PORE SPACES -
WHERE GW IS STORED AND MOVES THROUGH MATERIALS

POROSITY (TOTAL) - % OF MATERIAL THAT IS VOIDS

Porosity = Φ = \( \frac{V_V}{V_T} \)

\( V_V \) - VOL OF VOIDS
\( V_T \) - TOTAL VOLUME
SOIL ENGINEERS USE VOID RATIO, $e$

$$e = \frac{V_v}{V_s}$$

$V_v$ - VOL OF VOIDS
$V_s$ - VOL OF SOLIDS

Relationship of void ratio and porosity

$$\phi = \frac{e}{1+e} \quad e = \frac{\phi}{1-\phi}$$

METHODS OF MEASURING POROSITY ($\phi$, n)

DEDUCE from

PD - PARTICLE DENSITY : M/L$^3$
FD - FLUID DENSITY : M/L$^3$
BD - BULK DENSITY : M/L$^3$

$$BD = (1 - \phi) PD + \phi (FD)$$

OR (for fresh water in grams and cc’s)

SW - SATURATED WEIGHT
$V_T$ - TOTAL VOL
DW - DRY WEIGHT

$$\phi = \frac{SW - DW}{V_T}$$

$$\frac{DW}{V_T} = PD(1 - \phi)$$

$$\phi = 1 - \frac{DW}{PD * V_T}$$
Given:

Wet Bulk Density = 2.24 g/cm³
Particle Density = 2.65 g/cm³
Fluid Density (FD) = 1.0 g/cm³

What is:
Porosity = ?

BD = (1 - \( \phi \)) PD + \( \phi \) (FD)

\[
\phi = \frac{SW - DW}{V_T}
\]

\[
\frac{DW}{V_T} = PD(1 - \phi)
\]

\[
\phi = 1 - \frac{DW}{PD \times V_T}
\]

And If:

Total Volume = 25 cm³

What is:
Saturated Weight = ?
Dry Weight = ?

BD = (1 - \( \phi \)) PD + \( \phi \) (FD)

\[
\phi = \frac{SW - DW}{V_T}
\]

\[
\frac{DW}{V_T} = PD(1 - \phi)
\]

\[
\phi = 1 - \frac{DW}{PD \times V_T}
\]
PRIMARY POROSITY
- FORMED CONTEMPORANEOUSLY WITH ROCK
SECONDARY POROSITY
- FORMED AFTER ROCK IS FORMED

POROSITY DEPENDS ON:

SHAPE AND ARRANGEMENT OF PARTICLES

DEGREE OF SORTING (MIX OF PARTICLE SIZES)

CEMENTATION OR COMPACTION

REMOVAL OF MATERIAL BY SOLUTION

FRACTURING AND JOINTING

SHAPE AND ARRANGEMENT OF PARTICLES

magnitude of $\phi$ depends on packing as well as shape

packing - the spacing and mutual arrangement of particles within the mass

- will influence not only porosity but also density, bearing capacity, strength, amount of settling, permeability

- difficult to study with real particles because shapes are so varied, so consider spheres
Assume that you have two boxes that each have a volume of 8 cubic meters. Each box is filled with spheres in a cubic packing arrangement. Box number one is filled with spheres having a radius of 1 meter while the spheres in box number two have a radius of 0.5 meters.

Which box do you suppose has the highest pore volume?

This is a bad drawing but I hope you get the idea.

Calculate the porosity: the volume of a sphere is \( V = \frac{4}{3}\pi r^3 \)

PORTOSITY CAN BE DECREASED FURTHER BY FILLING VOIDS WITH SMALLER PARTICLES

SORTING (poor = lots of sizes, well = few sizes)
GRADING (poor = few sizes, well = lots of sizes)
i.e. well graded has a gradation of sizes

I.E. POORLY SORTED OR WELL GRADED YIELDS LOW \( \phi \)
WELL SORTED OR POORLY GRADED YIELDS HIGH \( \phi \)
CEMENTATION OR COMPACITION

DECREASES $\phi$

REMOVAL OF MATERIAL BY SOLUTION

INCREASES $\phi$

FRACTURING AND JOINTING

Generally INCREASES $\phi$

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**EFFECTIVE POROSITY** Contributes to Fluid Flow

% OF MEDIUM THAT IS INTERCONNECTED PORE SPACE

$$\phi_e = \frac{V_{IV}}{V_T}$$

$V_{IV}$ - VOL OF INTERCONNECTED VOIDS

MEASUREMENT OF **EFFECTIVE POROSITY**:

GRAVITY DRAINAGE @ 100% RELATIVE HUMID

TRACER TEST - MONITOR RATE OF MOVEMENT OF A TAG ON THE WATER
Darcy velocity is a DISCHARGE per unit AREA

\[ V_{\text{Darcy}} = \frac{Q}{A} \]

Average Linear Velocity

velocity through the pores
this governs rate of pollutant movement

\[ V_{\text{AverageLinear}} = \frac{Q}{A \phi_e} = \frac{V_D}{\phi_e} = \frac{V_D}{\text{effective porosity}} \]

Entire face of the porous medium

Often represented as \( \bar{v} \), pronounced \( v \) bar

OTHER NAMES
Seepage Velocity
Interstitial Velocity

Recall Darcy discharge calculation from the first class?

\[ Q = K \frac{\text{Head Difference}}{\text{Area}} \frac{\text{Distance between Heads}}{} \]

\[ Q = 0.01 \text{ cm} \hspace{1em} 0.19 \text{ m} \hspace{1em} 6\text{cm} \hspace{1em} 0.75\text{cm} \hspace{1em} 1 \text{ liter} \hspace{1em} \frac{86400\text{sec}}{1000\text{cm}^3} = \frac{1.17 \text{ liter}}{1 \text{ liter}} \]

What is the travel time for a drop of water from left to right if effective porosity is 31%?

\[ \text{constant head} \]

\[ 0.4 \text{ m} \]

\[ \text{effective porosity is 31\%} \]

\[ \text{FINE SAND} \]

\[ 0.63 \text{ m} \]

\[ 6 \text{ cm} \]

\[ 0.21 \text{ m} \]

\[ 0.75 \text{ cm} \]
WE CAN’T RECOVER ALL THE WATER FROM THE PORES, 
SO CONSIDER HOW MUCH WATER THEY WILL YIELD

**SPECIFIC YIELD** - % OF TOTAL VOLUME THAT CAN BE 
DRAINED BY GRAVITY

**SPECIFIC RETENTION** - % OF TOTAL VOLUME HELD 
AGAINST GRAVITY

BY DEFINITION - $\phi = SY + SR$

Consider the character of Occurrence 
of Water 
in various Zones
Zones of Different Water Occurrence

Degree of Saturation = \( \frac{\text{volume water filled pores}}{\text{volume of all pores}} \)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Type of Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 % Sat</td>
<td>Hygroscopic</td>
</tr>
<tr>
<td>100%</td>
<td>Pellicular</td>
</tr>
<tr>
<td>Unsaturated Zone</td>
<td>Gravitational Water</td>
</tr>
<tr>
<td>Zone of Aeration</td>
<td>Capillary Water</td>
</tr>
<tr>
<td>Capillary Fringe</td>
<td>Phreatic Water</td>
</tr>
<tr>
<td>Saturated Zone</td>
<td>Confined Water</td>
</tr>
</tbody>
</table>

**Zones of Different Water Occurrence**

Consider the pressure conditions

**ABOVE** Water Table
PRESSURES ARE < ATMOSPHERIC (-)

**BELOW** Water Table
PRESSURES ARE > ATMOSPHERIC (+)

WATER TABLE is the surface at which the pore water pressure is atmospheric

In a hydrostatic (still) system pressure increases with depth below the water table due to the weight of the overlying water

Pascal's Law: \( \Delta P = \rho g \Delta h = \gamma \Delta h \)
Pascal's Law:

\[ \Delta P = \rho g \Delta h = \gamma \Delta h \]

\( \Delta P \) difference in hydrostatic pressure (pascals)
\( \rho \) fluid density (kg m\(^{-3}\))
\( g \) acceleration due to Earth's gravity at sea level (ms\(^{-2}\))
\( \Delta h \) height of fluid above a datum (m), or difference in elevation of two points in a fluid column
\( \gamma \) specific weight (\( \rho g \))

Fluid does not support shear stress so pressure is transmitted equally throughout the fluid.

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### ABSOLUTE PRESSURE

LOCAL ATMOSPHERIC P + GAGE P

### GAGE PRESSURE

P RELATIVE TO PREVAILING ATMOSPHERIC P

### ATMOSPHERIC PRESSURE

DEFINED AS ZERO for many Hydrology calculations

Standard Atmospheric Pressure = 1.013\( \times 10^5 \) Pascals or 14.7 lb/in\(^2\)

1 pascal (Pa) = 1 N m\(^{-2}\) = 1 J m\(^{-3}\) = 1 kg m\(^{-1}\) s\(^{-2}\)

