Basic knowledge

Hydrogeology
- characteristics of ground water -

- Classification of ground formation
  - -unsaturated Vadose zone
  - -saturated above water able.
    (Capillary zone, u<0)
  - -saturated below water table (u>0)

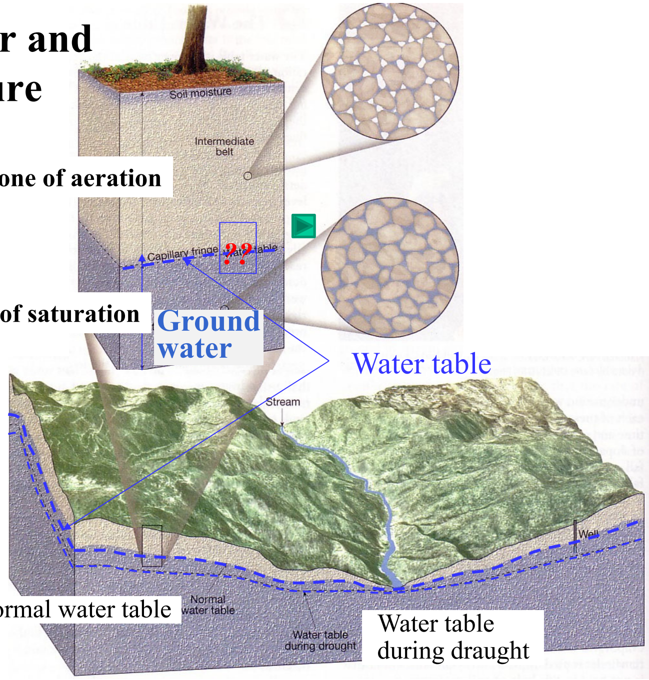
} Vadose water

P1
P2 bottom

Ground water
↑
hydrology

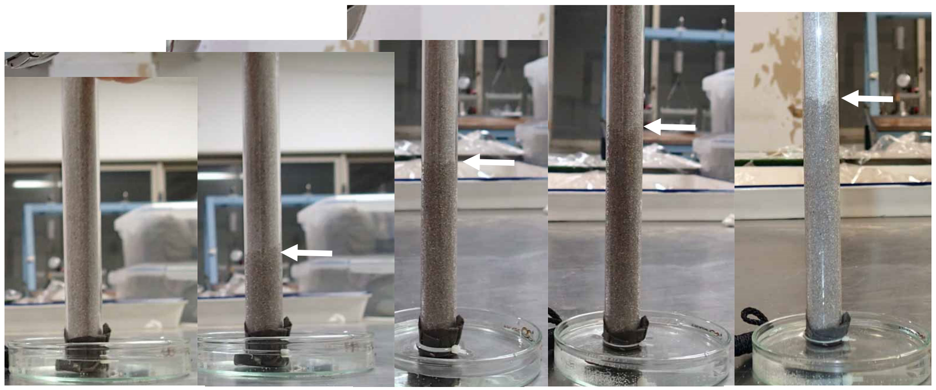
p47

Ground water and soil moisture



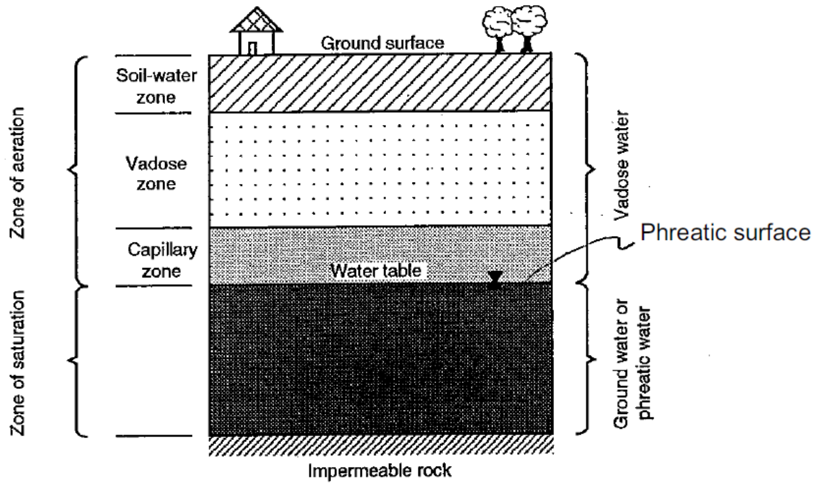
Demonstration of capillary rise

Sand used: Silica sand No.6 (D_{50}=0.32mm, D_{10}=0.30mm, D_{60}=0.39mm)

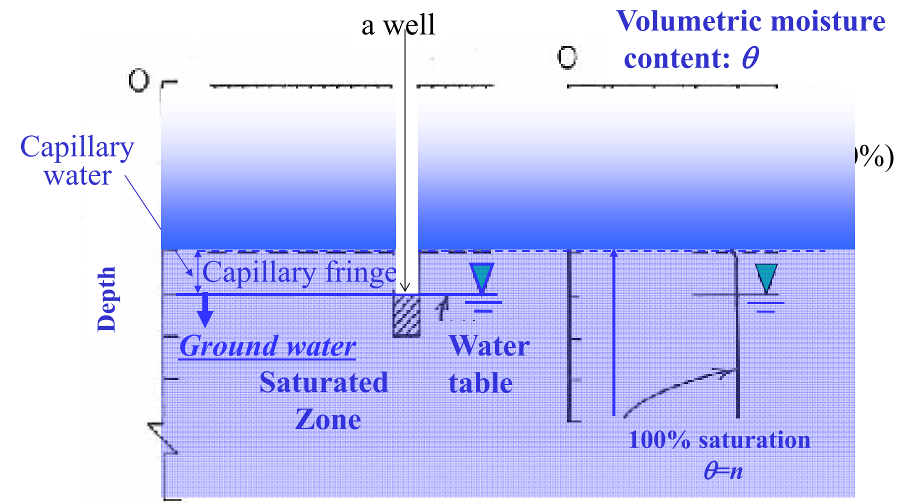


t=0s t=30s t=1m 45s t=3m 47s t=6m 32s

Vertical zones of subsurface water



Ground water and capillary water, volumetric moisture water content



porosity $n = \dfrac{V_v}{V}(\times 100\%)$

Basic properties of soil

Rock => Soil

Weathering => transportation => deposition

Basic properties of soil grain:

- grain size(D)
- density (ρ_s), or specific gravity :$G_s=\rho_s/\rho_w$)

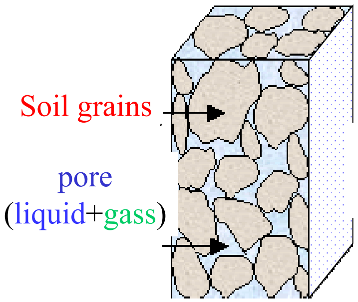
0.005 0.075 0.25 0.8 2.0 4.75 10 75 300 (mm)

clay	silt	sand			gravel			stone	
		fine	mid	coarse	fine	mid	coarse	cobble	boulder

Classification of soil grain (JGS)

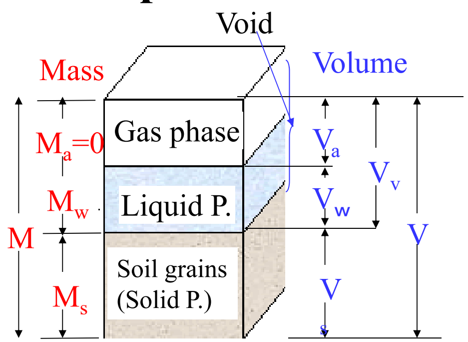
Soils in a ground ; aggregate with variety of grain sizes

