Properties of Aquifers

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Porosity of Earth Materials

\[ n = \frac{V_v}{V} \]

- \( n \) porosity
- \( V_v \) volume of void space in a unit volume of earth material \((L^3)\)
- \( V \) unit volume of earth material, including both voids and solids \((L^3)\)
Pores and Permeability
Porosity ($n$) = \[ \frac{\text{Volume of voids} (V_v)}{\text{Total volume} (V_t)} \]
## Engineering Grain Size Classification

<table>
<thead>
<tr>
<th>Name</th>
<th>Size Range (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boulder</td>
<td>&gt;305</td>
</tr>
<tr>
<td>Cobbles</td>
<td>76-305</td>
</tr>
<tr>
<td>Coarse gravel</td>
<td>19-76</td>
</tr>
<tr>
<td>Fine gravel</td>
<td>4.75-19</td>
</tr>
<tr>
<td>Coarse sand</td>
<td>2-4.75</td>
</tr>
<tr>
<td>Medium sand</td>
<td>0.42-2</td>
</tr>
<tr>
<td>Fine sand</td>
<td>0.075-0.42</td>
</tr>
<tr>
<td>Fines</td>
<td>&lt;0.075</td>
</tr>
</tbody>
</table>
## Porosity Range of Sediments

<table>
<thead>
<tr>
<th>Sediment Type</th>
<th>Porosity Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well-sorted sand or gravel</td>
<td>0.25-0.5</td>
</tr>
<tr>
<td>Sand and gravel, mixed</td>
<td>0.2-0.35</td>
</tr>
<tr>
<td>Glacial till</td>
<td>0.1-0.2</td>
</tr>
<tr>
<td>Silt</td>
<td>0.35-0.5</td>
</tr>
<tr>
<td>Clay</td>
<td>0.3-0.6</td>
</tr>
</tbody>
</table>
Effective Porosity

- \( n_e \)
- Porosity available for fluid flow
Porosity of Sedimentary Rocks

- **Primary porosity**
  - Pores between grains

- **Secondary porosity**
  - Fractures
Primary porosity

Gravel
Secondary porosity

Limestone
Specific Yield

• **Specific Yield** $S_y$ the ratio of the volume of water that drains from a saturated geomaterial owing to the attraction of gravity to the total volume of the geomaterial
Specific Retention

- **Specific retention** $S_r$, the ratio of the volume of water a geomaterial can retain against gravity drainage to the total volume of the geomaterial.

\[ n = S_y + S_r \]
Fig. 4.9 Pendular water clinging to spheres owing to surface tension. Gravity attraction is pulling the water downward
## Specific Yield

<table>
<thead>
<tr>
<th>Material</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>5</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Sandy clay</td>
<td>12</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Silt</td>
<td>19</td>
<td>3</td>
<td>18</td>
</tr>
<tr>
<td>Fine sand</td>
<td>28</td>
<td>10</td>
<td>21</td>
</tr>
<tr>
<td>Medium sand</td>
<td>32</td>
<td>15</td>
<td>26</td>
</tr>
<tr>
<td>Coarse sand</td>
<td>35</td>
<td>20</td>
<td>27</td>
</tr>
<tr>
<td>Gravelly sand</td>
<td>35</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>Fine gravel</td>
<td>35</td>
<td>21</td>
<td>25</td>
</tr>
<tr>
<td>Medium gravel</td>
<td>26</td>
<td>13</td>
<td>23</td>
</tr>
<tr>
<td>Coarse gravel</td>
<td>26</td>
<td>12</td>
<td>22</td>
</tr>
</tbody>
</table>
Fig. 4.10  Specific yield of sediments from the Humboldt River Valley of Nevada as a function of the median grain size
Bernoulli Equation

\[ h = \frac{v^2}{2g} + z + \frac{P}{\rho g} = \text{constant} \]

- Bernoulli equation
  - \( h \) hydraulic head (L, J/N)
  - First term – velocity head (ignored in ground water flow)
  - Second term – elevation head
  - Third term – pressure head
Hydraulic Head

• Total head
• Elevation head
• Pressure head
• Velocity head
Hydraulic Conductivity

- $K$ hydraulic conductivity ($L/T$)
- A function of properties of both porous media and the fluid passing through it

- $k$ intrinsic permeability ($L^2$)
- A function of porous media only
\[ K = k \frac{\rho g}{\mu} \]

- \( \rho \)  density of fluid
- \( g \)  acceleration of gravity
- \( \mu \)  dynamic viscosity of fluid

- 1 cP = 0.01 dyn \cdot s/cm^2
- 1 darcy = 9.87 \times 10^{-9} \ cm^2
# Hydraulic Conductivity

<table>
<thead>
<tr>
<th></th>
<th>Hydrogeology</th>
<th>Geotechnical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic conductivity</td>
<td>$K$</td>
<td>$k$</td>
</tr>
<tr>
<td>Intrinsic permeability</td>
<td>$k$</td>
<td>$K$</td>
</tr>
<tr>
<td>Hydraulic gradient</td>
<td>$J$</td>
<td>$i$</td>
</tr>
</tbody>
</table>
## Ranges of Hydraulic Conductivity

