IMPORTANT ENGINEERING & HYDROGEOLOGIC PROPERTIES OF ROCKS (02)

I Main Topics

A Density
B Hardness
C Stress
D Strain
E Strength
F Elastic properties
G Creep behavior
H Porosity
I Hydraulic conductivity
J Chemical stability and reactivity

II Density

A Density: mass/volume (e.g. kg/m^3)
Example: $\rho_{water} = 10^3\ kg/m^3$
B Specific gravity (ρ/ρ_{water})
C Unit weight (γ = weight/volume)
D Factors affecting density
1 Composition
2 Porosity
3 Saturation

III Hardness

A Mohs hardness scale

1 Talc	2 Gypsum
3 Calcite	4 Flourite, Iron
4-4.5 Steel	
5 Apatite, Glass	6 Orthoclase
7 Quartz	8 Topaz
9 Corundum	10 Diamond

B Factors affecting rock hardness

1 Mineralogy (± cement)

2 Weathering: generally decreases rock hardness

IV Stress

A Dimensions: Force/area

B Units: 1 Pa = 1N/m^2

1 MPa = 10^6 N/m^2 = 145 psi

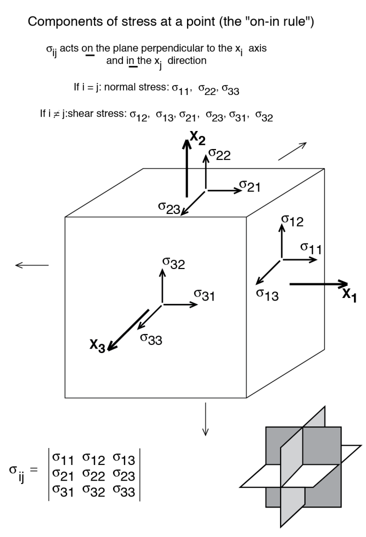
≈ 10 atm

C Pressure at bottom of a 10-m-deep pool ≈ 0.1 MPa ≈1 atmosphere

D Stress as a tensor (quantities with two associated directions)

1 σ_{ij} acts on a plane normal to the i- direction, and in the j-direction

2 Normal stress acts normal to a surface; shear stress acts parallel to a surface



V Strain

A Strain measures deformation

B Elongation

$$\varepsilon = \left(L_f - L_0\right)/L_0 = \Delta L/L_0$$

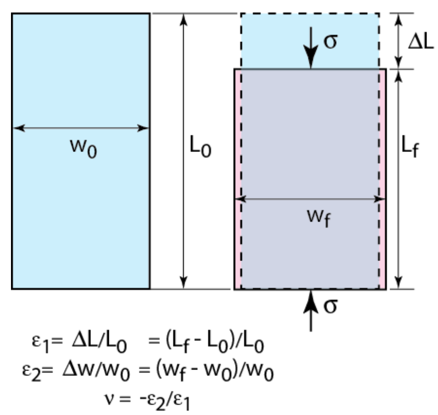
C ε is dimensionless

D Poisson's ratio

$$\nu = -\varepsilon_2/\varepsilon_1$$

from uniaxial stress tests

Dimension changes from a uniaxial compression test



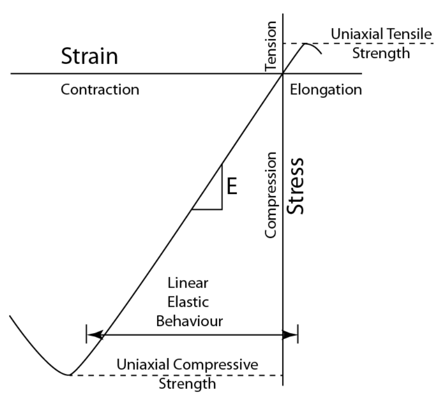
VI Strength

A Strength: maximum stress that a rock can withstand

B Uniaxial compressive strength ~ 10x uniaxial tensile strength

C Factors affecting rock strength

1. Rock type (crystalline vs. clastic) and mineralogy
2. Weathering: generally decreases rock strength
3. Discontinuities: these decrease rock strength
4. Sample size: small samples stronger than large samples; see (3)



