CHAPTER 2

PROPERTIES OF AQUIFERS

PROPERTIES OF AQUIFERS

- **Pore spaces in porous media – voids, pores, interstices**
- **Characterized by size, shape, distribution, and irregularity.**

PROPERTIES OF AQUIFERS

- **Original interstices – created by geologic process; Alluvium,clay**

- **Secondary interstices – developed after rock formation; limestone, fractured rock**

PROPERTIES OF AQUIFERS

- **Size of interstices**
  - Capillary – water filled by capillary forces
  - Super capillary – capillary forces insignificant
  - Sub capillary – water held by adhesive forces

PROPERTIES OF AQUIFERS

- **Specific Surface** $= \frac{\text{Surface Area of Grains}}{\text{BulkVolume}}, (L^{-1})$

$$= \frac{\text{Surface Area of Grains}}{\text{Bulk Weight}}, (m^2/g)$$

- **S_S value more for clay than sand and gravel**
- **more sp. surface - more potential of contaminant removal**

PROPERTIES OF AQUIFERS

Specific Surface (S_s)	$\mathbf{cm^{-1}}$
Silicate powder	6.8×10^3 - 8.9×10^3
Loose sand	1.5×10^2 - 2.2×10^2
Soils	2×10^3 - 4×10^3
Sandstone	1.5×10^6 - 10×10^5
Limestone	0.15×10^4 - $1.3\ 10^4$

$\mathbf{cm^{-1}}$

PROPERTIES OF AQUIFERS

- **U.S. Dept Agriculture - Soil Analysis and classification**

	Size, mm	
Clay	< 0.002	
Silt	0.002 - 0.05	
Very fine silt	0.05 - 0.1	Fine
sand	0.10 - 0.25	
Medium sand	0.25 - 0.50	
Coarse sand	0.50 - 1.00	
Very coarse sand	1.0 - 2.0	
Gravel	> 2.0	

PROPERTIES OF AQUIFERS

SCS classification of gravel –

Fine gravel	0.6 -- 1.0 cm
Coarse gravel	1.0 -- 7.6 cm
Small cobbles	7.6 -- 15.2 cm
Large cobbles	15.2 -- 30.5 cm
Boulders	> 30.5 cm

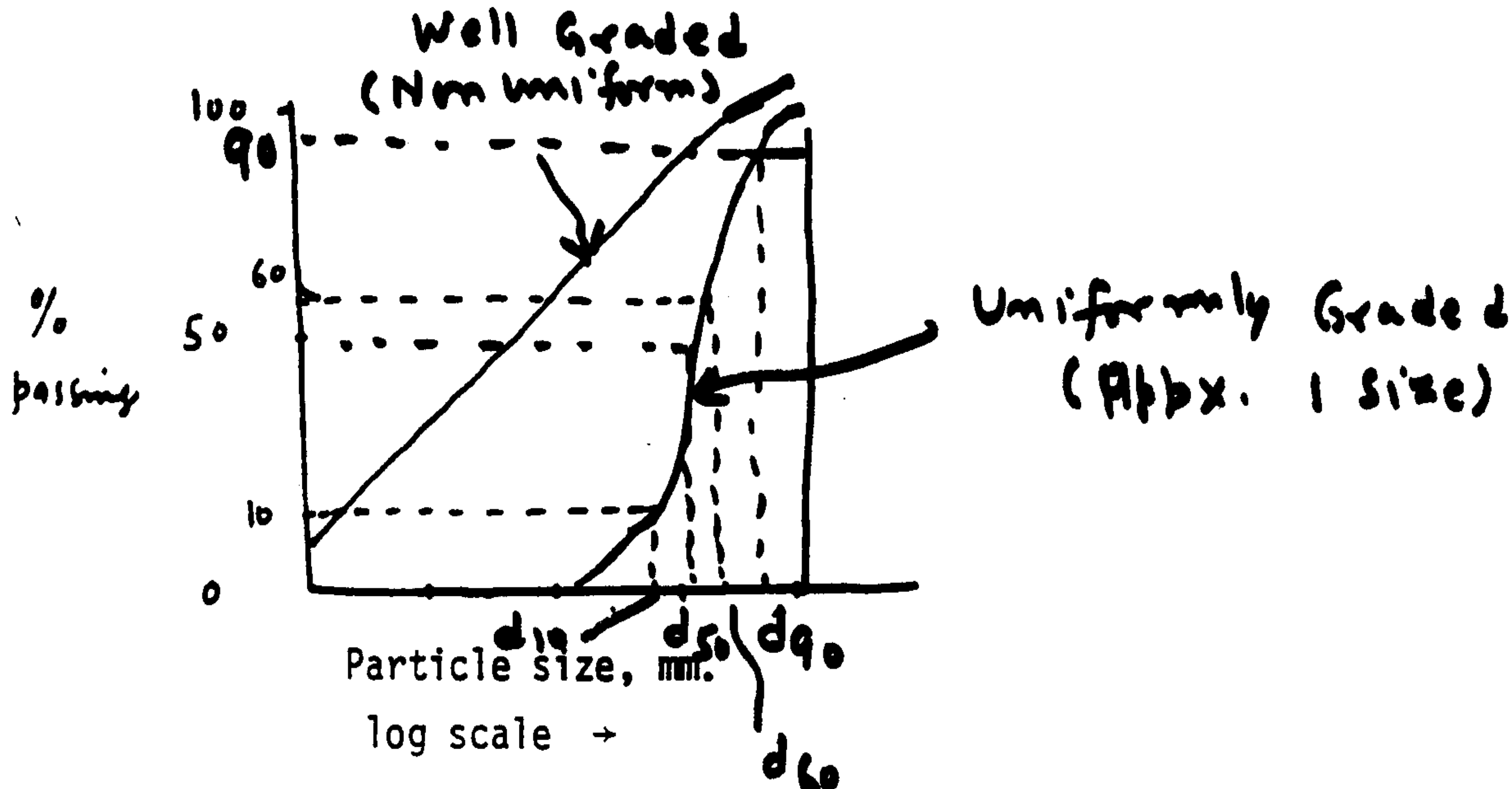
PROPERTIES OF AQUIFERS

- **Grain size Distribution (Sieve analysis):**

  Well graded material

  Uniform graded material

PROPERTIES OF AQUIFERS



PROPERTIES OF AQUIFERS

- Effective size (d_{10}) - maximum diameter of the smallest 10% passing by weight.
- Hazen's Uniformity coefficient = $\frac{d_{60}}{d_{10}}$
- U.C. from 1.0 to > 1.0

uniform material well graded material

PROPERTIES OF AQUIFERS

- **When U.C. = 1; d_{60} = d_{10} material is one of size**
- **For well graded material, 5 < U.C. < 10 or more**

PROPERTIES OF AQUIFERS

Porosity - measure of volume of interstices.