<table>
<thead>
<tr>
<th>Material</th>
<th>Intrinsic Permeability (darcy)</th>
<th>Hydraulic Conductivity (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>$10^{-6} – 10^{-3}$</td>
<td>$10^{-9} – 10^{-6}$</td>
</tr>
<tr>
<td>Silt, sandy silts, clayey sands, till</td>
<td>$10^{-3} – 10^{-1}$</td>
<td>$10^{-6} – 10^{-4}$</td>
</tr>
<tr>
<td>Silty sands, fine sands</td>
<td>$10^{-2} – 1$</td>
<td>$10^{-5} – 10^{-3}$</td>
</tr>
<tr>
<td>Well-sorted sands, glacial outwash</td>
<td>$1 – 10^{2}$</td>
<td>$10^{-3} – 10^{-1}$</td>
</tr>
<tr>
<td>Well-sorted gravel</td>
<td>$10 – 10^{3}$</td>
<td>$10^{-2} – 1$</td>
</tr>
</tbody>
</table>
Measurement of $K$ in the Lab

- Constant Head Method
- Falling Head Method
- Rising/Falling Head Method
- Constant Rate of Flow
Constant-Head Method
Falling Head Method
Types of $K$ Test Apparatus

- Fixed-Wall Permeameter
  - No control of effective stress
- Flexible-Wall Permeameter
  - Can control effective stress
- Consolidation Cell
  - Can control vertical effective stress
- Other
Factors Affecting Measurement of $K$

- Effective stress
- Hydraulic gradient
- Volume of Flow
Termination Criteria
Pressure control and the flexible-wall cell setup
Homogeneity and Isotropy
Fig. 4.26 Grain shape and orientation can affect the isotropy or anisotropy of a sediment
Fig. 4.27 Anisotropy of fractured rock units due to directional nature of fracturing
Fig. 4.28 Heterogeneous formation consisting of three layers of differing hydraulic conductivity
Transmissivity

• Amount of water that can be transmitted horizontally through a unit width by the full saturated thickness of the aquifer under a hydraulic gradient of 1.

\[ T = K B \]

- \( T \): transmissivity (\( L^2/T \ or \ m^2/d \))
- \( K \): hydraulic conductivity (\( L/T \))
- \( B \): saturated thickness of the aquifer (\( L \ or \ m \))
Storativity

- *Storativity* (S) or *Storage coefficient*
- The volume of water that a permeable unit will absorb or expel from storage per unit surface area per unit change in head.
Specific Storage

- **Specific storage** ($S_s$) or **Elastic storage coefficient**

- The amount of water per unit volume of a saturated formation that is stored or expelled from storage owing to compressibility of the mineral skeleton and the pore water unit change in head.
Specific Storage

\[ S_s = \rho_w g (\alpha + n\beta) \]

- \( \rho_w \) density of water
- \( g \) the acceleration of gravity
- \( \alpha \) compressibility of aquifer skeleton \((1/(M/LT^2))\)
- \( \beta \) compressibility of water \((1/(M/LT^2))\)
- \( n \) porosity \((L^3/L^3)\)
Confined aquifer

\[ S = B S_s \]

Unconfined aquifer

\[ S = S_y + h S_s \]
Water Table

- The surface at which pore water pressure is equal to atmospheric pressure
Definition of Aquifer

• A *aquifer* is a geologic unit that can store and transmit water at rates fast enough to supply reasonable amounts to wells.
Confining Layer

• A **confining layer** is a geologic unit having little or not intrinsic permeability – less than about $10^{-2}$ darcy.
- **Aquifuge** is an absolutely impermeable unit that will not transmit any water.

- **Aquiclude** is a formation that has very low hydraulic conductivity, which hardly transmit water.

- **Aquitard** is a layer of low permeability that can store ground water and also transmit it slowly from one aquifer to another; also know as *leaky confining layer*. 
Types of Aquifers

- **Unconfined aquifer**  (*Water-table aquifer*)
- **Confined aquifer**  (*Artesian aquifer*)
Unconfined Aquifer

• An aquifer that is close to the ground surface, with continuous layers of materials of high intrinsic permeability extending from the land surface to the base of the aquifer.

• Recharge from downward seepage through the unsaturated zone, lateral ground water flow, or upward seepage from underlying strata.
Unconfined Aquifer
Confined Aquifer

• An aquifer that are overlain by a confining layer.

• Recharge occurs in recharge area, where the aquifer crops out, or by slow downward leakage through a leaky confining layer.

• *Potentiometric surface* is the surface representative of the level to which water will rise in a well cased to the aquifer.
Confined Aquifer
Perched Aquifer

- Water intercepted by a layer of low-permeability material in more permeable materials and accumulated on top of the low-permeability layer.
- Occurs above the main water table.
Definitions
Surface water

Rivers and Lakes

UNSATURATED ZONE

CAPILLARY FRINGE

WATER TABLE

GROUND WATER

WATER LEVEL

Well
Vadose Zone

• The upper layer of the earth that contain a three-phase system of solid, liquid, and gaseous material.
• Also called the zone of aeration or unsaturated zone.
Zone of Aeration

- The zone where the soil moisture is under tension
Capillary Fringe

• Capillary pores in the zone of aeration draw up water from the zone of saturation beneath the water table.
• In very fine-grained soils, this capillary fringe can saturate the soil above the water table.
• Tensiometer reading is negative.
• Capillary fringe is a part of vadose zone.