State of soils and parameters



- Void size:
  - void ratio(e): volume of pore / volume of soil grains
  - porosity(n): volume of pore / volume of soil
- Content of pore water: dry⇔moist⇔saturated
  - moisture content (w) : mass of water / mass of soil grains
  - volumetric moisture content(θ) : volume of water / total volume of soil
  - degree of saturation (S_r) : volume of water / volume of pore

Composition of soil



Volume of pore

void ratio: $e = \dfrac{V_v}{V_s}$

porosity: $n = \dfrac{V_v}{V}$

Mass of water

moisture content: $w = \dfrac{M_w}{M_s}\times 100(\%)$

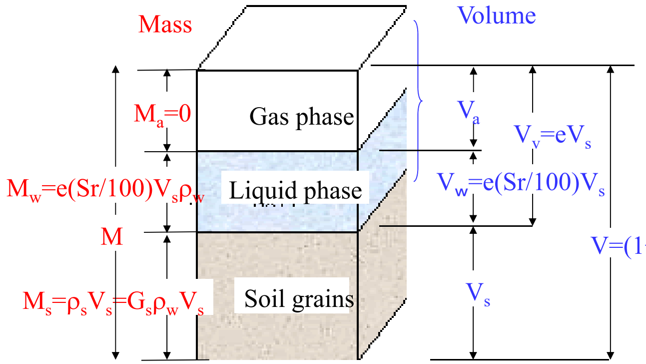
volumetric moisture content: $\theta = \dfrac{V_w}{V}\times 100(\%)$

Degree of saturation: $S_R = \dfrac{V_w}{V_v}\times 100 \quad (\%)$

S_r=100% => $n=\theta$

- saturated soils: $V_v=V_w$ (V_a=0)
- unsaturated soils: $V_v\neq V_w$ ($V_a\neq 0$)

Volume and mass composition of soils, their relation

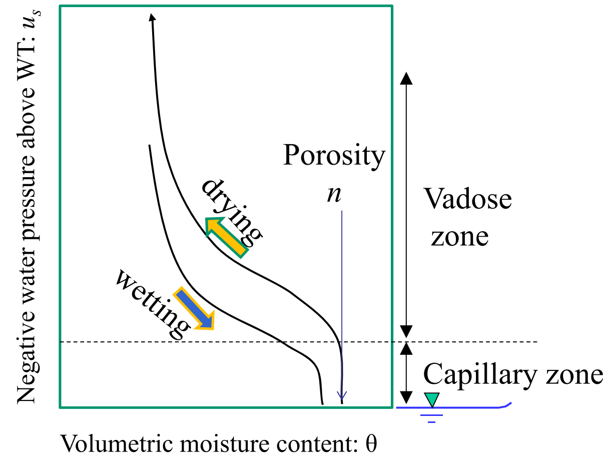


saturated density: $\rho_{sat}=\frac{M_s+M_w(S_r=100\%)}{V}=\frac{V_s\rho_s+V_v\rho_w}{(1+e)V_s}=\frac{\rho_s+e\rho_w}{1+e}$

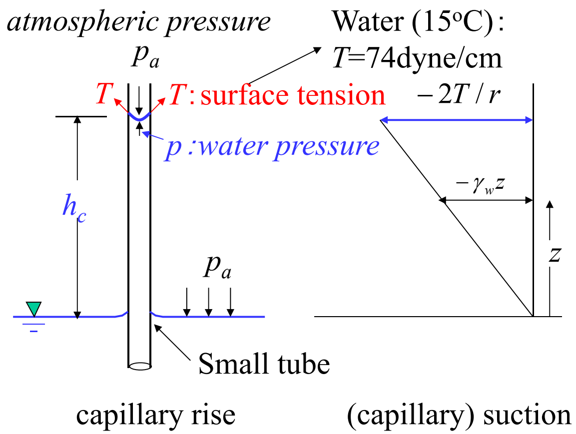
bulk density: $\rho_t=\frac{M_s+M_w(S_r\neq 100\%)}{V}=\frac{V_s\rho_s+\frac{S_r}{100}V_v\rho_w}{(1+e)V_s}=\frac{\rho_s+\frac{S_r}{100}e\rho_w}{1+e}$

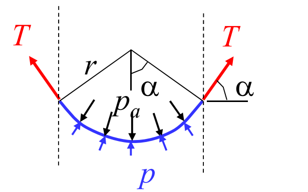
dry density: $\rho_d=\frac{M_s+M_w(S_r=0\%)}{V}=\frac{V_s\rho_s}{(1+e)V_s}=\frac{\rho_s}{1+e}=$

Typical soil-moisture and suction relationship



Capillary rise and suction





Meniscus and pressure difference

Vertical equilibrium :

$$p\pi r^2\sin^2\alpha+2T\pi r\sin^2\alpha$$

$$=p_a\pi r^2\sin^2\alpha$$

$$\therefore p=p_a-\frac{2T}{r}<0 \quad (1)$$

0   ***suction***

$$h_c=\frac{2T}{\gamma_w r} \quad (2)$$

Radius r ~ grain size => the smaller r, the higher $\boldsymbol{h_c}$

Height of capillary rise in sediments

Sediment	Grain Diameter (mm)	Pore radius (mm)	Capillary rise (m)
Fine silt	0.008	0.002	7.5
Coarse silt	0.025	0.005	3
Very fine sand	0.075	0.015	1
Fine sand	0.15	0.03	0.5
Medium sand	0.3	0.06	0.25
Coarse sand	0.5	0.1	0.15
Very coarse sand	2	0.4	0.04
Fine gravel	5	1	0.015

"Geotechnical and Geoenvironmental Handbook", Ed. R.K. Rowe, KAP,2001

Classification of geologic formation -saturated ground formation-

- **Aquifer（帯水層）**
- Aquiclude（不透水層）
- Aquitard（難透水層）

Note: definitions of term depends on areas of interest, e.g.,geology, water-well industry.

Classification of saturated ground formation

P2 top

- **Aquifer** :
  / permeable geologic unit
  / contains a significant amount of water
  / transmits significant quantities of water under ordinary hydraulic gradient.

↓

yields economic quantities of water to well

Classification of saturated ground formation (contn.)

P2 top

- **Aquiclude**
  / contains water but incapable of transmitting it under ordinary hydraulic gradient. (*in geological sense*)
- **Aquitard**
  / less permeable thin layer in a stratigraphic sequence, which underlies or overlies aquifers.
  / behaves as a thin semi-permeable membrane through which leakage can occur, often called "leaky formation"

↓

transmitting water in geological sense, but often assumed impervious in many practices, *e.g., not good for well*

Classification of aquifer (1)

P3 top

- **unconsolidated aquifer（未固結）:**
  / uncemented granular materials, e.g., sand, gravel.
  / stores water in the interstitial pore space among the grains.
- **consolidated aquifer（固結）:**
  / permeable sedimentary rocks, e.g., sandstone, limestone, heavily fractured volcanic and crystalline rocks.
  / stores water primarily in solution channels, fractures and joints and also in the interstitial pore spaces in dual porosity rock systems.

Classification of aquifer (2)

P2 top

•unconfined, phreatic or water table aquifer（自由地下水層）

/ water table forming the upper boundary near the ground surface.

/ water directly recharged from the ground surface.