- express as % of void space to total volume of the mass.

$$\alpha = \frac{\text{void space}}{\text{bulk volume}} = 100 * \frac{w}{v}$$

PROPERTIES OF AQUIFERS

w - volume of water to saturate the pore space

v - total volume of rock or soil (volume of pores & grains)

α - f (shape, arrangement of grains, size distributions, degree of cementation and compaction)

PROPERTIES OF AQUIFERS

Unconsolidated formation - sand, gravel, silt, clay

Consolidated formation - sandstone, limestone, and igneous rocks

PROPERTIES OF AQUIFERS

- **Porosity changes with fracturing and solution**

PROPERTIES OF AQUIFERS

- **Porosity range for sedimentary materials:**

Material	α, %
Soils	50-60
(unconsolidated material)	
Clays	45-55
Silts	40-50
Sands	30-40
Gravel & Sand	20-35
Sandstone	10-20
Shale & Limestone	1-10

PROPERTIES OF AQUIFERS

Saturated Zone

$$\alpha = \frac{\text{Vol. of Voids}}{\text{Bulk Vol.}}$$

Specific Retention - % vol. Of water retained after saturation and drainage

PROPERTIES OF AQUIFERS

$$S_r = \frac{\text{Water Retained}}{\text{Bulk Vol.}} = \frac{W_r}{V}$$

Specific yield - % vol. Of water drained after saturation.

$$\alpha = S_r + S_y$$

S_y = f(grain size, shape and distribution of pores, compaction of aquifer)

PROPERTIES OF AQUIFERS

- **Specific yield is a fraction of porosity of an aquifer**
- **Uniform sand, S_y = 0.30**
- **Most alluvial aquifers, S_y = 0.10 - 0.20**

PROPERTIES OF AQUIFERS

- **Approximate values of S_y –**
- **(from Sacromento Valley, Ca.)**

Sy, %, α

- **Gravel 25**
- **Sand & gravel 20 30%**
- **Fine sand, sandstone 10**
- **Clay & gravel 5**
- **Clay, silt, & fine-grained deposits 3 55%**

PROPERTIES OF AQUIFERS

EXAMPLE 2.2.1 An undisturbed sample of a medium sand weighs 484.68 g. The core of the undisturbed sample is 6 cm in diameter and 10.61 cm high. The sample is oven-dried for 24 hr at 110°C to remove the water content. At the end of the 24 hr, the core sample weighs 447.32 g. Determine the bulk density, void ratio, water content, porosity, and saturation percentage of the sample.

SOLUTION: The dry weight of the sample is $W_d = 447.32$ g and the total weight is $W_T = 484.68$ g. The total volume of the undisturbed sample is

$$V_t = \pi r^2 h = \pi(3\text{ cm})^2(10.61\text{ cm}) = 300\text{ cm}^3$$

The *bulk density* is defined as the density of solids and voids together, after drying. Thus,

$$\rho_d = \frac{W_d}{V_t} = \frac{447.32\text{ g}}{300\text{ cm}^3} = 1.491\text{ g/cm}^3$$

Assuming quartz is the predominant mineral in the sample, then $\rho_m = 2.65\text{ g/cm}^3$

Thus, the volume V_s of the solid phase of the sample is

$$V_s = \frac{W_d}{\rho_m} = \frac{447.32\text{ g}}{2.65\text{ g/cm}^3} = 168.8\text{ cm}^3$$

Thus, the *total volume of voids* in the sample is

$$V_v = V_t - V_s = 300\text{ cm}^3 - 168.8\text{ cm}^3 = 131.2\text{ cm}^3$$

PROPERTIES OF AQUIFERS

With this information, we can calculate the *void ratio e* of the sample is

$$e = \frac{V_v}{V_s} = \frac{131.2\ \text{cm}^3}{168.8\ \text{cm}^3} = 0.777$$

The *volumetric water content* of a sample is the volume of the water divided by the volume of the sample

$$\theta_v = \frac{V_{water}}{V_t} = \frac{(W_T - W_d)/\rho_{water}}{V_t} = \frac{484.68\ \text{g} - 447.32\ \text{g}}{300\ \text{cm}^3} / 1\text{g}/\text{cm}^3 = 0.1245\ \text{g/cm}^3 = 0.125$$

where W_w is the total weight of the undisturbed sample before drying.
The *gravimetric water content* of the sample is

$$\theta_w = \frac{W_T - W_d}{W_d} \times 100 = \frac{484.68\ \text{g} - 447.32\ \text{g}}{447.32\ \text{g}} \times 100 = 8.35\%$$

The porosity of the sample is

$$\alpha = \frac{V_t - V_s}{V_t} \times 100 = \frac{300\ \text{cm}^3 - 168.8\ \text{cm}^3}{300\ \text{cm}^3} \times 100 = 43.73\%$$

Finally, the *saturation percentage of a sample* is defined as the percentage of the pore space that is filled by water,

$$\frac{\theta_v}{\alpha} \times 100 = \frac{(0.1245)}{(0.4373)} \times 100 = 28.47\%$$

■

PROPERTIES OF AQUIFERS

EXAMPLE 2.2.2 The void ratio of an unconsolidated clay sample is 1.19. Determine the porosity of the sample.

SOLUTION Using the definition of the void ratio of an undisturbed sample, $e = \frac{V_v}{V_s}$, and substituting $V_v = V_t - V_s$, then the void ratio is $e = \frac{V_t - V_s}{V_s} = \frac{V_t}{V_s} - 1 \rightarrow \frac{V_t}{V_s} = 1 + e$.

Substituting this into the porosity equation, we obtain

$$\alpha = \frac{V_t - V_s}{V_t} \times 100 = \left[1 - \frac{V_s}{V_t}\right] \times 100 = \left[1 - \frac{1}{1+e}\right] \times 100 = \frac{e}{1+e} \times 100$$

Thus, the porosity of the sample is

$$\alpha = \frac{e}{1+e} \times 100 = \frac{1.19}{1+1.19} \times 100 = 54.34\%$$

■

PROPERTIES OF AQUIFERS

EXAMPLE 2.2.3 The porosity of a quartz sand sample is 38.41%. Determine the bulk density of the sample.

SOLUTION The bulk density and porosity of an undisturbed sample are defined as $\rho_d = \frac{W_d}{V_t}$ and $\alpha = \frac{V_t - V_s}{V_t} \times 100$, respectively.

Substituting the dry weight of a sample $W_d = \rho_m V_s$ into the bulk density expression, we have $\rho_d = \frac{W_d}{V_t} = \frac{\rho_m V_s}{V_t}$ and the porosity is

$$\alpha = \frac{V_t - V_s}{V_t} \times 100 = \left[1 - \frac{V_s}{V_t}\right] \times 100 \rightarrow \frac{V_s}{V_t} = 1 - \frac{\alpha}{100}$$

Using the bulk density expression then yields $\rho_d = \frac{\rho_m V_s}{V_t} = \rho_m \left[1 - \frac{\alpha}{100}\right]$.

For quartz sand, $\rho_m = 2.65$ g/cm^3, the bulk density is

$$\rho_d = \rho_m \left[1 - \frac{\alpha}{100}\right] = \left(2.65\ \text{g/cm}^3\right)\left[1 - \frac{38.41}{100}\right] = 1.63\ \text{g/cm}^3$$

■

PROPERTIES OF AQUIFERS

EXAMPLE 2.2.4

Using the tabulated results of a grain size distribution test on a field sample, perform the following tasks:

(a) Prepare a grain size distribution curve for this sample.

(b) Is this a well-graded or poorly graded sample?

(c) Classify the sample using Table 2.2.2.

(d) What would be reasonable porosity values for this sample?

U.S. Standard Sieve Number	Mass retained (g)
3/8	49.95
4	26.70
8	25.29
16	50.58
30	72.57
40	25.50
100	33.60
200	7.53
Pan (passes through #200 sieve)	8.28
Total sample weight	300.00

SOLUTION

(a) The given data are analyzed as shown in the table below. Note that the particle size (sieve opening) corresponding to each U.S. Standard Sieve number is given in the table. The results yield the grain-size distribution curve shown in Figure 2.2.4.

