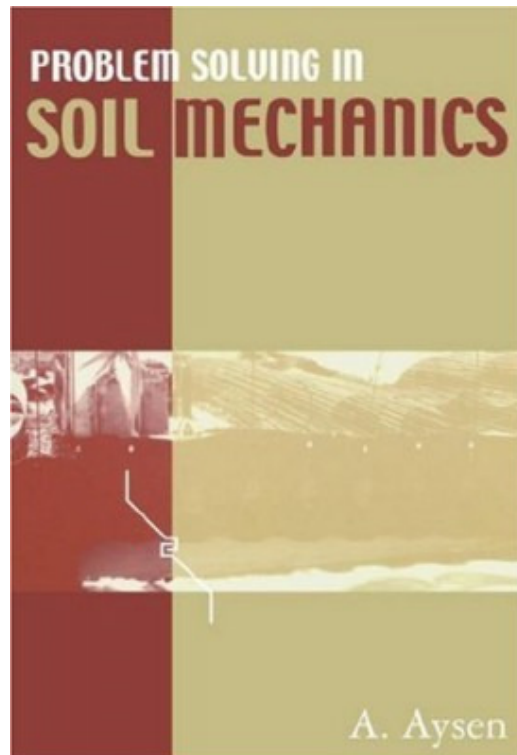
Readings

Chapter 7, Das.

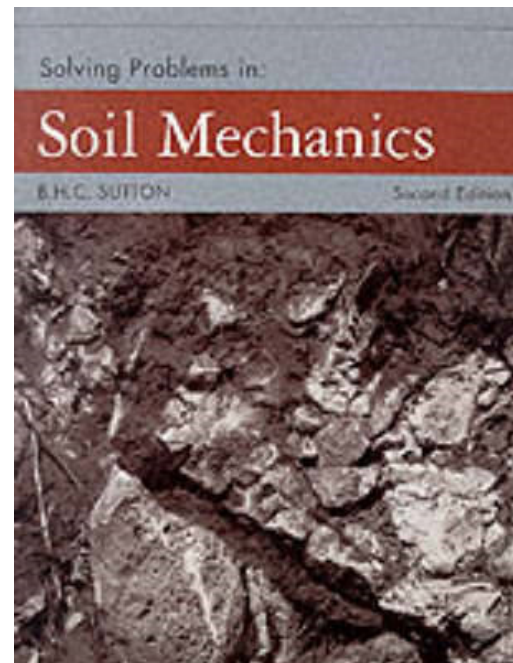
Internet research: Geoslope student edition software.



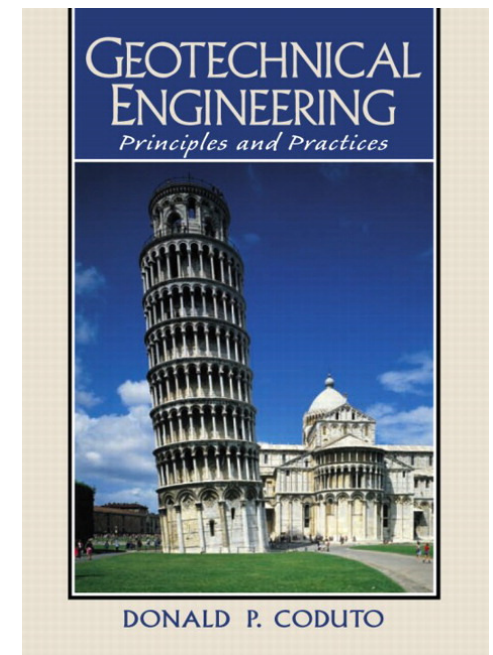
<http://www.bookdepository.com/Solving-Problems-Soil-Mechanics-BHC-Sutton/9780582089716>



<http://www.ebay.com/ctg/Problem-Solving-Soil-Mechanics-A-Aysen-2004-Paperback-/52853454>



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<http://www.tower.com/foundation-design-principles-practices-donald-p-coduto-hardcover/wapi/100501083>