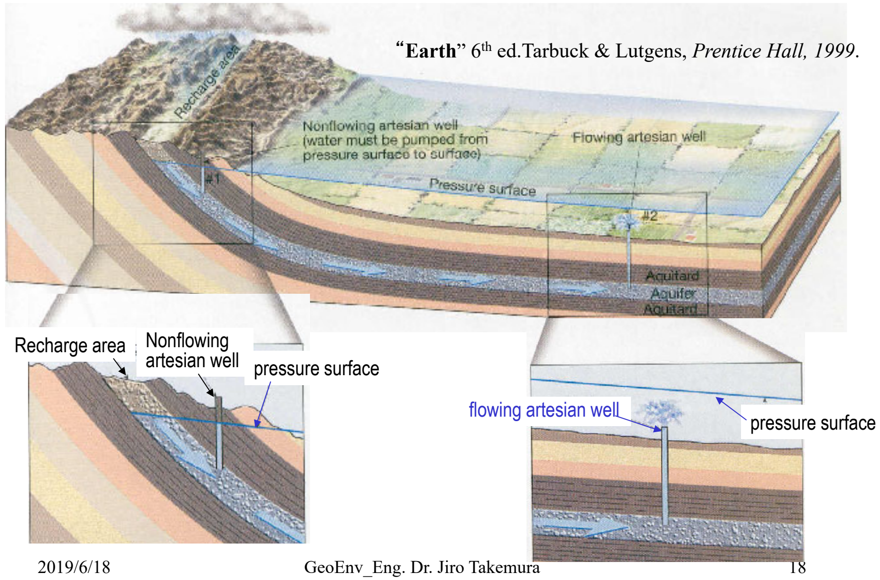
•confined aquifer（不透水層に挟まれた層）

/ confined between two impervious formations (aquitards)

/ ***artesian condition***(被圧状態)：piezometeric head in the confined aquifer may reach the level above phreatic surface of the unconfined aquifer.

/ ***flowing artesian conditions***: piezometeric head is above ground level. A well in such an aquifer will flow freely without pumping.(自噴井戸）

Confined aquifer and artesian condition



"**Earth**" 6th ed.Tarbuck & Lutgens, *Prentice Hall, 1999.*

Physical properties of fluid and porous media to identify aquifer or aquitard

Basic properties

fluid or water

•density(密度）ρ **[M/L³]**

•viscosity(粘度): μ **[M/LT]**

•compressibility(圧縮性): β **[LT²/M]**

Specific storage

media or soils

•porosity: n or void ratio: e

•intrinsic permeability: k
絶対透水係数

•compressibility: $\alpha \sim m_v$

P7 middle

Other hydrogeologic properties of geologic formation can be derived from these six basic properties and representative dimensions of the formations, ex)

•hydraulic conductivity: ***K***
（透水係数）

•specific storage: S_s

•storativity: S

•transmissivity: T

Effective porosity: n_e
(有効間隙率）

P3

Range in values of total porosity and effective porosity

Total and effective porosity of unconsolidated sediments are usually similar, but they may not be similar in lithified sediments of rocks.

	Total porosity	Effective porosity
Anhydrite （無水石膏）	5×10^{-3} - 5×10^{-2}	5×10^{-4} - 5×10^{-3}
Chalk	5×10^{-2} - 4×10^{-1}	5×10^{-4} - 4×10^{-2}
Limestone, dolomite	0 - 4×10^{-1}	1×10^{-3} - 5×10^{-2}
Sandstone	5×10^{-2} - 1.5×10^{-1}	5×10^{-3} - 1×10^{-1}
Shale （頁岩）	1×10^{-2} - 1×10^{-1}	5×10^{-3} - 5×10^{-2}
Salt	5×10^{-3}	1×10^{-3}
Granite （花崗岩）	1×10^{-3}	5×10^{-6}
Fractured crystalline rock	-	5×10^{-7} - 1×10^{-4}

"Geotechnical and Geoenvironmental Handbook", Ed. R.K. Rowe, KAP,2001

Hydraulic conductivity

P13

Darcy's law: $v = K\,i$

Hydraulic conductivity [L/T] [cm/s, m/s, gal/day/ft^2]

Hydraulic gradient $i = -dh/dl$

$$K = \frac{k \rho g}{\mu} \quad (1)$$

K is not constant value.

Specific or intrinsic permeability [L^2] [darcy, cm^2, m^2, ft^2]

Variety of range

P4,5

Definition: 1 darcy is defined as k that will lead to v=1cm/s for a fluid with μ=1cp under a hydraulic gradient that makes the term ρgdh/dl=1atm/cm. 1 darcy ≒10^{-8}cm^2. ← petroleum engineering

Factors affecting permeability

For *k* value:

•type of soil and conditions of soil: **grain size**, **void ratio**, **structure**

\+ Chemical properties of fluid??

For *K* value:

•type of permeant or pore fluid (ρ, μ):
the higher the viscosity and the lower the density, the lower the hydraulic conductivity

Taylor (1948) using Poiseuille's law

$$K = D_s^2 \frac{\rho g}{\mu} \frac{e^3}{(1+e)} C \quad (2)$$

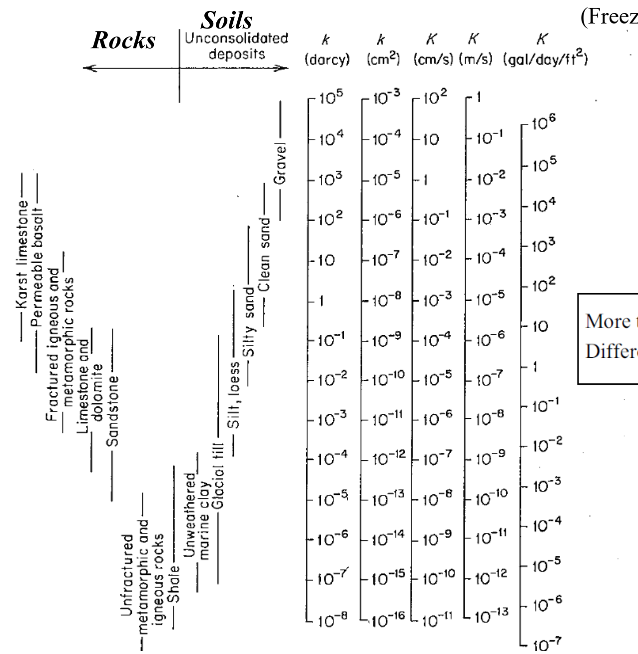
Kozey-Carman equation

$$K = \frac{1}{k_0 S^2} \frac{\rho g}{\mu} \frac{e^3}{(1+e)} \quad (3)$$

D_s: some effective particle diameter
C: shape factor
k_0: factor depending on pore shape and ratio of length of actual flow path to soil bed thickness
S: specific surface area

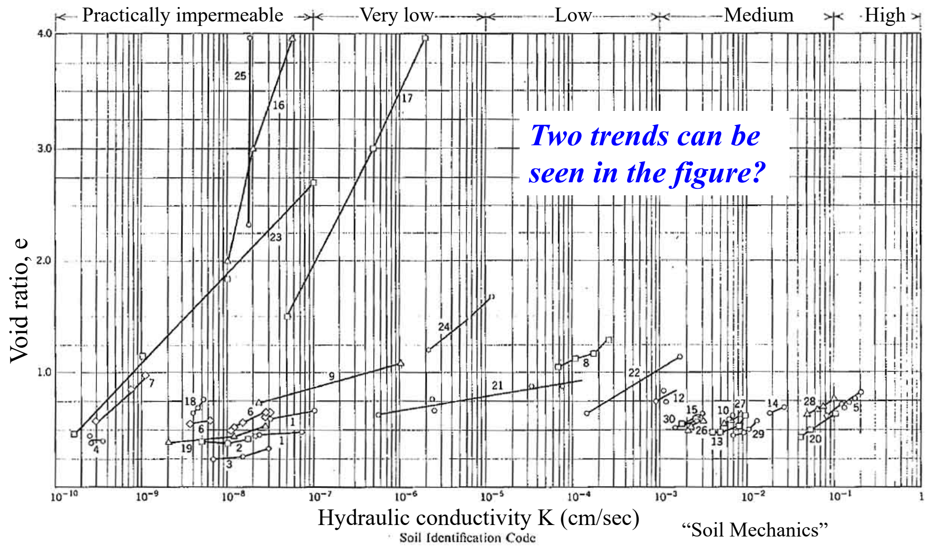
Range of value of Hydraulic Conductivity and intrinsic permeability

(Freeze and Cherry, 1979)



More than 10 orders Difference!!