Sieve	Grain size (mm)	Mass retained (g)	Percent finer by mass
3/8	9.5	49.95	83.35
4	4.75	26.70	74.45
8	2.36	25.29	66.02
16	1.18	50.58	49.16
30	0.6	72.57	24.97
40	0.425	25.50	16.47
100	0.15	33.60	5.27
200	0.075	7.53	2.76
Pan	<0.075	8.28	
Total sample weight		300	

PROPERTIES OF AQUIFERS

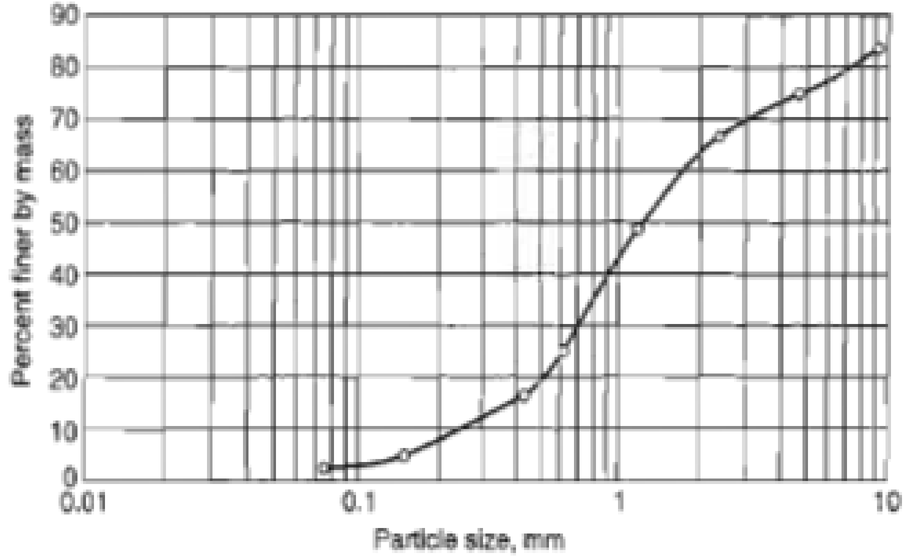


Figure 2.2.4. Grain-size distribution curve for Example 2.2.4.

(b) From the grain-size distribution curve:

$$d_{60} \cong 1.6 \text{ mm} \qquad \text{and} \qquad d_{10} \cong 0.23 \text{ mm}$$

From Equation 2.2.4, the uniformity coefficient is

$$U_c = \frac{d_{60}}{d_{10}} = \frac{1.6 \text{ mm}}{0.23 \text{ mm}} \approx 7$$

Since $U_c > 6$, the sample can be described as well graded (i.e., low uniformity).

(c) The percentage of clay and silt in the sample is approximately 2–3 percent, while about 60 percent of the sample is sand. The remaining 37–38 percent is composed of very fine to coarse gravel.

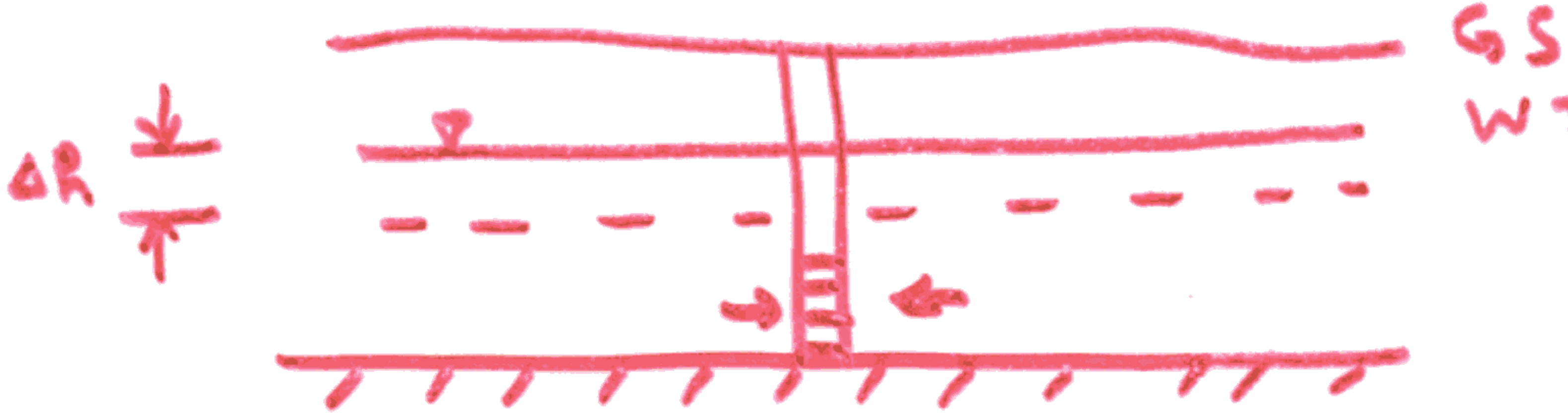
(d) The porosity of the sample could be somewhere between 20 and 35 percent based on our classification in part (c). ■

