# Introduction to fluid flow in rock (Week5, 28, 30 Sept)

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# Fluid flow

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- Fluid flow in porous media
  - Darcy's law
  - Permeability
  - Diffusion equation of fluid flow in porous media
- Fluid flow in fractured media
  - Cubic law
  - Permeability defined in fractured rock
  - Discrete Fracture Network
- Convective heat transfer

# Content of today's lecture



- Fluid flow in porous media
- Darcy's law
- Permeability vs. Hydraulic Conductivity
- Diffusion Equation for fluid flow in porous media

# Fluid flow in porous media

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- Problem of great importance to geological/energy resources engineering;
  - Groundwater hydrology
    - groundwater migration, tunnel inflow, Contaminant transport,
  - Oil/gas extraction
    - Reservoir engineering
  - Rock/soil mechanics
    - Stability (pore pressure) of underground structure
    - Fault mechanics
  - Geothermal Energy

# Fluid flow in porous media

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- Application of fluid mechanics to porous media
  - Fluid (water, oil, gas) flows through the pores of the rock
  - Porosity of rock: volumetric fraction of (interconnected) pore
  - Permeability: the ease with which fluid can move through a porous rock

# Representative Elementary Volume (REV)

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– minimum volume (or a range) beyond which the characteristics of the domain remain basically constant

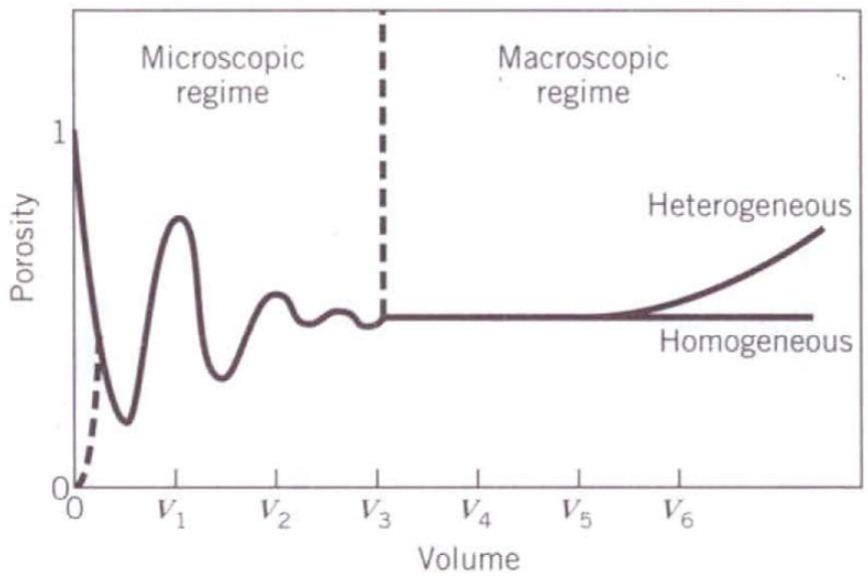


***Figure 3.14*** Diagram illustrating the representative elementary volume (from Hubbert, 1956). Reprinted with permission of the Amer. Inst. Mining, Met. and Petrol. Engrs.

Domenico & Schwartz, 1998

# Porosity

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- n: porosity, Vv: void volume, V: total volume

$$n = \frac{V_v}{V}$$

*Table 2.1* **Range in Values of Porosity**

| Material | Porosity (%) |
|---|---|
| **SEDIMENTARY** | |
| Gravel, coarse | 24–36 |
| Gravel, fine | 25–38 |
| Sand, coarse | 31–46 |
| Sand, fine | 26–53 |
| Silt | 34–61 |
| Clay | 34–60 |
| **SEDIMENTARY ROCKS** | |
| Sandstone | 5–30 |
| Siltstone | 21–41 |
| Limestone, dolomite | 0–40 |
| Karst limestone | 0–40 |
| Shale | 0–10 |
| **CRYSTALLINE ROCKS** | |
| Fractured crystalline rocks | 0–10 |
| Dense crystalline rocks | 0–5 |
| Basalt | 3–35 |
| Weathered granite | 34–57 |
| Weathered gabbro | 42–45 |

In part from Davis (1969) and Johnson and Morris (1962).

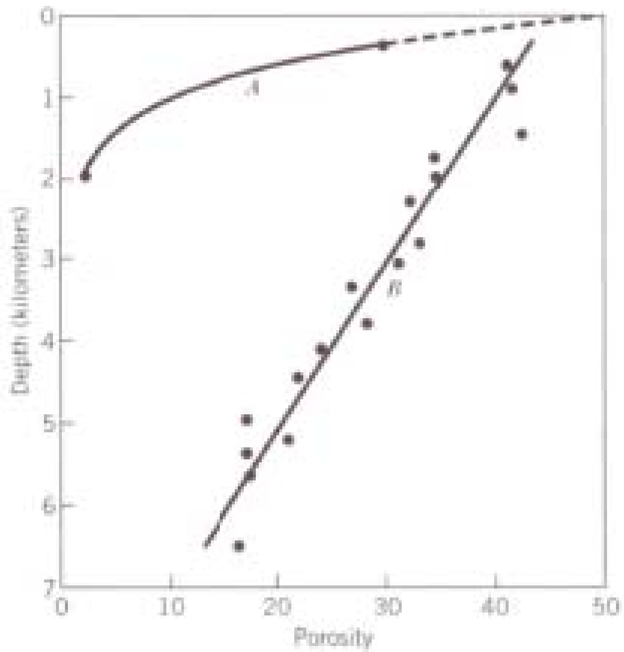


*Figure 2.18* Porosity versus depth curves. Curve *A* from Athy (1930) for shales; curve *B* from Blatt (1979) for sandstones. Data for Blatt's curve represent 1000-ft averages of 17,367 porosity measurements (from an unpublished manuscript by Atwater and Miller).

Domenico & Schwartz (1998)

# Darcy's law

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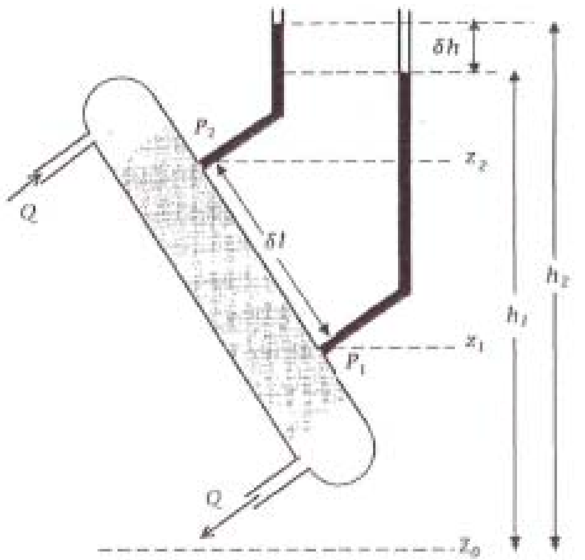


Fig. 6.1. Darcy's experiment (Hubbert's version).