Hydraulic conductivity of various types of soils



Two trends can be seen in the figure?

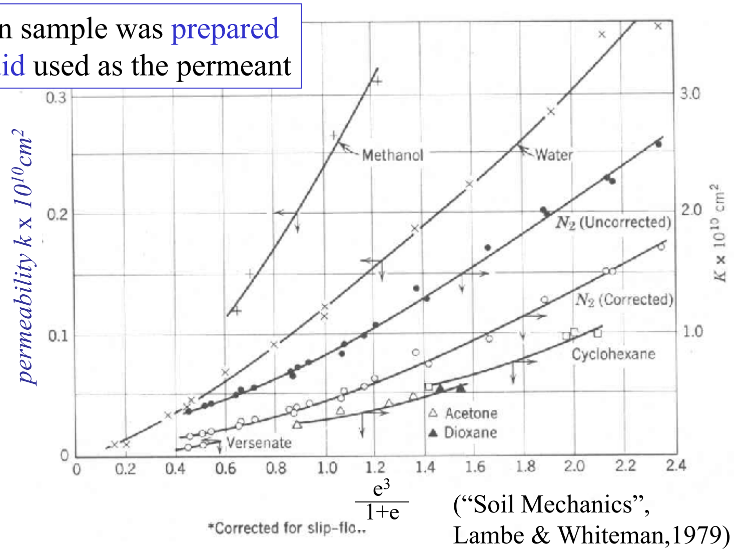
"Soil Mechanics" Lamb& Whitman (1979)

Soil Identification Code

1 Compacted caliche
2 Compacted caliche
3 Silty sand
4 Sandy clay
5 Beach sand
6 Compacted Boston blue clay
10 Ottawa sand
11 Sand—Gaspee Point
12 Sand—Franklin Falls
13 Sand—Scituate
14 Sand—Plum Island
15 Sand—Fort Peck
19 Lean clay
20 Sand—Union Falls
21 Silt—North Carolina
22 Sand from dike
23 Sodium—Boston blue clay
24 Calcium kaolinite

Effects of e and permeant: intrinsic k of kaolinite

kaolin sample was prepared in fluid used as the permeant

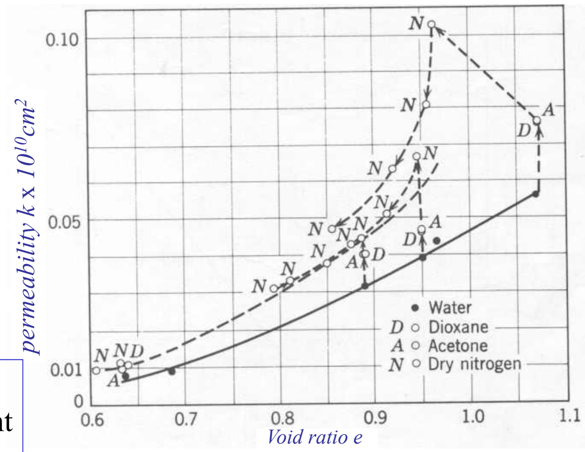


("Soil Mechanics", Lambe & Whiteman,1979)

Effects of e and permeant: intrinsic k of kaolinite

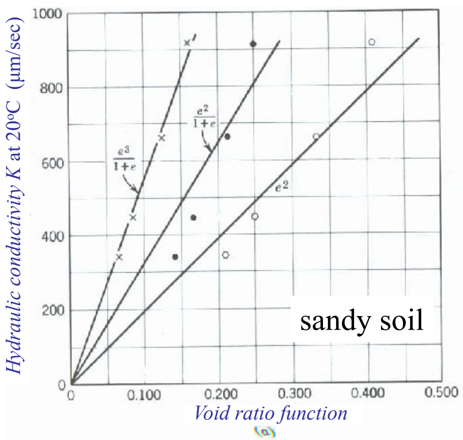
Water was used as the molding fluid and the initial permeant. After initial permeability test, each succeeding permeant displaced the previous one.

difference in different permeant is less significant than the result shown in one page before.

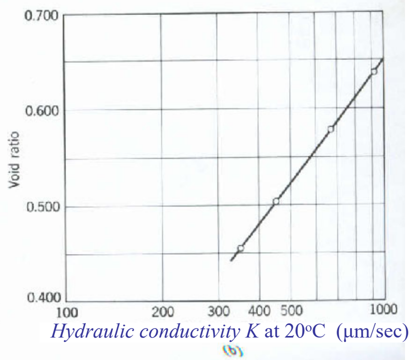


Soil fabric is created in sedimentation process; different structure in different permeant

Relationship between void ratio- permeability



("Soil Mechanics", Lambe & Whiteman,1979)

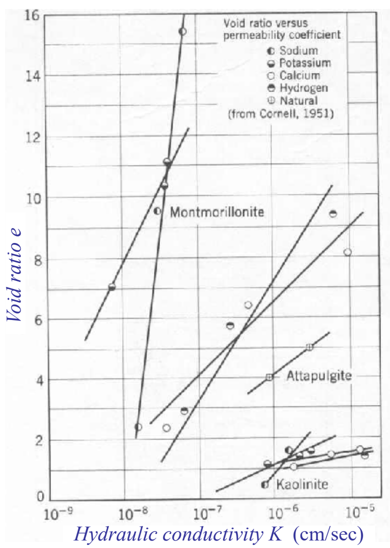


straight relation in $e^3/(1+e)$ - K and e -log$K$

clay and sand **P5**

("Soil Mechanics", Lambe & Whiteman,1979)

Effects of soil composition



Influence of soil composition on K is of little importance with ***silt, sand gravel***, but of significant importance for ***clay***.

Sodium and Potassium ions give the lowest permeability.

N_a *montmorillonite* is one of least permeable soil minerals: *impermeabilizing additive* ***why??***

ion exchange capacity(イオン交換能):
Montmorillonite>> Attapulgite > Kaolinite

The lower the ion exchange capacity of soil, the lower the effect of exchangeable ion on permeability.

Effect of structure

("Soil Mechanics", Lambe & Whiteman,1979)

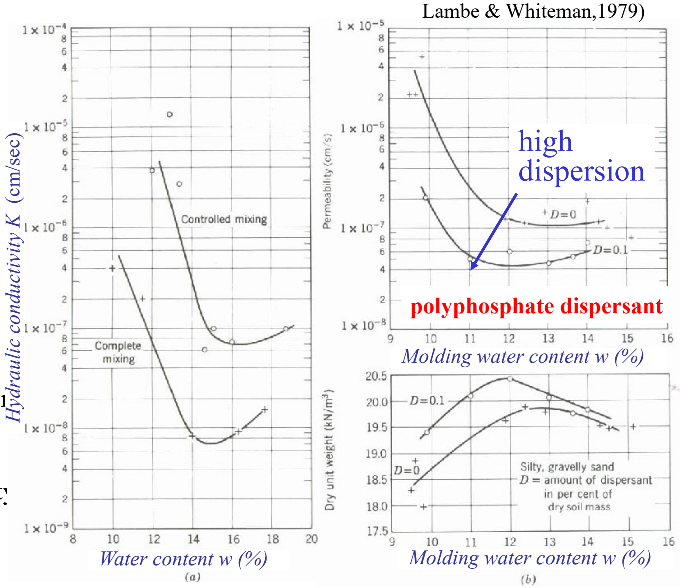
Dispersant(分散剤) increase the repulsion between fine particles,

⇩

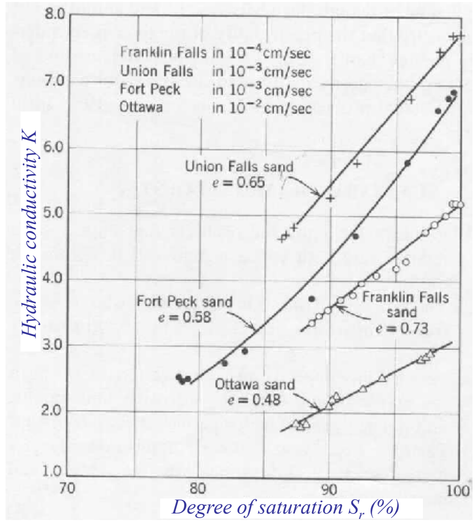
increasing double layer thickness

⇩

decreasing permeability



Effect of degree of saturation S_r



The effect of S_r is very significant, much more than the effects of reduction of flow channels available for water flow due to air bubbles.