PROPERTIES OF AQUIFERS

Storage of Groundwater

- 1. **Unconfined Aquifer :**

Total Available Volume of GW = $A \Delta h S_y$



PROPERTIES OF AQUIFERS

A - Area of horizontal plane

Δh - Decrease in water table

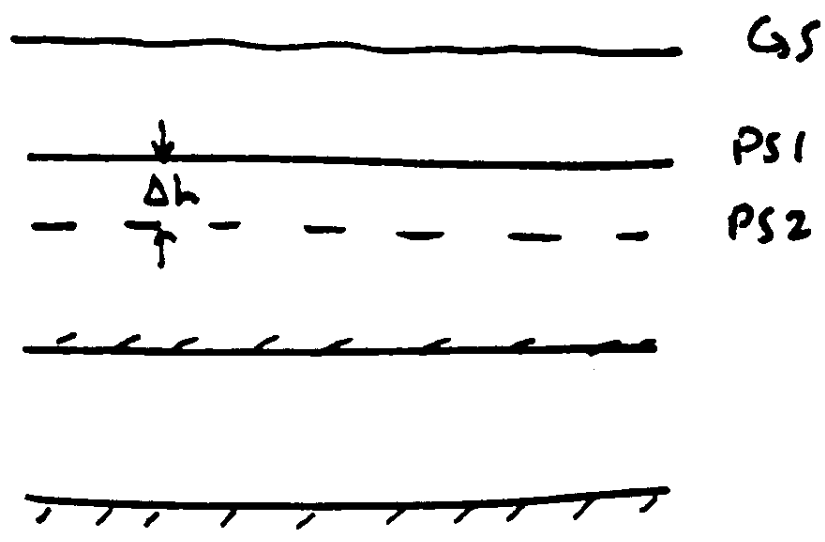
S_y - Specific yield

$S_y \approx 0.10 - 0.25$

PROPERTIES OF AQUIFERS

2. **Confined Aquifer :**

Total Available GW = A Δh S



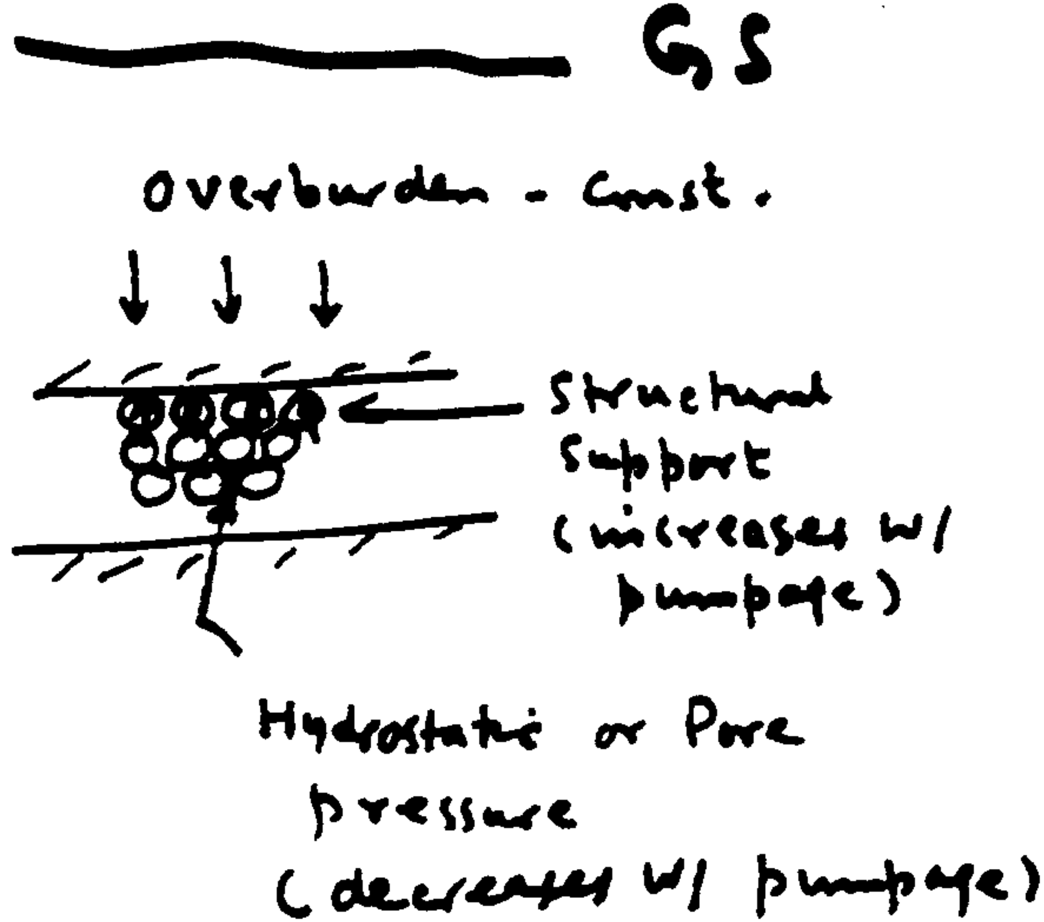
PROPERTIES OF AQUIFERS

- **Storage Coefficient (S) - Volume of water released from storage of unit area for unit decline in PS.**
- **$S = 10^{-3}$ to 10^{-5}**

PROPERTIES OF AQUIFERS

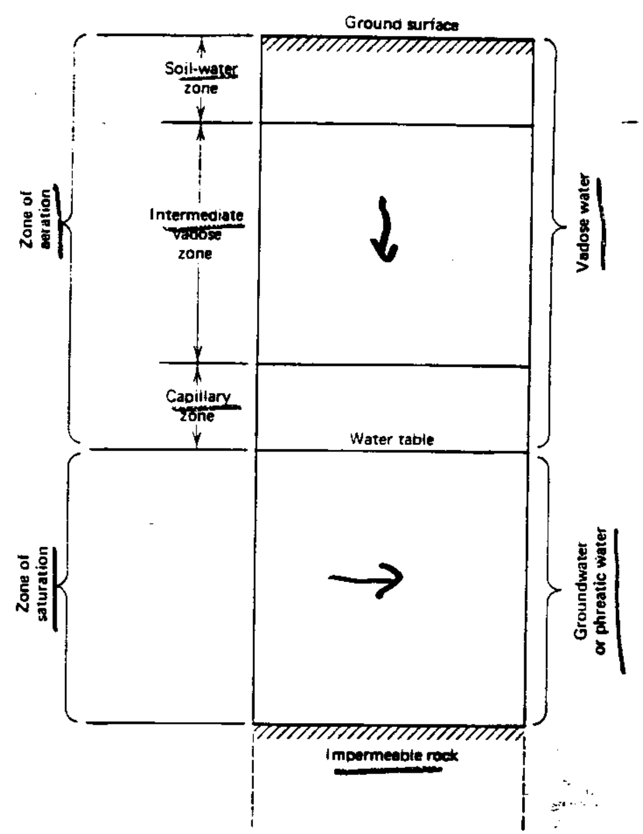
- Pressure of overburden
- Po = Pore pressure and intergranular pressure
  - With pumping from a well
    - hydrostatic pressure reduced, creating expansion of water
    - Aquifer load increases, reducing porosity.

PROPERTIES OF AQUIFERS



PROPERTIES OF AQUIFERS

- **Vertical Distribution of Groundwater**



PROPERTIES OF AQUIFERS

- **Wilting Point - Moisture Content of permanent wilting of plants. Not a unique value, but f = (type of plant, climate, root system, soil vol.)**

- **Field Capacity - Soil M.C. after excess gravitational water drained away and after downward rate of water movement materially decreased.**

PROPERTIES OF AQUIFERS

- **<u>Moisture Equivalent</u> - water content which saturated soil retains after being centrifuged at 1000 g force.**

  Sand: F.C. > M.E.

  loam: F.C. ≈ M.E.

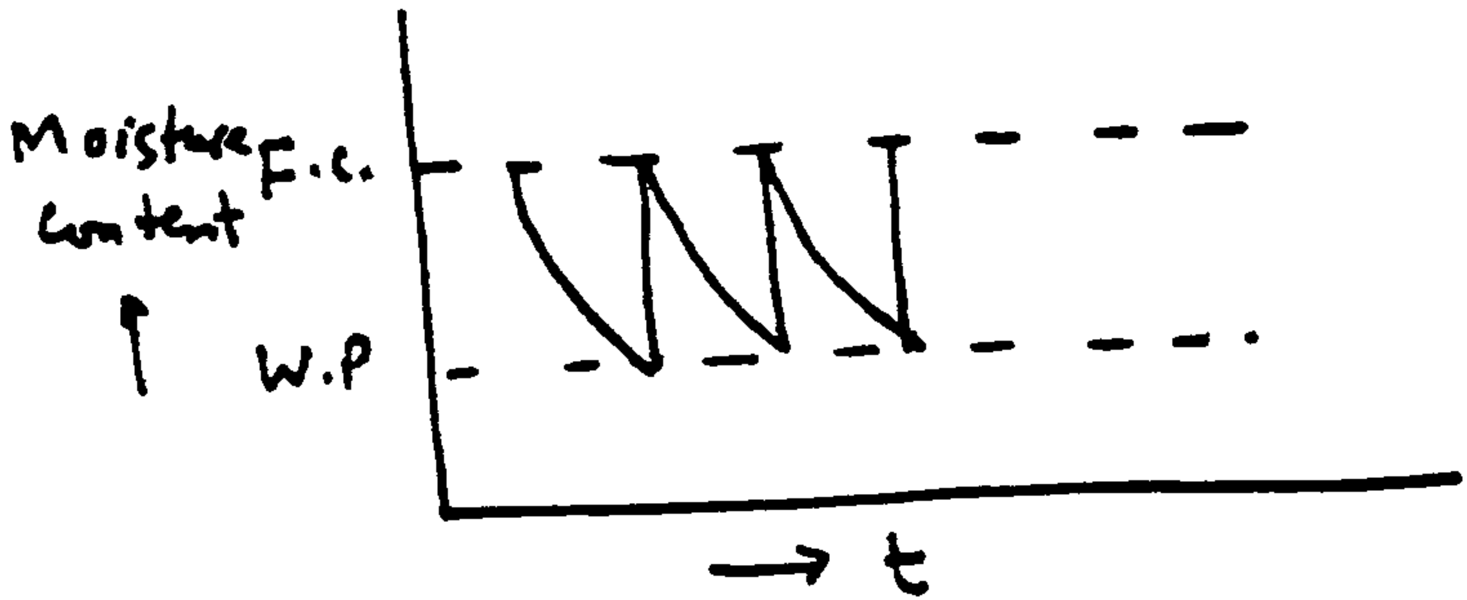
PROPERTIES OF AQUIFERS

- **Available water =**

  F.C. – wilting point M.C.
- **Maximum water capacity – maximum possible water content**