– Q: volumetric flow rate ($m^3$/sec)

– q: volumetric flow rate per unit area (fluid flux or specific discharge) (m/sec)

– K: hydraulic conductivity (m/sec), the ease with which fluid can move through a porous rock

– h: hydraulic head

$$Q = -KA\frac{\delta h}{\delta l} = -KiA \qquad q = -K\frac{\delta h}{\delta l} = -Ki$$

$$q_x = -K_x\frac{\partial h}{\partial x} \qquad q_y = -K_y\frac{\partial h}{\partial y} \qquad q_z = -K_z\frac{\partial h}{\partial z} \qquad \mathbf{q} = -K\nabla h$$

Middleton and Wilcock, 1994

# Hydraulic Head



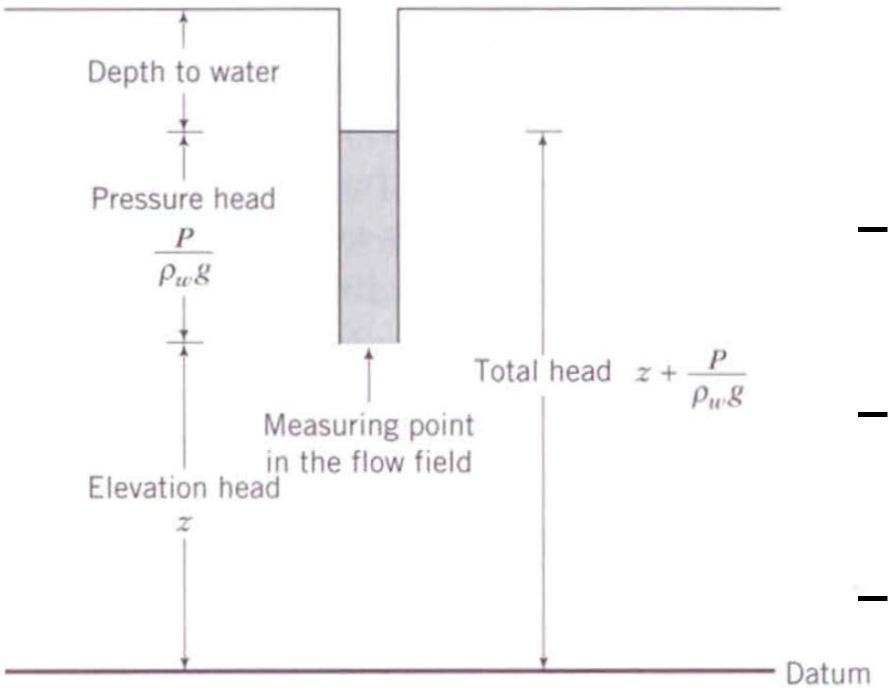


*Figure 3.2* Diagram showing elevation, pressure, and total head for a point in the flow field.

- Piezometer: a tube(pipe) used to measure water-level elevations in field situation
- Elevation head: elevation at the base of piezometer
- Pressure head: length of water column.
- Total head: potential energy of the fluid = elevation head + pressure head

$$h = z + \frac{P}{\rho_w g}$$

# Hydraulic head

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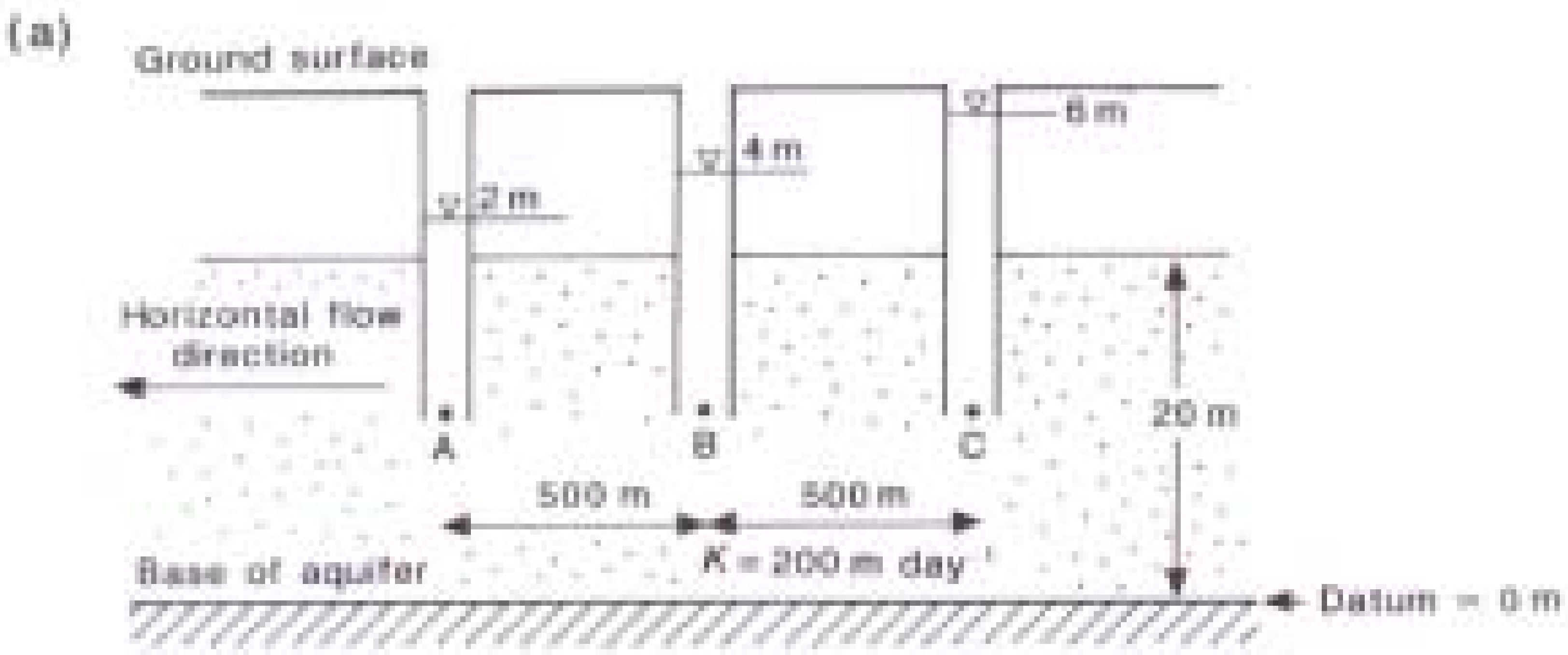
– Determination of flow direction from piezometric measurement