("Soil Mechanics", Lambe & Whiteman,1979)

Home work 1

Interpret the figures on the factors influencing permeability (intrinsic permeability & hydraulic conductivity)

What you can see in the figures?

What are the possible reasons or mechanism for those?

Due: June 21

Heterogeneity and Anisotropy of *K*

Heterogeneity(不均質性)

K usually shows variations through space in a geologic formation. ***heterogeneous*** (不均質)

(***K***: independent of position ***homogeneous*** (均質))

Types of heterogeneity:

- **layered heterogeneity**: sedimentary rock, **P6**
  lacustrine (湖成)and marine(海成) deposits
- **discontinuous heterogeneity**: faults, contact on bedrock
- **trending heterogeneity**: deltas, alluvial fans and glacial outwash plains
  2-3 orders of magnitude in a few miles

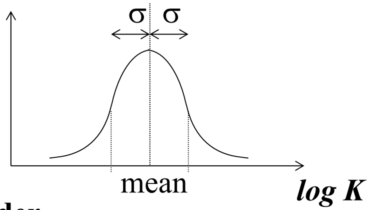
Heterogeneity of K

Distribution of K in a geologic formation:

(for internal heterogeneity)

log-normal distribution

common standard deviation σ of *log K* in homogeneous formation:



0.5-1.5 → internal variation of 1-2 order

Trending heterogeneity = trend of the mean value of *K*

Definition of heterogeneity of *K*

(= mean value of *K in probability distribution*)

Condition for *K* being constant everywhere : ***uniform***

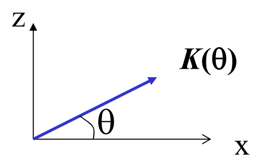
such as test specimen of glass beads of an identical diameter

Heterogeneity and Anisotropy of *K(contn.)*

Anisotropy(異方性)

K varies with the direction of measurement at a point in a geologic formation. ***Anisotropic***（異方）

K: independent of the direction ***isotropic***（等方）



Principal directions of anisotropy:
direction in space at which ***K*** attains its max. and min. values. The max and min directions are perpendicular to the other and so is intermediate direction(3D) to the others.

The principal directions → xyz coordinate directions

isotropy: $K_x=K_y=K_z$ ***anisotropy:*** $K_x \neq K_y \neq K_z$

in horizontally bedded sedimentary deposits

$K_x=K_y \neq K_z$ ***:transversely isotropic***

Heterogeneity and Anisotropy of *K*

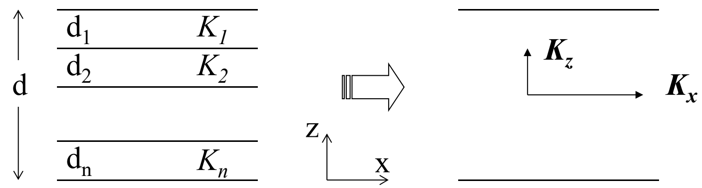
P6 middle

four possible systems in 2D

- ***Homogeneous, isotropic :*** $K_x(x,z)=K_z(x,z)=C$ ***for all (x,z)***
- ***Homogeneous, anisotropic :***
  $K_x(x,z)=C_1$ ***for all (x,z)***, $K_z(x,z)=C_2$ ***for all (x,z)***, $C_1 \neq C_2$
- ***Heterogeneous, isotropic:*** $K_x(x,z)=K_z(x,z)=C(x,z)$
- ***Heterogeneous, anisotropic:***
  $K_x(x,z)=C_1(x,z)$, $K_z(x,z)=C_2(x,z)$, $C_1 \neq C_2$

Relationship between layered heterogeneity and anisotropy

P6 bottom



From Darcy's law and continuous cond.

$$K_z = \frac{d}{\sum_{i=1}^{n} d_i / K_i} \quad (4)$$

$$K_x = \sum_{i=1}^{n} \frac{K_i d_i}{d} \quad (5)$$

(ex) $K_1=10^4$, $K_2=10^2$ → $K_x/K_z=25$

$K_1=10^4$, $K_2=1$ → $K_x/K_z=2500$

Heterogeneity and anisotropy depend on the size of area in consideration

Transmissivity and storativity
透水量係数　　　　　貯留係数

Specific storage（被貯留係数）S_s of saturated aquifer: [1/L]

the volume of water that a unit volume of aquifer (V_T=1) releases from storage under a unit decline in hydraulic head (Δh=-1).

Decrease of hydraulic head	➡	decrease in fluid pressure u increase in effective stress σ	P7 bottom

Water released from aquifer with V_T=1 and Δh=-1

①compression of aquifer by $\Delta\sigma$: $\Delta V_{w1} = \alpha V_T \Delta\sigma$

$$\Delta\sigma = -\rho g \Delta h \Rightarrow \Delta V_{w1} = \alpha\rho g \quad (6)$$

②expansion of water by Δu: $\Delta V_{w2} = -\beta V_w \Delta u$

$$V_w = nV_t,\quad \Delta u = \rho g \Delta h \Rightarrow \Delta V_{w2} = \beta n \rho g \quad (7)$$

α,β: p7 middle

$$\boxed{S_s = \rho g(\alpha + n\beta)} \quad (8)$$

Transmissivity and storativity (contn.)

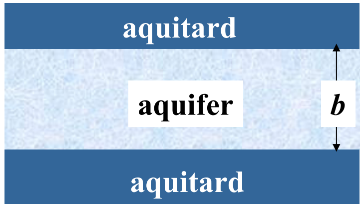
in a confined aquifer

•**Transmissivity**

$T = K\,b$　[L^2/T] (9)

•**Storativity (storage coefficient)**

$S = S_s\,b$　[ND]　(10)



Efficiency of pumping:　*rate*
ground water cleanup　*quantity*

T and ***S*** are widely used in water well industry in US.

T > 0.015m²/s : good aquifer for water well exploitation

S ranges 0.005-0.0005

T and *S* are useful for 2D analysis. For 3D, *K* or S_s better

Transmissivity and storativity (contn.)

in a unconfined aquifer　　　P7 bottom

•**Specific yield (unconfined storativity)** :S_y（比産出量、比進出量）

the volume of water that an unconfined aquifer releases from storage per unit surface area per unit decline in the water table.

S_y ranges 0.01-0.30　highly depending on porosity and grain size

including actual dewatering from pore.