1 bar = 100,000 Pa = 10\(^{5}\) dyn cm\(^{-2}\) = 1.0197 atm

1 atm = 1.01325 bar = 14.6959 lb/in\(^2\) = 760 Torr

1 Torr = 1.33322 Pa

1 mmHg = 133.322 Pa = 0.001 Torr

1 lb/in\(^2\) = 6894.76 Pa

Pressure Units: [http://en.wikipedia.org/wiki/Pascal](http://en.wikipedia.org/wiki/Pascal)
Calculate the pressure on your head if you stood at the bottom of a well with its:

- surface at sea level
- bottom at 600 ft
- water level 50 ft below the surface

Sketch a diagram
determine appropriate equation
label distances
gather constants / properties
calculate

**CAPILLARITY** (suction or negative pressure)
due to inter-molecular attraction at the liquid boundary

**Adhesion** - the attractive (wetting), or repulsive (non-wetting), force between the molecules of the liquid and solid

**Cohesion** - the attractive force between molecules of the liquid

Upward force of the attraction of the liquid to the solid would cause the liquid to continue rising except that it is balanced by downward force of gravity on the liquid

In a tube the **HEIGHT of RISE** is controlled by the **SIZE of TUBE** because as radius increases downward force of gravity increases more rapidly than upward force of attraction of liquid to solid (note the area grows as \( r^2 \) while the circumference grows as \( r \))
Capillary Rise

In a droplet, molecules within the liquid are attracted equally from all sides. Molecules near the surface are attracted toward the center of the liquid mass by this net force. Thus, the surface acts like a membrane. So a drop of liquid forms a sphere, and liquid in a tube forms a meniscus.
the capillary fringe will show hysteresis effects

Hysteresis (dependent on history) describes a phenomenon which is dependent on previous history as the water table moves up and down the capillary fringe will change in character.

For a cylinder capillary pressure can be calculated as:

\[ P_c = \frac{2\sigma \cos \lambda}{r} \]

\( \lambda \) contact angle

Pressure = specific-weight*height

so height of capillary rise is \( h_c \)

\[ P_c = \frac{2\sigma \cos \lambda}{r} \quad \text{and} \quad P = \gamma h \quad \text{so} \quad h_c = \frac{2\sigma \cos \lambda}{\gamma T} \]

Surface Tension - force (perpendicular to the surface) along a line of unit length, or work done per unit area

The numerical value of surface tension depends on the nature of the fluid and solid.
Let’s take a minute to think about units

Beware! of your units .... that is BE AWARE of your units

Force = mass * acceleration
\[ F = ma \]

... \[ W = Weight = mg \]

\( g \) is gravitational acceleration

weight has same units as force (not mass)

SI

Basic units: \( L \) \( M \) \( T \) length mass time

\( m \) \( kg \) \( s \) meter kilogram second

Derived unit \( F \) - force, \( N \) Newton

English

Basic units \( L \) \( F \) \( T \) length force time

\( ft \) \( lb \) \( s \) foot pound second

Derived unit \( M \) - mass, \( S \) slug

In SI (meter-kilogram-second) definition:

1 Newton (N) of force will accelerate

1 kilogram mass (kgm) 1 meter per second squared

\[ F = ma \]

1 Newton \( 1 \text{kgm} \) \( 1 \text{m} \) \( \text{sec}^2 \)

In English Units (foot-slug-second)

1 pound force (lbf) accelerates

1 slug mass 1 ft per second square

\[ F = ma \]

1 lbf \( 1 \text{slug} \) \( 1 \text{ft} \) \( \text{sec}^2 \)

it can be confusing

often mass is given in pounds mass (lbm)

given that one slug equals 32.2 lbm
Weight in US: a cubic foot of water weighs 62.4 lbs
In Europe we say a cubic foot of water weighs 28.3 kg
We mean it has a mass of 28.3 kg in earth's gravity: It weighs 273N

**Density** is **MASS** per **VOLUME**: kg/m³  slugs/ft³

**Specific Weight** is **WEIGHT** per **VOLUME**: N/m³  lb/ft³

We tend to use Density when working in SI and
What looks like Specific Weight in English Units

**Density of water is 1.94 slugs/ft³**
Recall 1 pound force (lbf) accelerates 1 slug mass 1 ft per second squared

\[
1 \text{lbf} = 1 \text{slug} \frac{\text{ft}}{\text{sec}^2}
\]

so there is 1 slug per 1 \( \left( \text{lbf} \frac{\text{sec}^2}{\text{ft}} \right) \)

\[
\gamma = \rho g = \frac{1.94 \text{slug}}{\text{ft}^3} \frac{1 \text{lbf} \text{ sec}^2}{\text{slug} \text{ ft}} 32.2 \frac{\text{ft}}{\text{sec}^2} = 62.4 \frac{\text{lbf}}{\text{ft}^3}
\]

\[
\rho = \frac{1.94 \text{slug}}{\text{ft}^3}
\]
so given that 1 slug = 32.17 lbm, then \( \rho = \frac{62.4 \text{lbm}}{\text{ft}^3} \)