# Hydraulic head

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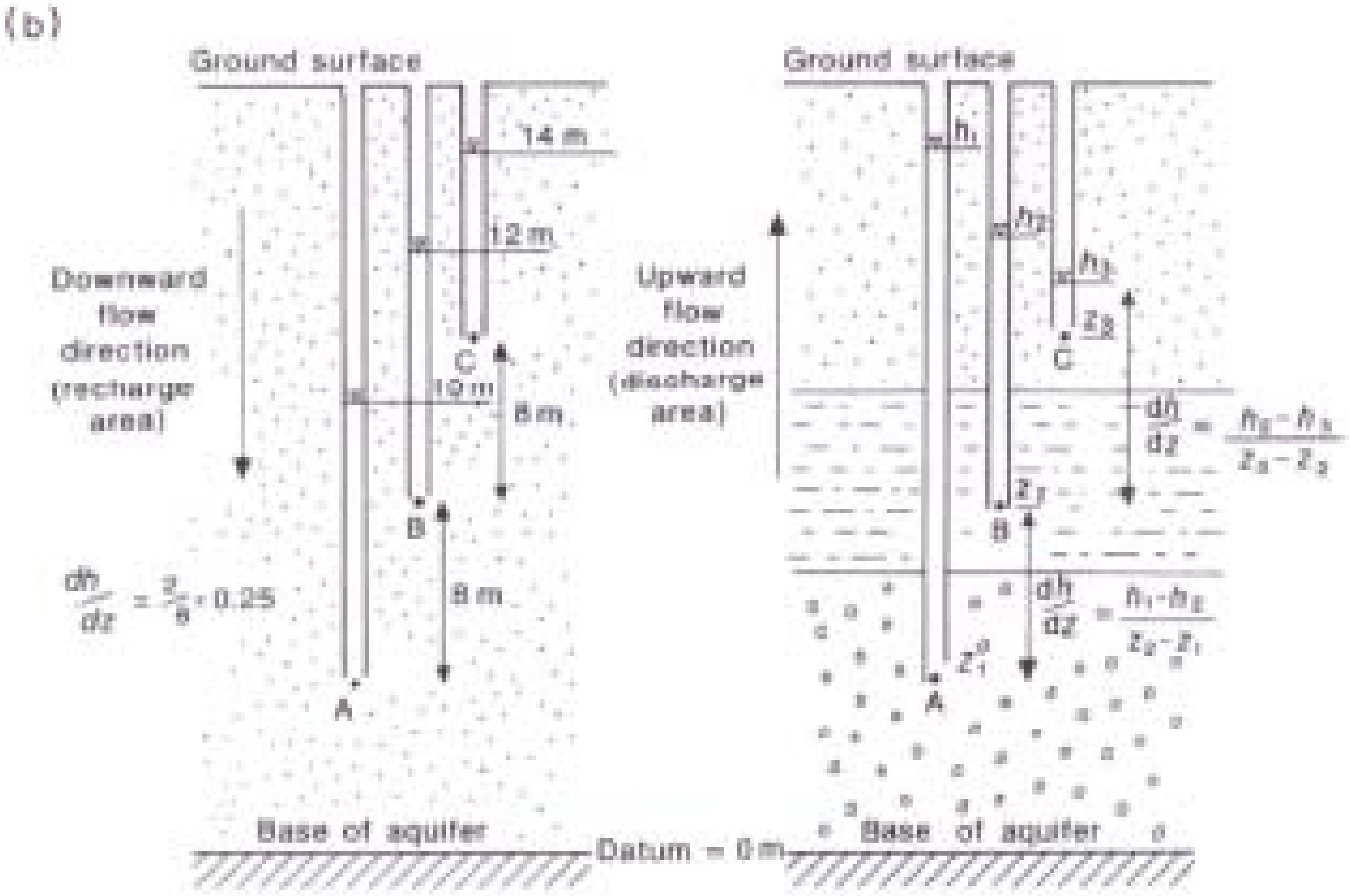
– Determination of flow direction from piezometric measurement



# Permeability

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- K (hydraulic conductivity, 수리전도도) is related to medium & fluid

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

  - μ: viscosity (점성도) of fluid, unit: Pa·s, water: ~$10^{-3}$ Pa·s = 1 cp
  - ρ: density of fluid, unit: kg/$m^3$, water: $10^3$ kg/$m^3$
  - g: acceleration due to gravity
  - k: permeability, unit: $m^2$

# Permeability

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| Rock Type | k (m2) | k (Darcies) | K (m/s) |
|---|---|---|---|
| Coarse gravels | $10^{-9}$-$10^{-8}$ | $10^{3}$-$10^{4}$ | $10^{-2}$-$10^{-1}$ |
| Sands, gravels | $10^{-12}$-$10^{-9}$ | $10^{0}$-$10^{3}$ | $10^{-5}$-$10^{-2}$ |
| Fine sands, silts | $10^{-16}$-$10^{-12}$ | $10^{-4}$-$10^{0}$ | $10^{-9}$-$10^{-5}$ |
| Clays, shales | $10^{-23}$-$10^{-16}$ | $10^{-11}$-$10^{-4}$ | $10^{-16}$-$10^{-9}$ |
| Dolomites | $10^{-12}$-$10^{-10}$ | $10^{0}$-$10^{2}$ | $10^{-5}$-$10^{-3}$ |
| Limestones | $10^{-22}$-$10^{-12}$ | $10^{-10}$-$10^{0}$ | $10^{-15}$-$10^{-5}$ |
| Sandstones | $10^{-17}$-$10^{-11}$ | $10^{-5}$-$10^{1}$ | $10^{-10}$-$10^{-4}$ |
| Granites, Gneiss | $10^{-20}$-$10^{-16}$ | $10^{-8}$-$10^{-4}$ | $10^{-13}$-$10^{-9}$ |
| Basalts | $10^{-19}$-$10^{-13}$ | $10^{-7}$-$10^{-1}$ | $10^{-12}$-$10^{-6}$ |