•**Specific retention** :S_r (=n - S_y)　（比残留量）

the volume of water retained in unit volume under the influence of gravity

Equation of transient saturate flow

Equation of continuity:

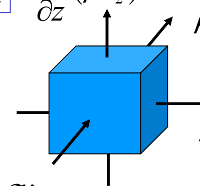
mass conservation

the rate of fluid mass flow into elemental control volume (ECV)

= the rate of fluid mass flow out of ECV

+ change of mass in unit time

mass rate of flow across **a unit** cross sectional area



$\rho v_z - \frac{\partial}{\partial z}(\rho v_z)$　$\rho v_y - \frac{\partial}{\partial y}(\rho v_y)$　ρv_x　$\rho v_x - \frac{\partial}{\partial x}(\rho v_x)$　ρv_y　ρv_z

$-\frac{\partial(\rho n)}{\partial t}$

elemental control volume

$$-\frac{\partial(\rho v_x)}{\partial x} - \frac{\partial(\rho v_y)}{\partial y} - \frac{\partial(\rho v_z)}{\partial z} = \frac{\partial(\rho n)}{\partial t} \quad (12)$$

Equations on transient saturate flow, cont.

$$-\frac{\partial(\rho v_x)}{\partial x}-\frac{\partial(\rho v_y)}{\partial y}-\frac{\partial(\rho v_z)}{\partial z}=n\frac{\partial\rho}{\partial t}+\rho\frac{\partial n}{\partial t} \qquad (13)$$

mass rate of water produced by an expansion of the water under a change in its density ρ.

mass rate of water produced by the compaction of porous medium as reflected by the change in its porosity n.

controlled by fluid compressibility β

controlled by aquifer or soil compressibility α

change in ρ and n are both caused by a change in hydraulic head ***h***

Mass rate of water produced (time rate of change of fluid mass storage) is

$$\rho S_s \,\partial h/\partial t \qquad S_s=\rho g(\alpha+n\beta) \qquad (8)$$

Equations on transient saturate flow, cont.

$$-\frac{\partial(\rho v_x)}{\partial x}-\frac{\partial(\rho v_y)}{\partial y}-\frac{\partial(\rho v_z)}{\partial z}=\rho S_s\frac{\partial h}{\partial t} \qquad (14)$$

Expanding the left terms by chain rule $+\rho\,\partial v_i/\partial i \succ\succ v_i\,\partial\rho/\partial i$

+ Darcy's law **P7 middle: β is 4.4x10^{-4} m^2/MN**

Equation of of transient flow through a saturated anisotropic porous medium

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right)=S_s\frac{\partial h}{\partial t} \qquad (15)$$

In case of homogeneous and isotropic medium

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}=\frac{S_s}{K}\frac{\partial h}{\partial t} \qquad (16)$$

Equations on transient saturate flow, cont.

(16) => " ***diffusion equation***"

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}=\frac{\rho g(\alpha+n\beta)}{K}\frac{\partial h}{\partial t} \qquad (17)$$

To obtain the solution *h(x,y,x,t),* the three basic hydrogeological parameters: ***K,α,n*** and three fluid parameters: ***ρ, μ*** and ***β*** are needed.

$$K=\frac{k\rho g}{\mu}$$

For the special case of a horizontal confined aquifer (2D) of thickness ***b***, ***S=S$_s$b*** and ***T=Kb,*** the three dimensional form eq.(17) becomes

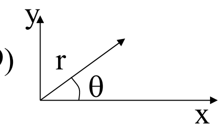
$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=\frac{S}{T}\frac{\partial h}{\partial t} \qquad (18)$$

***S,T:* input parameter for solution**

Well equations

Transformation of diffusion equation from Cartesian coordinates to polar coordinates

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=\frac{\partial^2 h}{\partial r^2}+\frac{1}{r}\frac{\partial h}{\partial r}+\frac{1}{r^2}\frac{\partial^2 h}{\partial\theta^2}=\frac{S}{T}\frac{\partial h}{\partial t} \qquad (19)$$

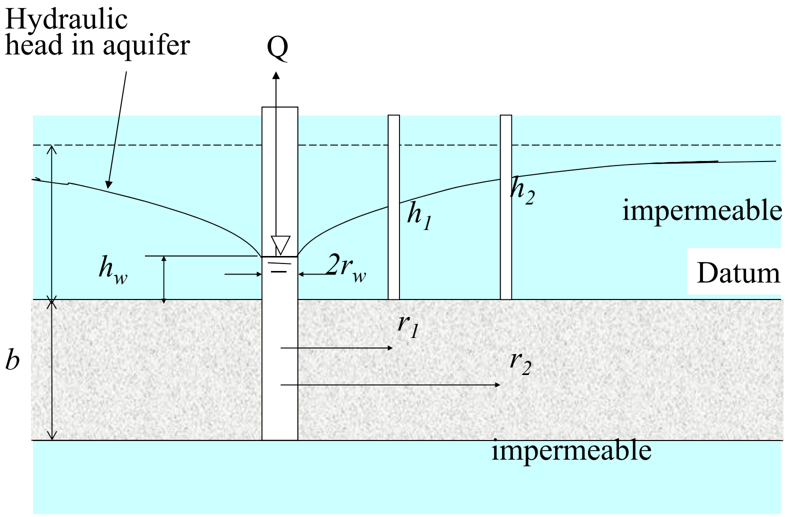


In case of well, radial flow can be assumed, where *h* is the function of *r* only.

$$\frac{\partial h}{\partial\theta}=\frac{\partial^2 h}{\partial\theta^2}=0 \qquad \Rightarrow \text{eq.}(19)$$

$$\frac{\partial^2 h}{\partial r^2}+\frac{1}{r}\frac{\partial h}{\partial r}=\frac{S}{T}\frac{\partial h}{\partial t} \qquad (20)$$

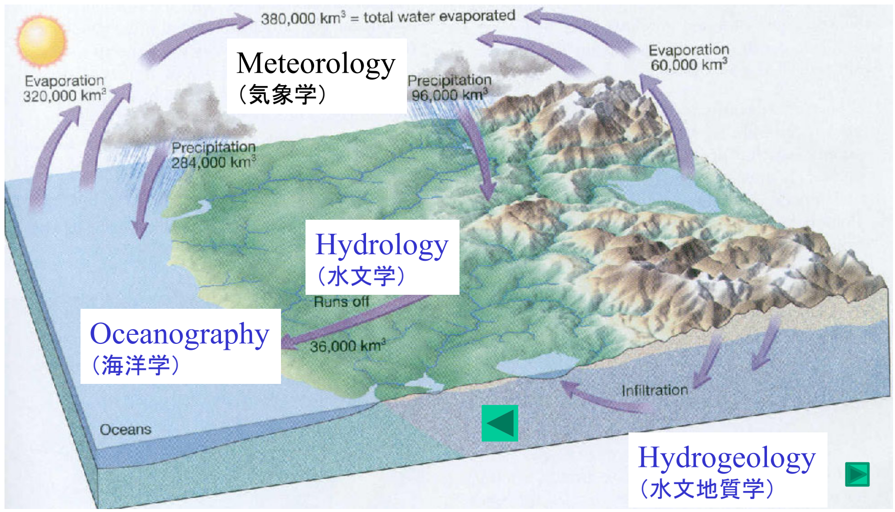
Radial flow toward a well in confined aquifer



Groundwater flow

Ground water flow in water balance on Earth

Earth water balance



"Earth" 6th ed. Tarbuck & Lutgens, Prentice Hall, 1999

Major influences on groundwater flow

- **Precipitation**: infiltrating ground and recharging aquifers
- **Gravity**: causing flow and eventually discharging to springs, rivers and oceans
- **Topology**: controlling the surface flow,etc.
- **Climate**: evapotranspiration, melts of snow

P8 top

In mid-latitude region,
groundwater recharge is the most likely to occur in **spring**.
snow melts, high precipitation and low evapotranspiration

P9 top

In summer, **evapotranspiration** and
soil moisture requirements use all infiltrating water.