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**From your text, Fetter**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>English Unit</th>
<th>SI Unit</th>
<th>Conversion Factor</th>
<th>Dimensional Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force</td>
<td>pound (lb)</td>
<td>newton (N)</td>
<td>1 lb = 4.448 N</td>
<td>MLT²</td>
</tr>
<tr>
<td>Mass</td>
<td>slug</td>
<td>kilogram (kg)</td>
<td>1 slug = 14.594 kg</td>
<td>M</td>
</tr>
<tr>
<td>Length</td>
<td>foot (ft)</td>
<td>meter (m)</td>
<td>1 ft = 0.3048 m</td>
<td>L</td>
</tr>
<tr>
<td>Time</td>
<td>second (s)</td>
<td>second</td>
<td>1 s = 1 s</td>
<td>T</td>
</tr>
<tr>
<td>Density</td>
<td>slug/ft³</td>
<td>kg/m³</td>
<td>1 slug/ft³ = 515.4 kg/m³</td>
<td>MLT³</td>
</tr>
<tr>
<td>Specific weight</td>
<td>lb/ft²</td>
<td>N/m³</td>
<td>1 lb/ft² = 157.1 N/m³</td>
<td>M²L²T</td>
</tr>
<tr>
<td>Pressure</td>
<td>lb/ft²</td>
<td>N/m²</td>
<td>1 lb/ft² = 47.88 N/m²</td>
<td>M²L²T</td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>lb-s/ft²</td>
<td>N·s/m²</td>
<td>1 lb-s/ft² = 47.88 N·s/m²</td>
<td>M²L²T</td>
</tr>
<tr>
<td>Bulk modulus</td>
<td>lb/ft²</td>
<td>N/m²</td>
<td>1 lb/ft² = 47.88 N/m²</td>
<td>M²L²T</td>
</tr>
</tbody>
</table>
Surface tension for distilled water in contact with air in a clean glass tube is 72.8 dynes/cm, contact angle is zero, cos is 1

1 dyne imparts an acceleration of 1 cm/sec^2 to a mass of 1 gram or an acceleration of g = 981 cm/sec^2 to 0.00102 grams force

\[ \sigma = \frac{72.8 \text{ dynes}}{\text{cm}} \left( \frac{0.00102 \text{ g}}{\text{dyne}} \frac{981 \text{ cm}}{\text{sec}^2} \right) = \frac{72.8 \text{ g}}{\text{s}^2} \]

\[ \gamma = \rho g = \frac{1 \text{ g}}{\text{cm}^3} \frac{980 \text{ cm}}{\text{s}^2} = \frac{980 \text{ g}}{\text{cm}^2 \text{s}^2} \]

\[ h_c = \frac{2 \sigma (\cos \lambda)}{\gamma r} \]

\[ h_c = 2 \frac{72.8 \text{ g}}{\text{s}^2} \frac{1}{r} \approx \frac{0.15 \text{ cm}}{r} \text{ (for \ r in \ cm)} \]
Grain size distribution:
a clue to pore size distribution

Estimate the height of capillary rise for water in sand.
Grain size distributions in Fetter (pg74-75)
Smallest ~ 0.08 mm 10% ~ 0.17mm = 0.017cm
What if the soil is a silty sand?
Grain size distributions in Fetter (pg74-75)
Smallest ~ 0.002 mm 10% ~ 0.017mm = 0.0017cm

What if the fluid is gasoline?
Substance Surface Tension (dyne/cm)
Water 72.8 dyne/cm
Gasoline ~33 dyne/cm (note < tension for water)
specific weight? check the web (~0.68 density of water)
Which will dominate, surface tension decrease or specific weight decrease?
Thus far we have looked at fluids with a contact angle near zero and the cosine of zero is one, so we have not had to consider it.

Some fluids have a contact angle approaching 90° and that needs to be considered in estimating capillary rise.

\[ h_c = \frac{2\sigma \cos \lambda}{\gamma r} \]

For a nonwetting fluid that angle will result in a depression rather than rise.

What is the MAXIMUM HEIGHT (in feet) THAT YOU CAN RAISE WATER BY SUCTION?

NOTE: IT IS LIMITED BY THE PREVAILING ATMOSPHERIC PRESSURE so choose your location.

(lb/in² sea-level ~14.7, Denver ~12.2, Mexico City ~11.1, Mt. Everest ~4.9)

Recall: \[ P = \gamma h \]