VI Strength

C Factors affecting rock strength
  1 Rock type (crystalline vs. clastic) and mineralogy; crystalline rocks generally stronger
  2 Weathering: generally decreases rock strength
  3 Grain-scale fabric
  4 Discontinuities: they decrease rock strength
  5 Sample size: strength decreases with sample size

Basalt with columnar joints

Granitic rock with sheeting joints

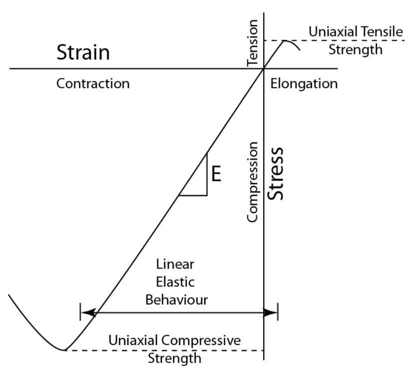
VII Elastic Properties

A Stress: strain relations
  1 Hooke's Law of Linear Elasticity (1D)

$$\sigma_{xx} = E\varepsilon_{xx}$$

  E = Young's modulus
  2 Shear stress & shear strain

$$\sigma_{xy} = 2\mu\varepsilon_{xy}$$



VII Elastic Properties

3 Hooke's Law of Linear Elasticity for isotropic materials (3D)

$\varepsilon_{xx} = \sigma_{xx}/E - (\sigma_{yy}+\sigma_{zz})(\nu/E)$

$\varepsilon_{yy} = \sigma_{yy}/E - (\sigma_{zz}+\sigma_{xx})(\nu/E)$

$\varepsilon_{zz} = \sigma_{zz}/E - (\sigma_{xx}+\sigma_{yy})(\nu/E)$

Summing these,
with $\sigma_{xx} = \sigma_{yy} = \sigma_{zz} = -P$,
yields the volumetric dilation (Δ) as a function of the pressure (P) and the bulk modulus (K)

$$\Delta = \frac{\Delta V}{V_0}$$
$$= \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}$$
$$= \frac{-3P}{E} - \frac{-6P\nu}{E}$$
$$= [-P]\left[\frac{3(1-2\nu)}{E}\right]$$
$$= [-P][K]$$

VII Elastic Properties

C Relationship between elastic properties and seismic wave speeds

The bulk modulus (K) and shear modulus (μ) can be deduced from the compressional wave speed (V_p) and shear wave speed (V_s) if the density is known

Two equations with two elastic unknowns if the density is known

$$V_p = \sqrt{\left(K + \frac{4}{3}\mu\right)\Big/\rho}$$

$$V_s = \sqrt{\mu/\rho}$$

$$\mu = \frac{E}{2(1+\nu)}$$

$$K = \left[\frac{3(1-2\nu)}{E}\right]$$

VIII Creep behavior

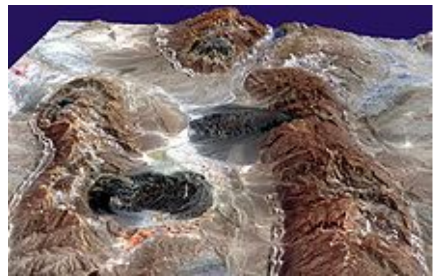
A Creep: "slow" inelastic deformation at low stress

B Rocks that creep

1 Ice

2 Salt

Salt glaciers (dark) in Iran



http://en.wikipedia.org/wiki/Salt_glacier

http://en.wikipedia.org/wiki/Waste_Isolation_Pilot_Plant

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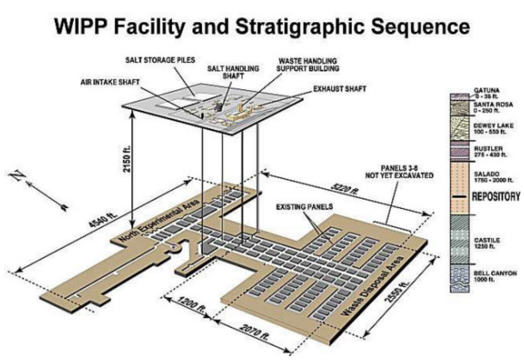
VIII Creep behavior