Groundwater flow system

- **Local flow:** nearby discharge area, e.g., ponds and streams

P8 bottom

- **Regional flow:** travelling greater distance and discharging into oceans, large lakes and rivers

Typical watershed, recharge area, is grater than the discharge area, 5-30 % of the watershed.

Effects of pumping on flow

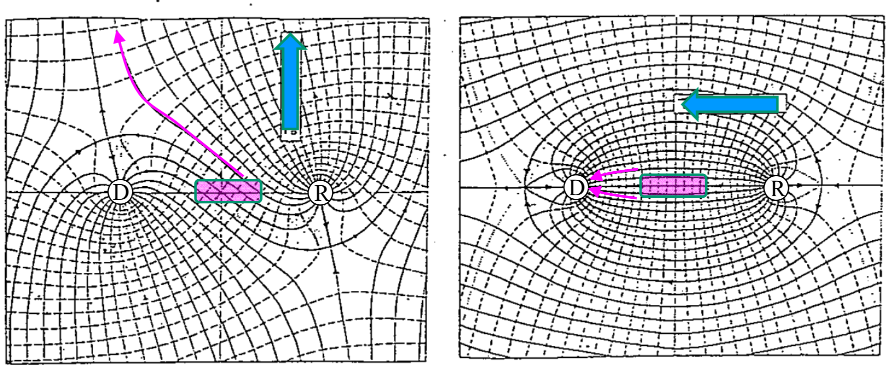
- Pump and treat system: one of the common remediation techniques

Pumping groundwater causes complex perturbations in flow even at a site with relatively simple hydrogeology.

Placement of the wells (relative to the direction of ground water flow) is critical in determining the flow from recharge well to discharge well.

P9 bottom

Flow net around recharge (R) and discharge (D) wells



Contaminated area

Direction of natural ground water flow

Geochemistry

Contaminants entering subsurface are subject to control not only by the aquifer's physical properties, but also by **geochemical actions**.

- Dissolution(溶解) - Precipitation(沈殿)
- Oxidation(酸化) - Reduction(還元) ***Redox***
- Sorption (吸着) - Desorption (脱着)
- Ion exchange(イオン交換)
- Complexation(化学合成)

p10 top
p11 top

concentration in chemical equilibrium

Influence on the operation of aquifer clean-up systems

various form of toxic chemicals
p10 bottom

Geochemistry(contn.)

Back ground values:（もともとの値）

(original values of chemical composition of the site) are important in any assessment and treatment of ground water system.

- Classification of ground water:
- Dissociation(解離) reactions from soil minerals to simple ions
- Chemistry of precipitation.
  （降雨、降雪）

p11 top

p11 bottom

Chemical equilibrium

$$\underbrace{bB + cC}_{\text{reactants}} \rightleftarrows \underbrace{dD + eE}_{\text{products}} \quad (21)$$

where *b,c,d* and *e* are the number of moles of the chemical constituents *B,C,D* and *E*

The law of mass action express the relation between the reactants and the products when the reaction is at equilibrium,

$$K = \frac{[D]^d [E]^e}{[B]^b [C]^c} \quad (22)$$

[ ]: thermodynamically effective concentration of the constituent: ***activity***

activity $a_i = m_i \gamma_i$ (23)

m_i:molality

γ_i:activity coefficient =f(*I*)

$$Ionic \quad strength : I = \frac{1}{2}\sum m_i z_i$$

z_i: *valence*

p12

Concentration units

Molality: the number of moles of solute dissolved in a 1-kg mass of solution. (mol/kg) *one mole <= one molecular weight*

Molarity: the number of moles of solute dissolved in 1m³ of solution. (mol/m³) 1mol/ m³=1mmol/*l*

Mass concentration: the mass of solute dissolved in a specified unit volume of solution. (kg/m³, g/*l*)

Equivalents per liter: the number of moles of solute multiplied by the valence of the solute species in liter of solution (ep*l*)

Equivalents per million: the number of moles of solute multiplied by the valence of the solute species in 10^6g of solution (ep*m*)

Parts per million: the number of grams of solute per million grams of solution (ppm).

Mole fraction: the ratio of the number of moles of a given solute species to the total number of moles of all components in the solutions.

Ground water classification based on Total Dissolved Solids (TDS)

category	TDS (mg/l or g/m³)
Fresh water	0-1,000
Brackish water	1,000-10,000
Saline water	10,000-100,000
Brine water	more than 100,000

units of concentration

The TDS of sea water: 35,000mg/l

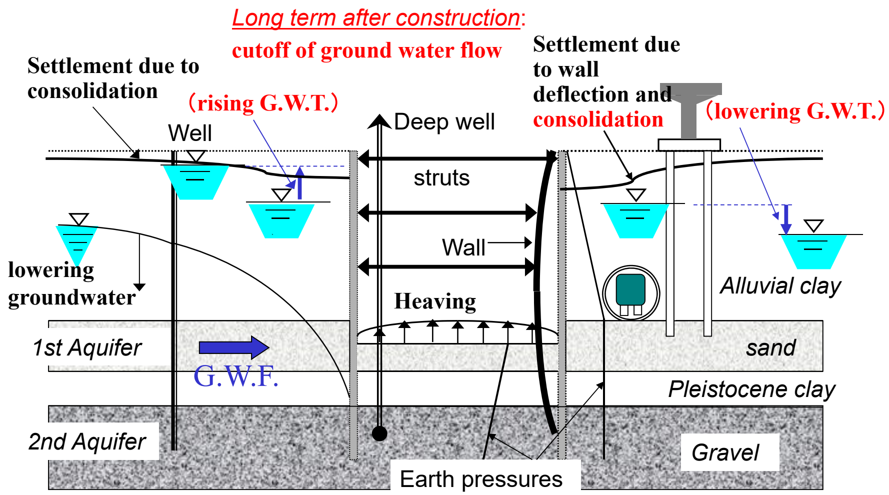
Six major inorganic ions in ground water:

Na^+, Mg^+, Ca^+, Cl^-, HCO_3^-, SO_4^{2-}

normally more than 90% of TDS

p12 top left

Various environmental problems associated with open excavation with retaining wall



Environmental Assessment on underground construction works

- **Effects of UGC on ground water** ***flow pattern, wells,***
- Excavated soils => ***wastes??*** (soils, industrial waste, hazardous soils)
- Impacts of construction works on the surrounding environments

impacts?? crucial conditions for them??