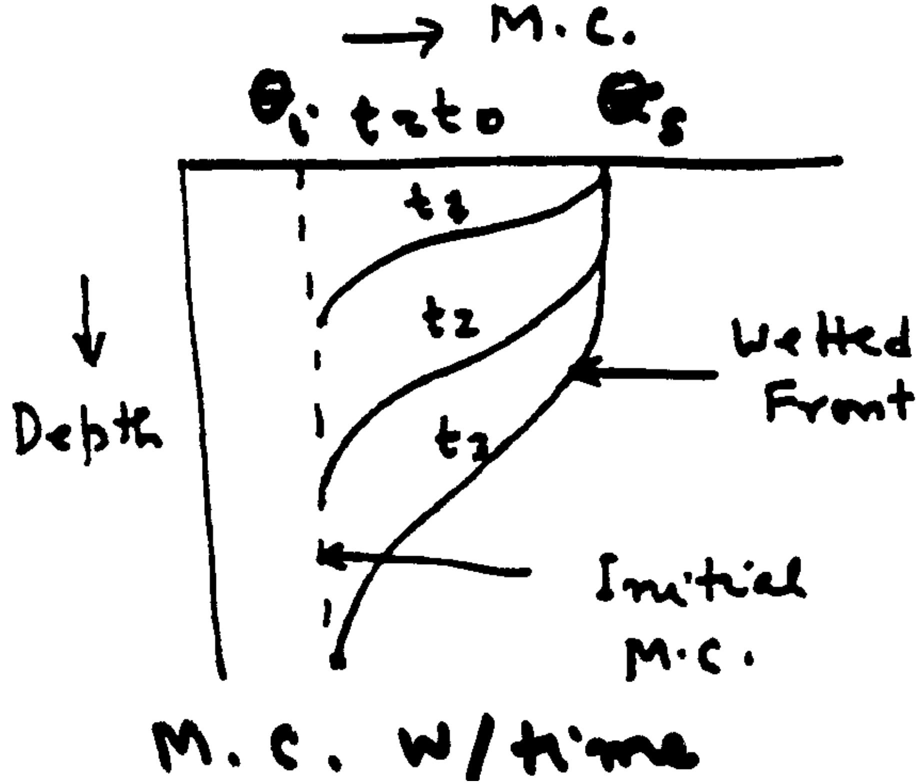
- **Optimal irrig. Water = Available water in root zone.**

PROPERTIES OF AQUIFERS



PROPERTIES OF AQUIFERS

Distribution of Moisture with depth:



PROPERTIES OF AQUIFERS

Intermediate Zone

-Extends from lower edge of soil-water zone to upper limit of capillary zone.

-In deep W.T., several hundred ft. thick

-Shallow W.T., non-existent

-Non-moving water held by hygroscopic and capillary forces.

PROPERTIES OF AQUIFERS

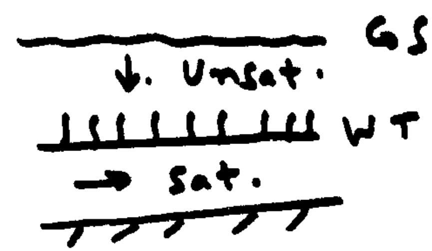
Capillary Zone

Extends from W.T. to limit of capillary rise of water.

Clay ≈ 4 ft. or 1.3 m

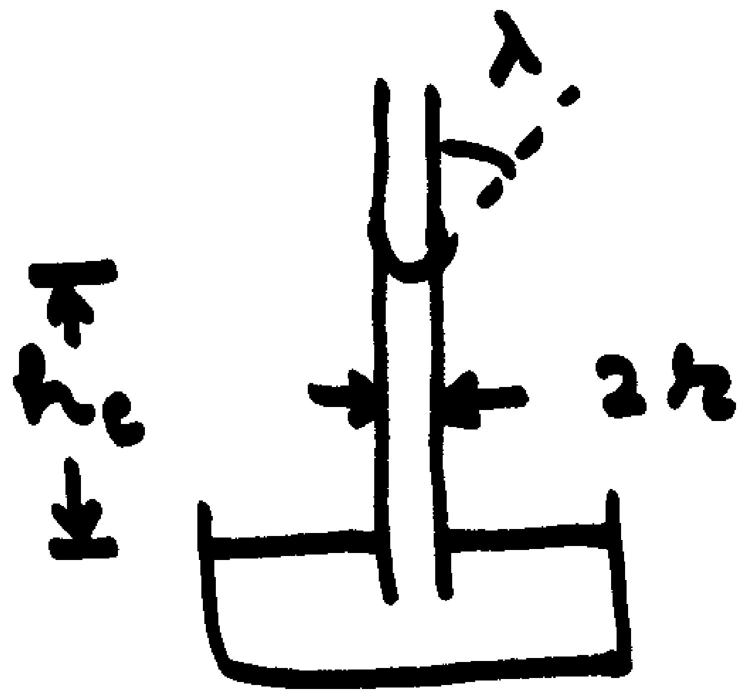
Sand ≈ 2 in. or 5 cm

Gravel < 1 in. or 2 cm



If pore represents a capillary tube

PROPERTIES OF AQUIFERS



PROPERTIES OF AQUIFERS

If τ = 0.074 gm/cm at 50^0 F, γ = 1 gm/cm^3

$$h_c = \frac{0.15}{\gamma r}\cos\lambda$$

PROPERTIES OF AQUIFERS

- **For four different sands, maximum capillary rise, h_c (in)**

$$h_c = \frac{2.2}{d_H}\left[\left(1-\alpha\right)/\alpha\right]^{2/3}$$

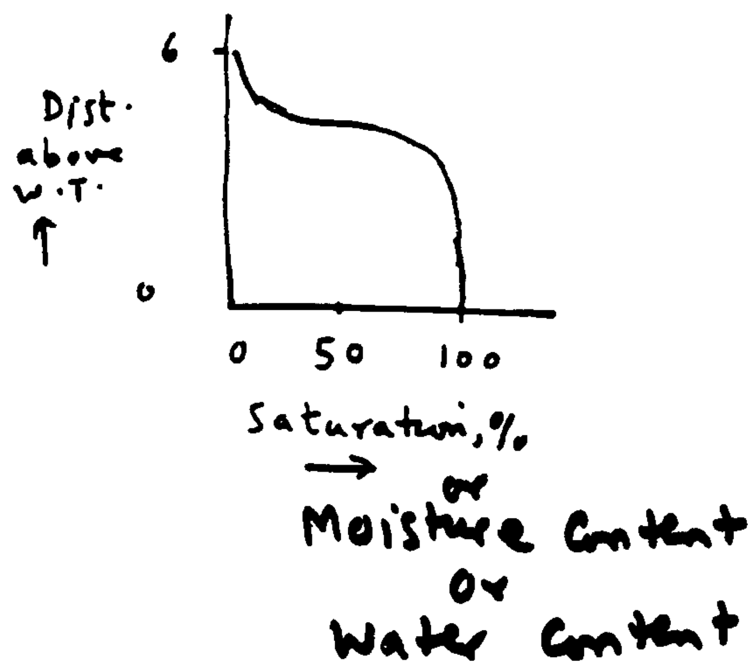
- **d_H - harmonic mean grain diameter, mm**
- **α - porosity**
- **d_{10}, d_{30}, d_{50}, d_{70}, d_{90}**