- k (permeability, 투수율) is a measure of only 'medium'
- Also called, coefficient of permeability, intrinsic permeability
- 1 darcy = $0.987 \times 10^{-12}$ $m^2$ ~ $10^{-12}$ $m^2$ = $10^{-5}$ m/sec
- 1 m/sec = $10^{-7}$ $m^2$

**Answer to Kyungjin's question**

$$K = \frac{\rho g k}{\mu} = \frac{10^3 \times 10 \times k}{10^{-3}} = 10^7 \times k$$

- Permeability has very large variation → very important to characterize/determine its value

Jaeger et al., 2007

# Darcy's law

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- Expressed in terms of pressure and elevation head,

$$q = -K\nabla\left(z + \frac{P}{\rho_w g}\right)$$

- When all piezometers are bottomed at the same elevation

$$q = -\frac{k}{\mu}\nabla p \longleftarrow K = \frac{\rho g k}{\mu}$$

- In 1D,

$$q = -\frac{k}{\mu}\frac{dP}{dl}$$

# Darcy's law

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- Nature of Darcy's velocity
- Fluid flux, q: superficial velocity
- linear or pore velocity (*v*) of groundwater with porosity, *n*

$$v = \frac{q}{n}$$

- Pore velocity (v) will be always larger than the superficial velocity.

# Reminder
## Heat Diffusion Equation

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$$\dot{E}_{in} + \dot{E}_g - \dot{E}_{out} = \dot{E}_{st}$$

$$\dot{E}_{in} : energy\ inflow$$

$$\dot{E}_{out} : energy\ outflow$$

$$\dot{E}_g : energy\ generation$$

$$\dot{E}_{st} : energy\ storage$$

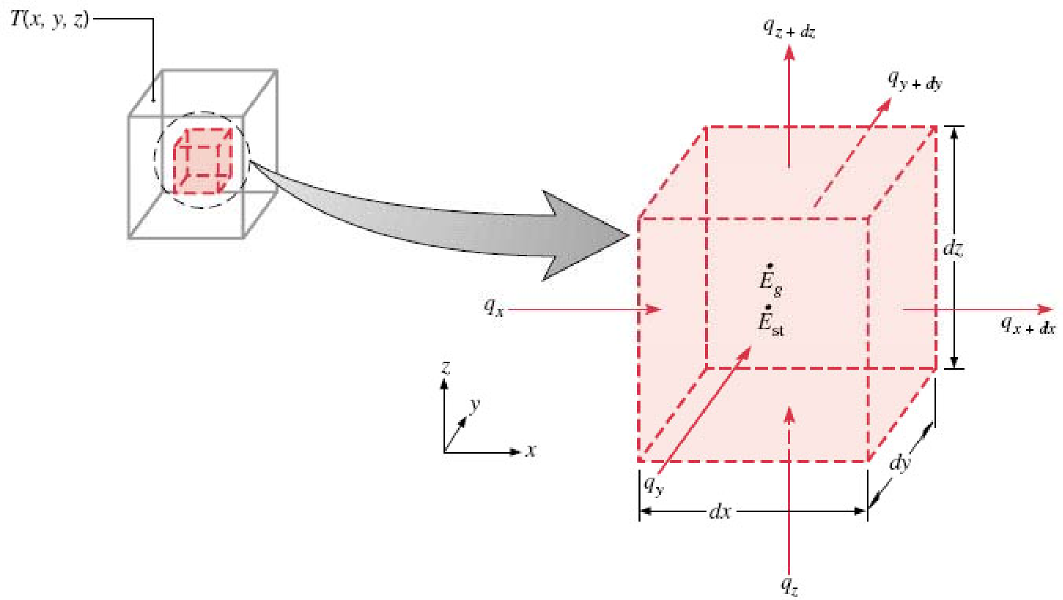


FIGURE 2.11 Differential control volume, $dx\,dy\,dz$, for conduction analysis in Cartesian coordinates.

- $E_g$: some energy conversion process, e.g., chemical or nuclear reaction
- $E_{st}$: rate of change of thermal energy stored by the matter

# Analogy with Heat diffusion equation

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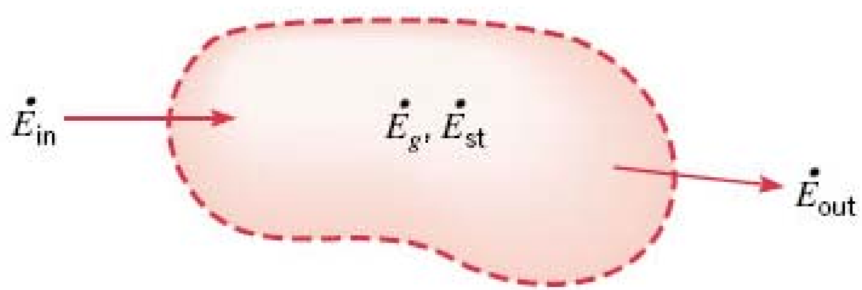


| Heat transfer<br>Energy Conservation | Fluid flow in porous rock<br>Mass Conservation |
|---|---|
| $\Delta E_{st} = E_{in} - E_{out} + E_g$ | $\Delta m_{st} = m_{in} - m_{out} + m_g$ |
| $E_{st}$ : *Energy stored in control volume* | $m_{st}$ : *mass stored in control volume* |
| $E_{in}$ : *Energy entering the control volume* | $m_{in}$ : *mass entering the control volume* |
| $E_{out}$ : *Energy leaving the control volume* | $m_{out}$ : *mass leaving the control volume* |
| $E_g$ : *Thermal Energy Generation* | $m_g$ : *mass Generation* |

# Diffusion equation
## Derivation (1)

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- We follow the exactly same procedure with the heat diffusion equation
- Energy conservation → mass conservation
- Heat → fluid flow
- Temperature → hydraulic head
- Hydraulic conductivity → hydraulic conductivity
- Fourier's law → Darcy's law