Map of Tokyo

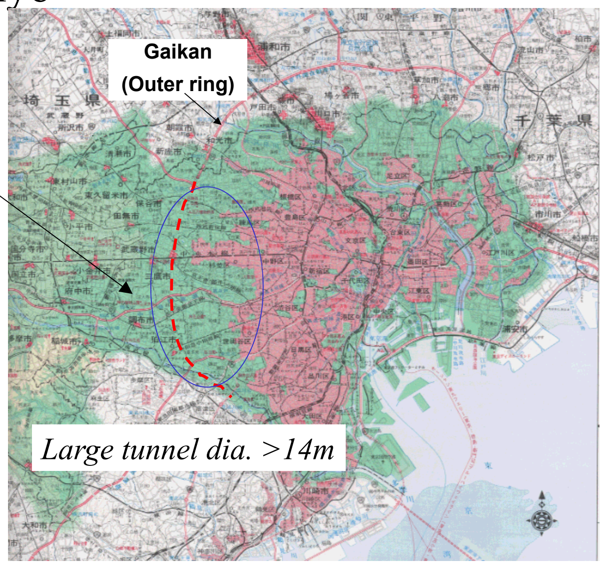
Highly populated area

⇩

No space for highway construction above ground

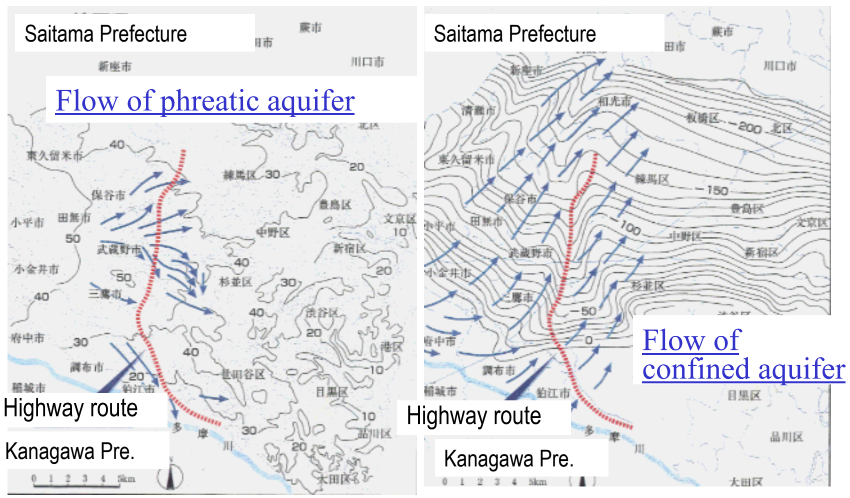
⇩

Tunnel with large cross section is only feasible way for completion of ring highway

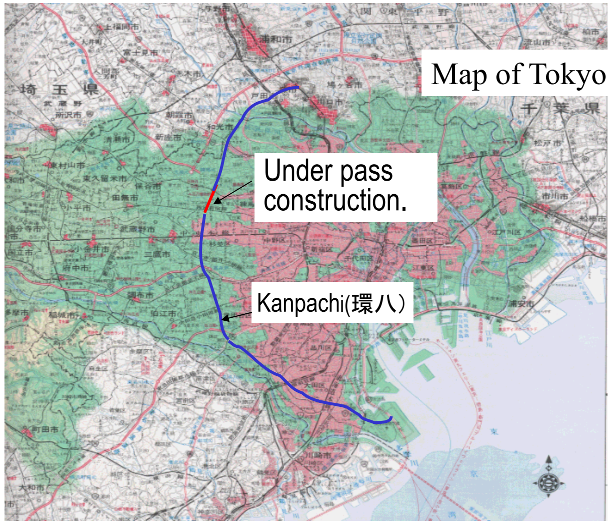


Ground water flow at the route of circuit highway

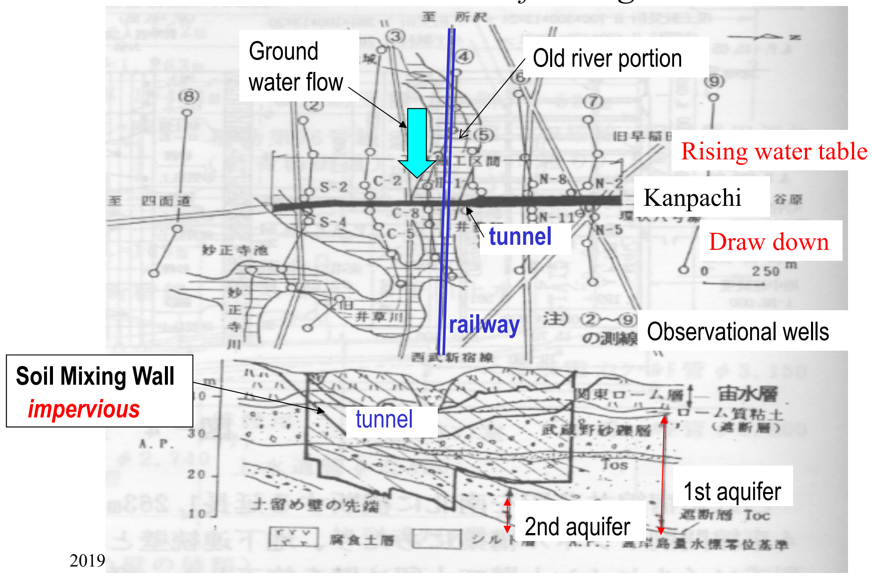
Effects of long large UGS



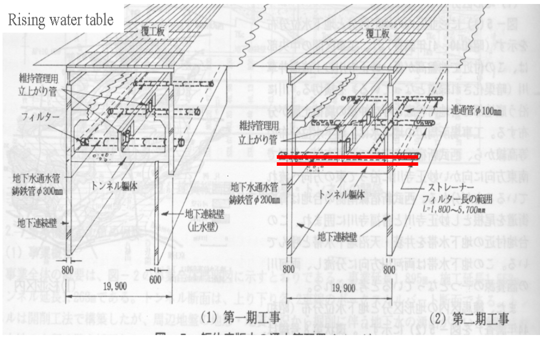
Effect of underground structure on ground water flows
Flow Interruption（地下水流動阻害）



Plane and cross section at a under pass tunnel construction site: *after Sugimoto*

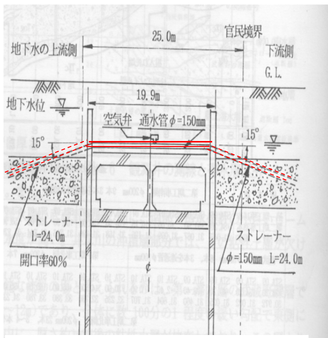


Countermeasures against ground water lowering



Countermeasure in design

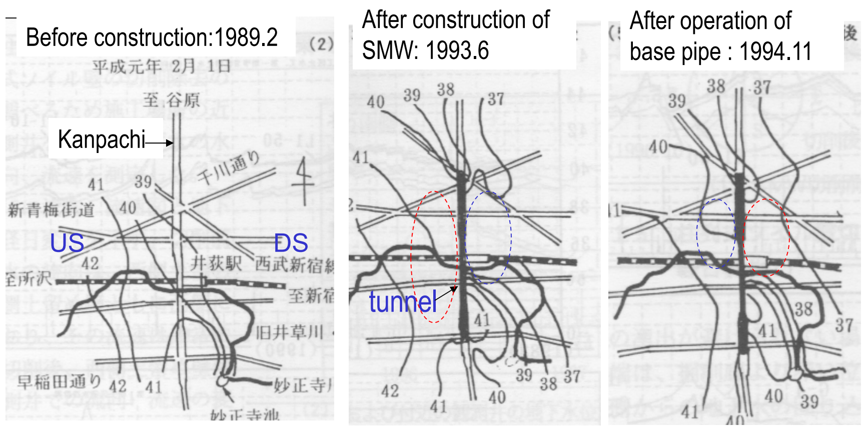
Water pipe at base slab



Countermeasure added in construction stage

Water pipe above tunnel

Change of ground water level:1



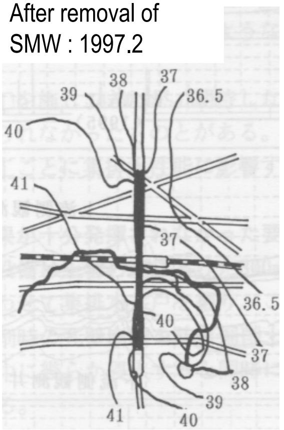
Continuous change of G.W.L.

Rising at US

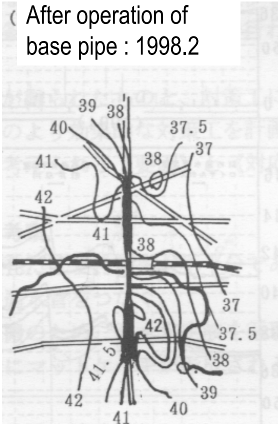
Lowering at DS

Small lowering at US and rising of W.L.at DS

Change of ground water level:2



After removal of SMW : 1997.2



After operation of base pipe : 1998.2

Rising of W.L. but still some gap between up and down stream