PROPERTIES OF AQUIFERS

$$\frac{1}{d_H} = \frac{\frac{1}{d_{10}} + \frac{1}{d_{30}} + \frac{1}{d_{50}} + \frac{1}{d_{70}} + \frac{1}{d_{90}}}{5}$$

PROPERTIES OF AQUIFERS

M.C. distribution above water table



PROPERTIES OF AQUIFERS

Measurement of Soil Moisture

Gravimetric Method –

Soil sample weighed, dried, and reweighed

PROPERTIES OF AQUIFERS

Gravimetric Block Method –

Sorption blocks inserted in soil and removed. Porous blocks develop moisture equilibrium with soil so that their weight correlated with soil M.C.

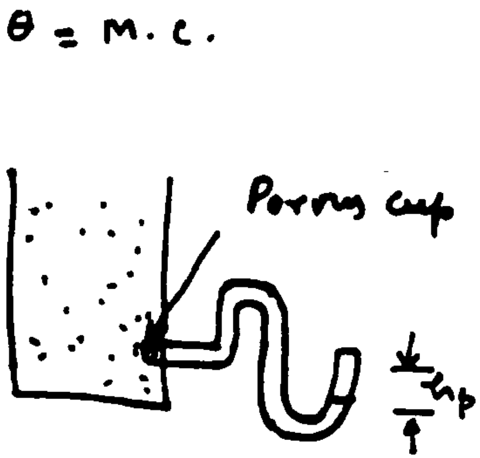
PROPERTIES OF AQUIFERS

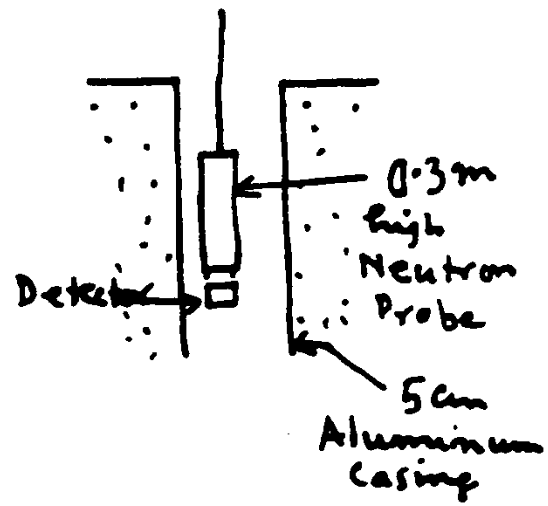
Tensiometer –

- tension pressure < atm. pressure = f(θ)
- range - 0 (sat.) to 0.85 atm.
  - Initially fill tensiometer with water
  - hp is pressure head, cm of H_2O

PROPERTIES OF AQUIFERS

Measurement of Soil Moisture





PROPERTIES OF AQUIFERS

Neutron Method –

Neutron source – particle of zero charge with mass equal to hydrogen atom.

Fast neutrons enter (soil & water) system moderated by H atoms of water (elastic collision) become slow neutrons.

PROPERTIES OF AQUIFERS

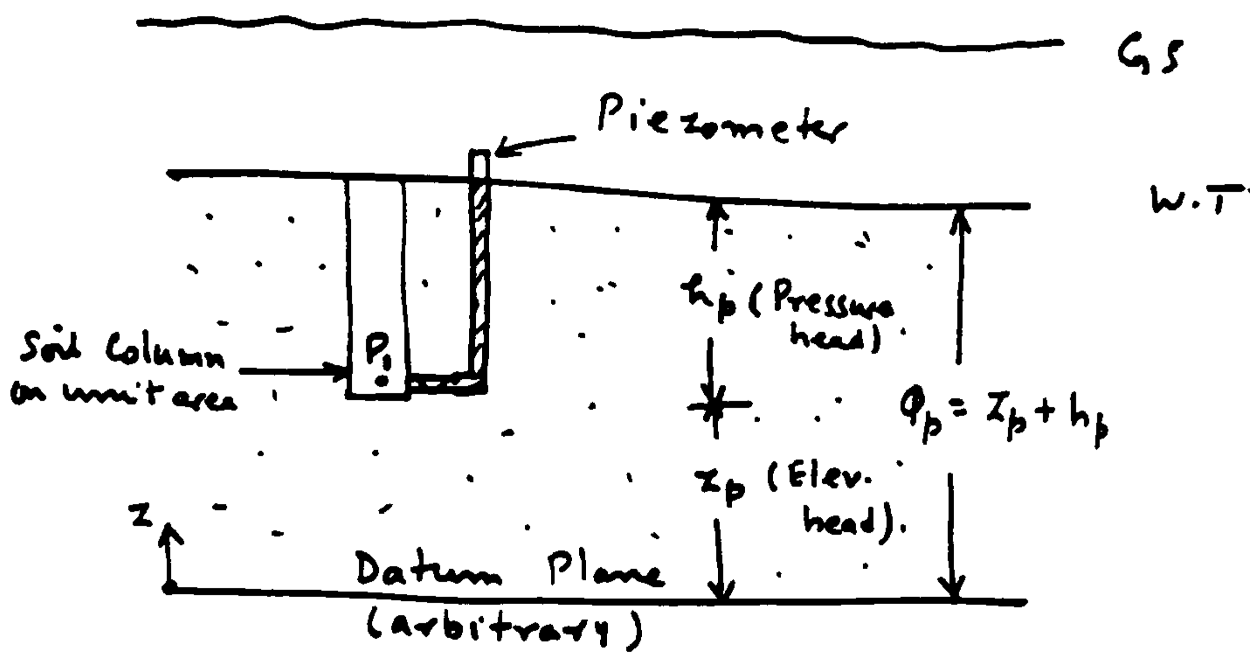
Neutron Method –

- Slowing process $\propto$ soil moisture
- Slow neutrons scatter in all direction
- Backscattered slow neutrons measured by detector.
- Source – Ra^{226} (Radium) mixed with beryllium,
  - 5-mci – (m curi cone)

PROPERTIES OF AQUIFERS

Piezometric Head - hydraulic head

Saturated zone:



PROPERTIES OF AQUIFERS

Pore Pressure – pressure experienced by water in voids such as pores of saturated soil