# Diffusion equation
## Derivation (2)

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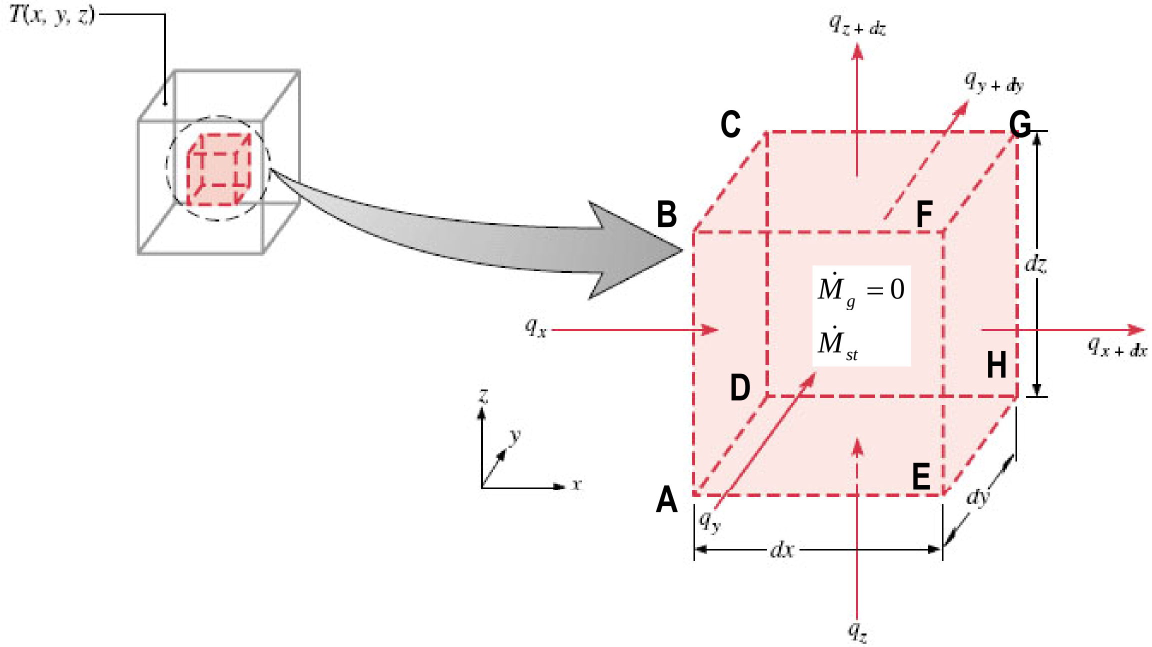
- The basis for developing such an equation is a conservation of **”mass”**.
- When there is no mass generated (= there is no sink or source)→ a conservation of fluid mass statement may be given as; mass inflow rate – mass outflow rate = change in mass storage with time.



# Diffusion equation
## Derivation (3)

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**Unit: mass per time**

- Mass inflow rate through the face ABCD = $\rho_w q_x \Delta y \Delta z$
  where $\rho_w$: density of fluid, $q_x$: specific discharge or flow flux (L/T)
- Mass outflow rate through the face EFGH = $\left[\rho_w q_x + \dfrac{\partial(\rho_w q_x)\Delta x}{\partial x}\right]\Delta y \Delta z$
- Net outflow rate is the difference between the inflow and outflow,
  Net outflow rate through EFGH = $-\dfrac{\partial(\rho_w q_x)\Delta x \Delta y \Delta z}{\partial x}$
- Making similar calculations for the remainder of the cube,
  Net outflow rate through CDHG = $-\dfrac{\partial(\rho_w q_y)\Delta x \Delta y \Delta z}{\partial y}$

  Net outflow rate through BCGF = $-\dfrac{\partial(\rho_w q_z)\Delta x \Delta y \Delta z}{\partial z}$

# Diffusion equation
## Derivation (4)



- Adding these results,
  Net outflow rate through **ALL** the faces =

$$-\left[\frac{\partial(\rho_w q_x)}{\partial x}+\frac{\partial(\rho_w q_y)}{\partial y}+\frac{\partial(\rho_w q_z)}{\partial z}\right]\Delta x\Delta y\Delta z$$

- Right hand side of the conservation statement is merely a change in mass storage with time (please confirm if units are mass/time),

$$\frac{\partial(\rho_w n)}{\partial t}\Delta x\Delta y\Delta z$$

- Collecting above two equations and dividing by unit volume,

$$-\left[\frac{\partial(\rho_w q_x)}{\partial x}+\frac{\partial(\rho_w q_y)}{\partial y}+\frac{\partial(\rho_w q_z)}{\partial z}\right]=\frac{\partial(\rho_w n)}{\partial t}$$

- Above equations states that net outflow rate per unit volume equals the time rate of change of fluid mass per unit volume.

# Diffusion equation
## Derivation (5)

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– By further assuming that density of fluid does not vary spatially,

$$\underbrace{-\left[\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}\right]}_{\text{Net fluid outflow rate for the unit volume}}=\underbrace{\frac{1}{\rho_w}\frac{\partial(\rho_w n)}{\partial t}}_{\text{Time rate of change of fluid volume within the unit volume = gain or loss in fluid volume per time within the unit volume}}$$

– By substituting Darcy's law into specific discharge term, *q*;

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right)=\frac{1}{\rho_w}\frac{\partial(\rho_w n)}{\partial t}$$

– We need to do something with the term in the right (because it is not expressed in terms of '*h*'.

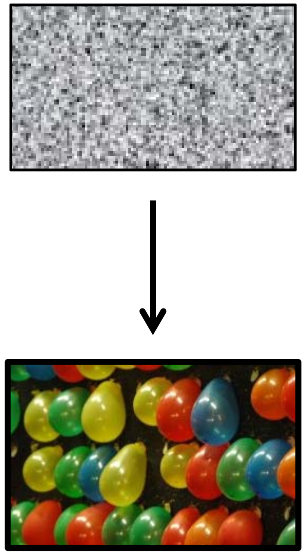
# Diffusion equation
## Derivation (5)



- Let's assume that the gains or losses in fluid volume within the unit volume are proportional to changes in hydraulic head - h↑:water gone into the storage, h↓: water removal from the storage.

$$\frac{1}{\rho_w}\frac{\partial(\rho_w n)}{\partial t} = S_s \frac{\partial h}{\partial t}$$

$S_s$ : specific storage ($L^{-1}$) – a measure of the volume of water(fluid) withdrawn from or added to the unit volume when h changes a unit amount. A difficult concept to grasp but remember that this has to do with three things: porosity, compressibility of water & compressibility of rock pore.