- WIPP repository for nuclear waste hosted in Salado Formation (salt) near Carlsbad, NM



http://en.wikipedia.org/wiki/Waste_Isolation_Pilot_Plant

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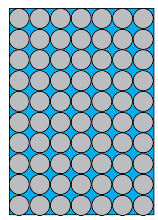
IX Porosity (n)

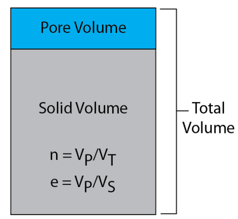
A Porosity (n)
  n = pore volume /total volume

B Void ratio (e)
  e = void volume /volume of solids

C Fluids (e.g. air, water, petroleum, natural gas) occupy voids

D Factors affecting porosity
  1 Rock type
  2 Cementation
  3 Weathering
  4 Sorting: excellent sorting (or poor grading) ➔ high porosity





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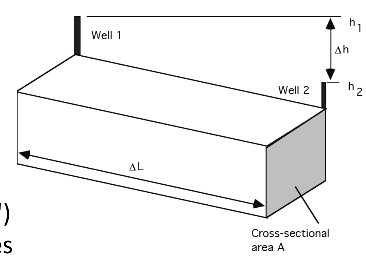
X Hydraulic conductivity (K)

A Darcy's Law for porous media flow

Q	=	-K	i	A
Discharge	=	(Hyd. cond)	(head gradient)	(Area)
m^3/sec	=	(m/sec)	(m/m)	(m^2)

B Hydraulic conductivity: how readily rock, modeled as a continuum, conducts fluid

C Factors affecting hydraulic conductivity
  1 Dynamic viscosity and density of fluid
  2 Character of rock ("intrinsic permeability")
    a Interconnection and apertures of pores
    b Interconnection and apertures of fractures



i = head gradient

$$i = \frac{\Delta h}{\Delta L} = \frac{h_2 - h_1}{\Delta L}$$

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Mechanical Energy in Flowing Water

- Consider the mechanical energy contained by a small mass of water *m*, volume V, and density ρ.
- For steady state, isothermal flow of an incompressible fluid (ρ is constant)
- (1) Total energy = kinetic energy + elevation potential energy + pressure potential energy.
- (2) Dimension of pressure: (force/area) or energy/volume (i.e. force x distance/volume).
- Pressure measures internal energy in a volume of fluid.
- (3) Total head = Velocity head + elevation head (H) + pressure head

(1) $$E_{total} = \frac{1}{2}mv^2 + mgH + E_{pressure}$$

Dividing through by V

(2) $$\frac{E_{total}}{V} = \frac{1}{2}\rho v^2 + \rho gH + P$$

Dividing through by ρg

(3) $$\frac{E_{total}}{\rho gV} = \frac{1}{2g}v^2 + H + \frac{P}{\rho g}$$

Mechanical Energy in Flowing Water

$$\frac{E_{total}}{\rho gV} = \frac{1}{2g}v^2 + H + \frac{P}{\rho g}$$

- Dimensions of hydraulic head: length.
- Hydraulic head: the standing elevation that water rises to in a well
- Usually the kinetic energy loss is negligible for ground water flow, so the hydraulic head is effectively the elevation head plus the pressure head.
- Water flows from high head (high potential energy) to low head (low potential energy): Q = -K i A
- If water flowed from high pressure to low pressure, then water would flow from the bottom of a swimming pool to the top!

XI Chemical stability and reactivity

Calcite or gypsum

The Great Blue Hole, Belize

http://en.wikipedia.org/wiki/Great_Blue_Hole

Sulphides (e.g., pyrite)

http://en.wikipedia.org/wiki/Acid_mine_drainage

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XI Chemical stability and reactivity

- Alkali–silica reaction ASR (pozzolanic reaction)
- An acid-base reaction between calcium hydroxide (Portlandite or $Ca(OH)_2$), and silicic acid (H_4SiO_4 or $Si(OH)_4$)
- Causes swelling of amorphous (glassy) silica

Cracks in a highway barrier from ASR

http://en.wikipedia.org/wiki/Alkali–silica_reaction

$$Ca(OH)_2 + H_4SiO_4 \rightarrow Ca^{2+} + H_2SiO_4^{2-} + 2\ H_2O \rightarrow CaH_2SiO_4 \cdot 2\ H_2O$$

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