Pore pressure = γh_p at pt. P_1,

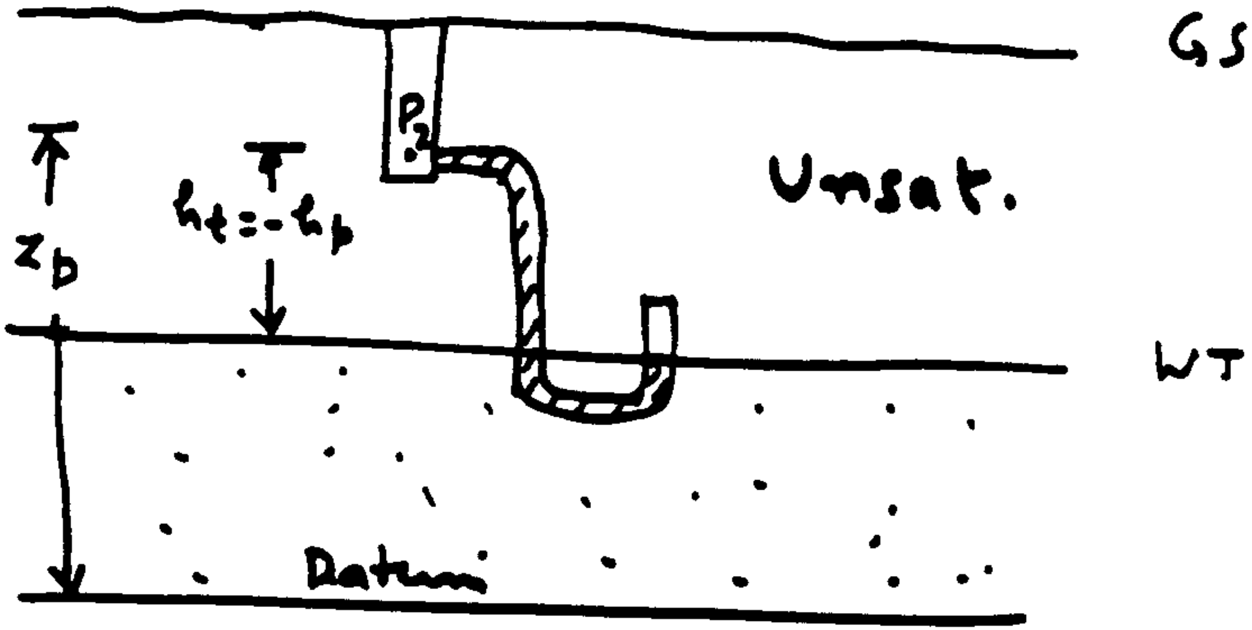
Pressure head = h_p (height of water in piezometer)

Elevation head = z_p above the datum

Piezometric head $(\phi_p) = z_p + h_p$

PROPERTIES OF AQUIFERS

Unsaturated Zone



PROPERTIES OF AQUIFERS

Pore pressure at P_2 $= \gamma h_t$

$= -\gamma h_p$

Pressure head $= - h_p$

Elevation head $= z_p$

Piezometric head $(\phi_p) = zp - hp$

PROPERTIES OF AQUIFERS

EXAMPLE 2.5.1

Estimate the average drawdown over an area where 25 million m^3 of water has been pumped through a number of uniformly distributed wells. The area is 150 km^2 and the specific yield of the unconfined aquifer is 25 percent.

SOLUTION

The volume of water drained is $w_y = 25 \times 10^6$ m^3. Eq. 2.5.2 is used to determine the bulk volume, V_t, of the aquifer to extract this volume of water:

$$S_y = \frac{w_y}{V_t}$$

$$0.25 = \frac{25 \times 10^6 \text{ m}^3}{V_t} \rightarrow V_t = 1 \times 10^8 \text{ m}^3$$

Thus, the average water level drop over the area is $\Delta h = \frac{V_t}{A} = \frac{1 \times 10^8 \text{ m}^3}{150 \times 10^6 \text{ m}^2} = 0.67$ m.

EXAMPLE 2.5.3

Determine the volume of water released by lowering the piezometric surface of a confined aquifer by 5 m over an area of $A = 1$ km^2. The aquifer is 35 m thick and has a storage coefficient of 8.3×10^{-3}.

SOLUTION

The released volume can be determined utilizing the definition of the storage coefficient, $V = (A)(\Delta h)(S) = (1 \times 10^6 \text{ m}^2)(5 \text{ m})(8.3 \times 10^{-3}) = 41{,}500 \text{ m}^3$.

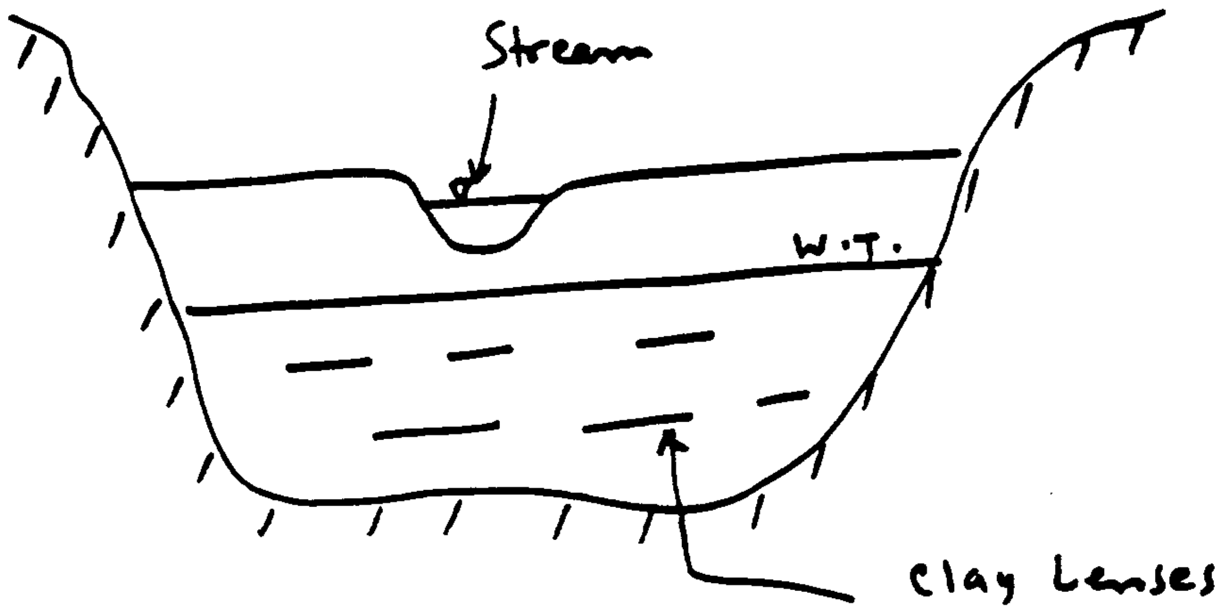
PROPERTIES OF AQUIFERS

Geologic Formation as Aquifers:

Alluvial Deposits –

unconsolidated sand and gravel

PROPERTIES OF AQUIFERS



PROPERTIES OF AQUIFERS

Limestone Deposits –

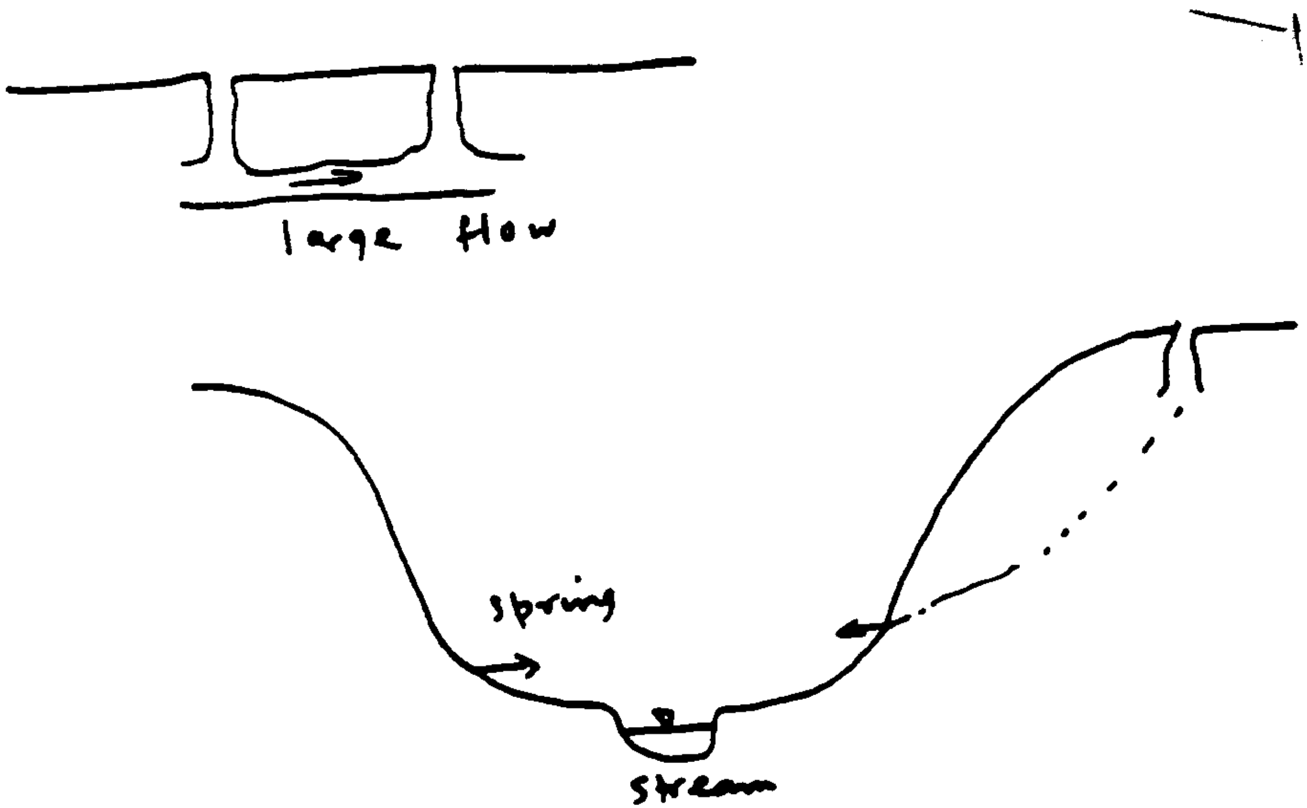
density, porosity, and permeability variable openings – microscopic cracks (S.E. England)

- fractures

- solution channels, have large springs

- karst development : Rapid water movement into ground

PROPERTIES OF AQUIFERS



Missouri, Arkansas, Texas, Florida

PROPERTIES OF AQUIFERS

Volcanic Rocks -

- **Lavas & basalt - highly fractured & high permeable**
- **Common in Idaho, Oregon, N. Cal., Hawaii**
- **Have large springs**

PROPERTIES OF AQUIFERS

Sandstone Deposits -

- **Cemented sands & gravels; less porosity with increased cementation.**
- **Highly fractured areas with high pressure condition - Texas , Mexico, Dakotas**

PROPERTIES OF AQUIFERS

Crystalline & Metamorphic Rocks -

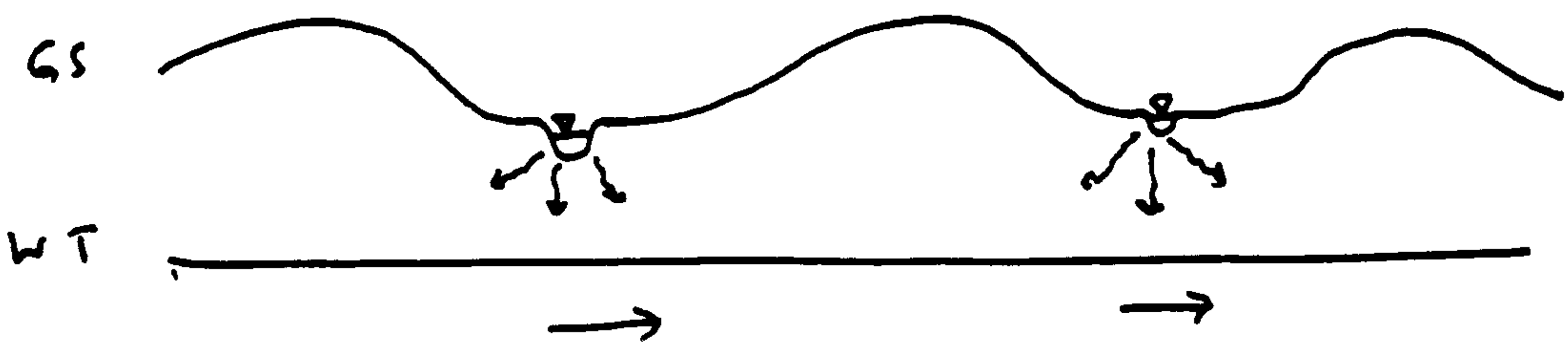
- **Highly fractured - limited local source of supply**

Clays -

- **High porosity; low specific yield**
- **Not enough water supply yielded**

GROUNDWATER BASIN

- **Relatively large physiographic unit containing one or more aquifers capable of development GW movement is independent of GS.**



GROUNDWATER BASIN

- **Variations in porosity:**
  - **Uniform spheres**
    - **6 packing possible**
    - **α ranges 0.2595 - 0.4764**
    - **Due to bridging, porosity often increases**

GROUNDWATER BASIN

- **Variations in porosity:**
  - **Clay**
    - **porosity is a fraction of depth**
    - $\alpha = \alpha_0 e^{-az}$
    - α_0 **- surface porosity**
    - **z - depth**
    - **a - const.**

GROUNDWATER BASIN

- **Variations in porosity:**
  - At depth of 5000 ft., clay becomes shale; α =5%

GROUNDWATER BASIN

- Measurement of Porosity
  - **Direct Method**
    - **measure bulk volume**
    - **crush & compress to obtain non-porous solid volume.**

GROUNDWATER BASIN

- Measurement of Porosity
  - **Optical Method - determine porosity by a real examination**

$$\alpha = \frac{w}{v} = \frac{Av}{A_T} = \frac{Lv}{L_T}$$

GROUNDWATER BASIN

- Measurement of Porosity
  - **Density Method**

$$\alpha = 1 - \frac{\rho_B}{\rho_S}$$

$\rho_B = bulk$ density

$\rho_S =$ solid matter density

GROUNDWATER BASIN

- Measurement of Porosity
  - **Soaking Method - Take initially oven dry sample and saturated with water. Measure volume of water.**

$$\alpha = \frac{\text{Vol. of voids to sat. the sample}}{\text{Bulk volume}}$$

GROUNDWATER BASIN

- Measurement of Porosity
  - **Gas Expansion Method**
    - **pv = const.**
      - **p - pressure**
      - **v - gas volume**
    - **Initially known p_1, p_2, v_2; to find v_1 - volume of pores**
    - **open valve and measure p_3**
      - **p_3 - equilibrium pressure**
    - **$v_3 = v_1 + v_2$**
    - **$p_3v_3 = p_1v_1 + p_2v_2$ or $p_3(v_1 + v_2) = p_1v_1 + p_2v_2$**
    - **solve for v_1**

$$\alpha = \frac{V_1}{\text{Bulk volume}}$$