- Finally we obtain the diffusion equation for fluid flow for porous media

**Baloon ~ pore**
**Air ~ water**

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

**Higher head (pressure) → more water due to compressed water & expansion of pore**

# Diffusion equation
## Derivation (6)

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- When K is isotropic, the equation becomes;

$$\frac{\partial}{\partial x}\left(K\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K\frac{\partial h}{\partial z}\right)=S_s\frac{\partial h}{\partial t}$$

- When K is homogeneous (does not change spatially);

$$K\left[\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}\right]=S_s\frac{\partial h}{\partial t}$$

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

- By putting $\frac{K}{S_s}=c$

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}=\frac{1}{c}\frac{\partial h}{\partial t}$$

- *c*: hydraulic diffusivity ($L^2/T$)

$$\nabla^2 h=\frac{S_s}{K}\frac{\partial h}{\partial t}$$

# Diffusion equation
## Derivation (7)

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– For steady state;

$$K\left[\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}\right]=\cancel{S_s\frac{\partial h}{\partial t}} \rightarrow 0$$

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}=\nabla^2 h=0 \longleftarrow \textbf{Laplace Equation}$$

# Diffusion equation
## Expression in terms of hydraulic pressure

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- From, $h = z + \frac{P}{\rho_w g}$
- When z = 0, which is when the elevation is the same (i.e., plate with the same elevation) $h = 0 + \frac{P}{\rho_w g}$

$$K\left[\frac{\partial^2}{\partial x^2}\left(\frac{p}{\rho_w g}\right) + \frac{\partial^2}{\partial y^2}\left(\frac{p}{\rho_w g}\right) + \frac{\partial^2}{\partial z^2}\left(\frac{p}{\rho_w g}\right)\right] = S_s \frac{\partial}{\partial t}\left(\frac{p}{\rho_w g}\right)$$

$$\frac{k}{\mu}\left[\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2}\right] = S\frac{\partial p}{\partial t} \longleftarrow S = \frac{S_s}{\rho_w g}$$

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} = \frac{\mu S}{k}\frac{\partial p}{\partial t} = \frac{1}{c}\frac{\partial p}{\partial t}$$

Diffusion equation expressed in terms of pore hydraulic pressure

# Diffusion equations
## Heat diffusion and porous media flow

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– Heat diffusion equation

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q}=\rho c_p\frac{\partial T}{\partial t}$$

– Diffusion equation for fluid flow in porous media

$$\frac{\partial}{\partial x}\left(K\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K\frac{\partial h}{\partial z}\right)+\dot{q}=S_s\frac{\partial h}{\partial t}$$

# Term Paper

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| Group | Members | Title |
|---|---|---|
| 1 | Han Na Kim, Hun Joo Lee, Hun Hoe Cho | Case studies of Geothermal Power Plant and remaining issues for Korea |
| 2 | Eun Ji Oh, Jong oong Joo, Chang jo Choi | Case studies of Soultz site (France) and Cooper Basin (Australia) |
| 3 | Min-Su Kim, Jin son, Sung-Min Kim, Sung-Chan Oh | Is EGS applicable in Korea? |
| 4 | Ki Yeol Kim, Young Soo Lee, Seong Moon Kim | Environmental Impacts |
| 5 | Bona Park, YeongSook Park, Kyungjin Yoo | Geothermal Heat Pump – Comparison between installations of GHP in Korea |
| 6 | Taehyun Kim, Jaewon Lee | Thermally induced permeability changes for a Geothermal Reservoir Simulation |
| 7 | Sunghoon Ryu, Seungbum Choi | Study on Drilling & Borehole stability for Geothermal Energy Development |
| 8 | Jiyoung Shin, DongKeun Lee | Numerical Simulation of conductive heat transfer under the biaxial stress and fracture presence |

# Fluid flow in fractured rock

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- In many rock types (especially hard rocks), fractures are the main pathways of fluid flow – note that hard rocks are attractive for underground space.
- Understandings on fluid flow in fractures are essential.
  - Enhanced Geothermal System
  - Fractured Oil Reservoir
  - Geological repository of high level nuclear waste
  - Underground structure (mines, tunnels and oil storages)

# Fractured rock fluid flow
## How do we tackle it?

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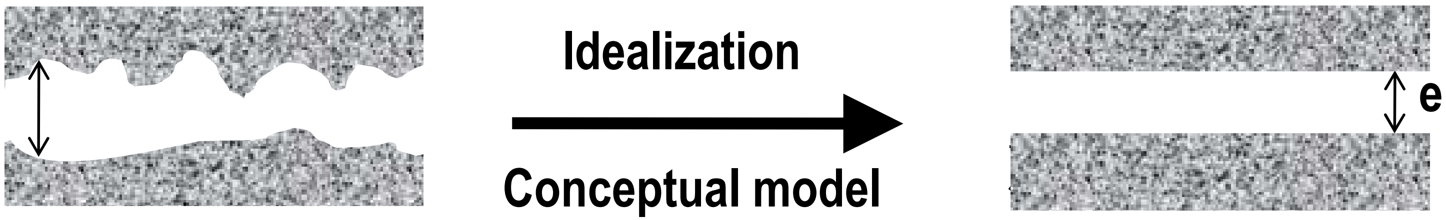
**Aperture: size of opening measured normal to the fracture wall**




**Real rock fracture**

**Idealized rock fracture**

- Hard to estimate Q due mainly to complex geometry

-Analytical solution exist to calculate Q and velocity profile

# Fractured rock fluid flow
## Cubic Law

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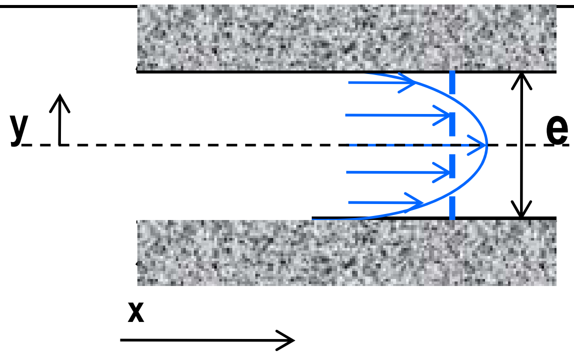


Velocity ($v$)distribution between parallel plates

$$v = -\frac{1}{8\mu}\left(e^2 - 4y^2\right)\frac{d}{dx}(p + \rho_w gz) = -\frac{1}{8\mu}\left(e^2 - 4y^2\right)\frac{d(\rho_w gh)}{dx}$$

- Navier-Stokes' equation for laminar flow.
- most of geological application involves laminar flow (low Reynolds number, <2000, de Marsily, 1986)

$$\mathrm{Re} = \frac{\rho V d}{\mu}$$

ρ: density of fluid
V: mean velocity of fluid
D: diameter of the pipe
μ: viscosity

# Fractured rock fluid flow
## Cubic Law

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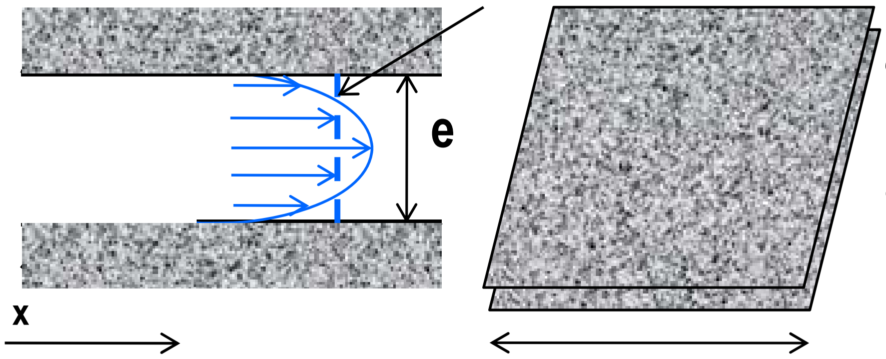
We take average velocity. $V_{av}=2/3\ V_{max}$




$$Q=\int_{-\frac{e}{2}}^{\frac{e}{2}} v(wdy)=-\frac{we^3}{12\mu}\frac{d}{dx}(p+\rho_w gz)$$

$$average\ velocity, v=Q/ew=-\frac{e^2}{12\mu}\frac{d}{dx}(p+\rho_w gz)=-\frac{e^2}{12\mu}\frac{d}{dx}\rho_w gh$$

**Hydraulic conductivity (K) of parallel plate model**

$$q=-\frac{\rho_w ge^2}{12\mu}\frac{\partial h}{\partial x}$$

$$Q=qA=-\frac{\rho_w ge^2}{12\mu}A\frac{\partial h}{\partial x}=-\frac{\rho_w ge^2}{12\mu}(e\times 1)\frac{\partial h}{\partial x}$$

$$\boxed{Q=-\frac{\rho_w ge^3}{12\mu}\frac{\partial h}{\partial x}}$$

$$\boxed{Q=-\frac{e^3}{12\mu}\frac{\partial p}{\partial x}} \leftarrow$$ **with zero elevation**

$\rho_w$: density of fluid
g: acceleration of gravity
μ: viscosity

- Cubic law: for a given gradient in head and unit width (w), flow rate through a fracture is proportional to the **cube** of the fracture aperture.

# Fractured rock fluid flow
# Measurement of aperture

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- Direct measurement
  - Insertion of feeler gauge (steel with different thickness)
  - Impression packer
  - Borehole camera

- Indirect measurement
  - Back calculation from the flow rates

unknown

$$Q = \frac{\rho_w g e^3}{12\mu} \frac{\partial h}{\partial x} \qquad e = \left( \frac{12\mu Q}{\rho_w g} / \frac{\partial h}{\partial x} \right)^{1/3}$$

www.wikipedia.org

# Fractured rock fluid flow
# Equivalent permeability

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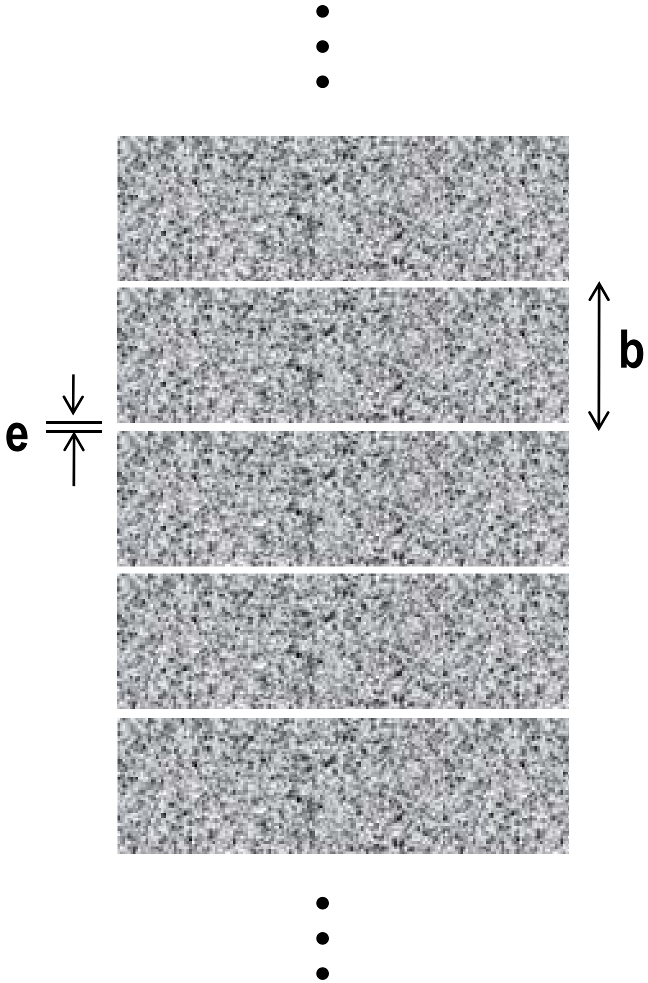



**Flow rate of N fractures**

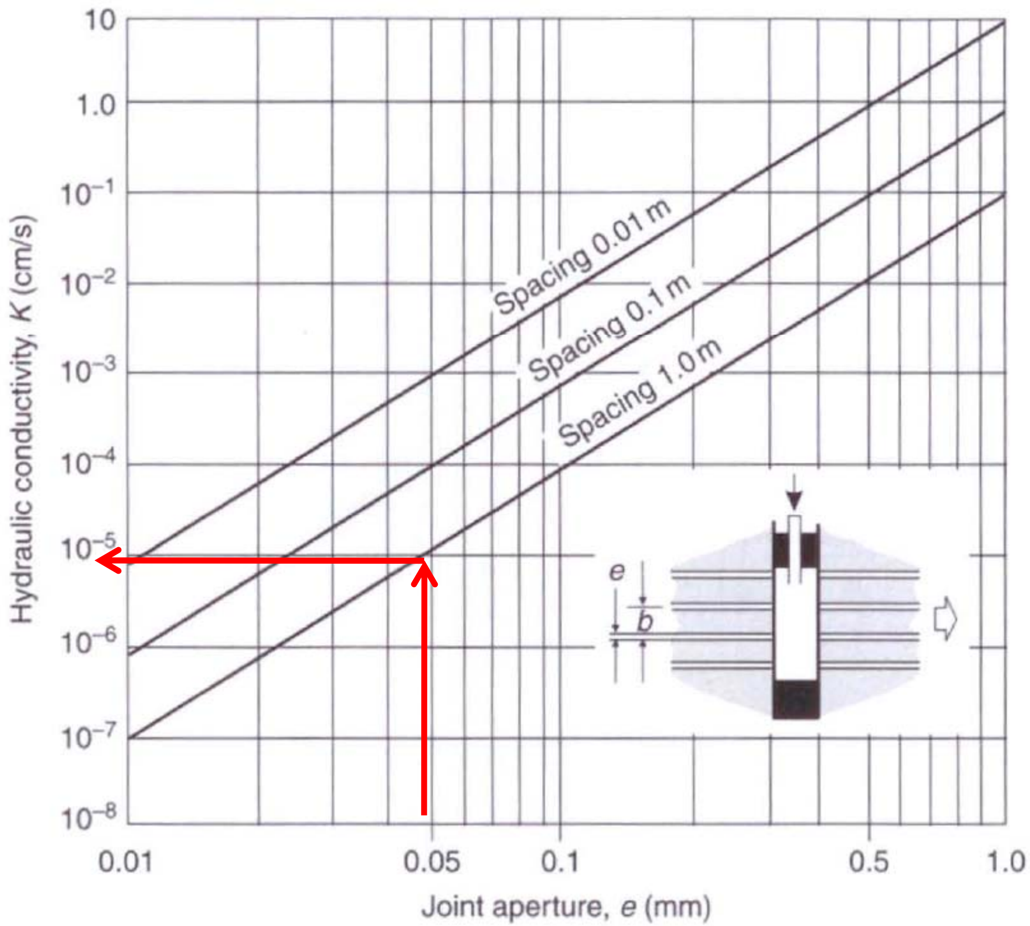
**Equivalent hydraulic conductivity (K) of multiple parallel plate models**

$$Q = \frac{\rho_w g e^3}{12\mu}\frac{\partial h}{\partial x} \times N = \frac{\rho_w g e^3}{12\mu}\frac{1}{b} bN \frac{\partial h}{\partial x}$$

$$K = \frac{\rho_w g N e^3}{12\mu} = \frac{\rho_w g e^3}{12\mu b} \qquad k = \frac{Ne^3}{12} = \frac{e^3}{12b}$$

- K: hydraulic conductivity
- k: permeability
- e: aperture
- N: number of fracture per unit distance, ($L^{-1}$)
- b: spacing (L)

# Fractured rock fluid flow
## Equivalent permeability




$$K = \frac{\rho_w g e^3}{12\mu b}$$

**A sandstone with K of $10^{-5}$ cm/s (which is $10^{-7}$ m/s ~$10^{-14}$ $m^2$~$10^{-2}$Darcy~10mD) correspond to aperture 50μm in 1 m interval.**

**Influence of fracture aperture e and spacing b on hydraulic conductivity K in the direction of a set of smooth parallel fractures in a rock mass (Hoek et al., 2004)**

# Fractured rock fluid flow
## Characterisation

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- Geometrical properties of fractures
  - Orientation (dip and dip direction), size (trace length in 2D), density (spacing in parallel infinite fracture), location, aperture, roughness
- Characterization method
  - Exposed rock faces
    - scanline sampling: line-based sample, use measuring tape (줄자) of 2-30 m.
    - Window sampling: area-based sample, rectangle of measuring tapes
  - Borehole sampling
- We then need to construct a geometric model of fractured rock – deterministic or stochastic generation of fractures

# Fractured rock fluid flow
# Discrete Fracture Network

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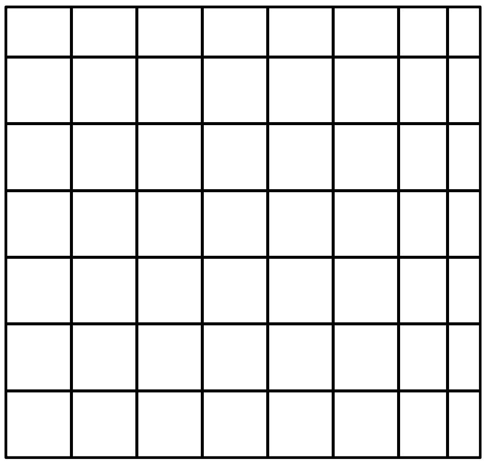
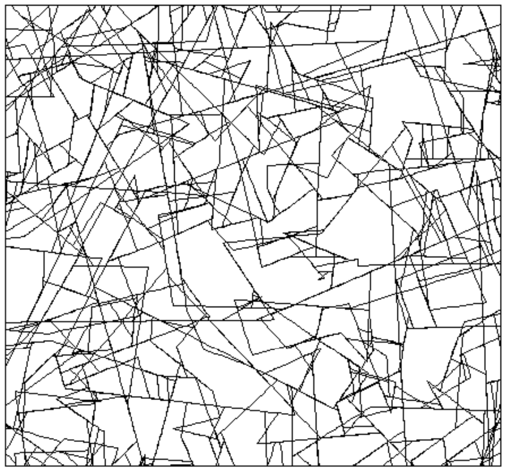
- Geometrical models based on the characterisation



**Idealized regular fracture model**



**Discrete Fracture Network (암반균열망)**

# Content of this week's lecture



- Fluid flow in porous media
- Darcy's law
- Permeability vs. Hydraulic Conductivity
- Diffusion Equation for fluid flow in porous media
- Fluid flow in fractured media
  - Cubic law
  - Permeability defined in fractured rock
  - Characterisation and Discrete Fracture Network (DFN)

# Content of next week's lecture

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- Monday
  - Some useful solutions for steady and transient state fluid flow
  - Convective heat transfer

- Wednesday
  - Exploration techniques
    By Tae Jong Lee from KIGAM (Korea Institute of Geosciences and Mineral Resources)
  - One question gives 2 points. (attendance of one lecture = 2 points)

# References

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- de Marsily G, 1986, Quantitative Hydrogeology, Academic press, Inc.
- Duncan CW and M CW, 2004, Rock Slope Engineering, 4th Ed. (based on Hoek and Bray's 3rd edition), Spon Press
- Hiscock KM, 2005, Hydrogeology – Principles and Practice, Blackwell publishing