Engineering Characterization of Soils

Soil Properties that Control its Engineering Behavior

- Particle Size
  - Sieve Analysis
  - Hydrometer Analysis

Coarse-grained

- Particle/Grain Size Distribution
- Particle Shapes (?)

Fine-grained

- Soil Plasticity
Particle Size; Standard Sieve Sizes
## ASTM Particle Size Classification

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Passes</th>
<th>Retained on</th>
<th>Particle Diameter (in)</th>
<th>Particle Diameter (mm)</th>
<th>Soil Classification</th>
<th>Rock Fragments</th>
<th>Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>12 in</td>
<td>&gt; 12</td>
<td>&gt; 350</td>
<td>Boulder</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>12 in</td>
<td>3 in</td>
<td>3 - 12</td>
<td>Cobble</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 in</td>
<td>3/4 in</td>
<td>0.75 - 3</td>
<td>Coarse gravel</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3/4 in</td>
<td>#4</td>
<td>0.19 - 0.75</td>
<td>Fine gravel</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>#4</td>
<td>0.079 - 0.19</td>
<td>Coarse sand</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>#10</td>
<td>#40</td>
<td>0.016 - 0.079</td>
<td>Medium sand</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>#10</td>
<td>#40</td>
<td>0.0029 - 0.016</td>
<td>Fine sand</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>#200</td>
<td>&lt; 0.0029</td>
<td>&lt; 0.075</td>
<td>Fines (silt + clay)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 0.0029</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Sieve Analysis (Mechanical Analysis)

- This procedure is suitable for coarse grained soils
- See next slide for ASTM Standard Sieves
- No. 10 sieve …. Has 10 apertures per linear inch
# ASTM Standard Sieves

<table>
<thead>
<tr>
<th>Sieve Identification</th>
<th>Opening Size</th>
<th>Sieve Identification</th>
<th>Opening Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(in)</td>
<td>(mm)</td>
<td>(in)</td>
</tr>
<tr>
<td>3 inch</td>
<td>3.00</td>
<td>76.2</td>
<td>#16</td>
</tr>
<tr>
<td>2 inch</td>
<td>2.00</td>
<td>50.8</td>
<td>#20</td>
</tr>
<tr>
<td>1½ inch</td>
<td>1.50</td>
<td>38.1</td>
<td>#30</td>
</tr>
<tr>
<td>1 inch</td>
<td>1.00</td>
<td>25.4</td>
<td>#40</td>
</tr>
<tr>
<td>3/4 inch</td>
<td>0.75</td>
<td>19.0</td>
<td>#50</td>
</tr>
<tr>
<td>3/8 inch</td>
<td>0.375</td>
<td>9.52</td>
<td>#60</td>
</tr>
<tr>
<td>#4</td>
<td>0.187</td>
<td>4.75</td>
<td>#100</td>
</tr>
<tr>
<td>#8</td>
<td>0.0929</td>
<td>2.36</td>
<td>#140</td>
</tr>
<tr>
<td>#10</td>
<td>0.0787</td>
<td>2.00</td>
<td>#200</td>
</tr>
</tbody>
</table>
Hydrometer Analysis

- Also called Sedimentation Analysis
- **Stoke’s Law**

\[
v = \frac{D^2 \gamma_w (G_s - G_L)}{18 \eta}
\]
Grain Size Distribution Curves
Terminology

- C..... Poorly-graded soil
- D .... Well-graded soil
- E .... Gap-graded soil
- $D_{10}$, $D_{30}$, $D_{60}$ = ??
- Coefficient of Uniformity, $C_u = D_{60}/D_{10}$
- Coefficient of Curvature,

$$C_c = (D_{30})^2/(D_{10})(D_{60})$$
**TABLE 2-3**
Sieve Analysis Data for Example 2–1

<table>
<thead>
<tr>
<th>(1) Sieve Number</th>
<th>(2) Opening (mm)</th>
<th>(3) Weight Retained (g)</th>
<th>(4) Percentage Retained</th>
<th>(5) Cumulative Percentage Retained</th>
<th>(6) Percentage Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>¼ in.</td>
<td>19.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>¾ in.</td>
<td>9.50</td>
<td>158</td>
<td>7.9</td>
<td>7.9</td>
<td>92.1</td>
</tr>
<tr>
<td>No. 4</td>
<td>4.75</td>
<td>308</td>
<td>15.4</td>
<td>23.3</td>
<td>76.7</td>
</tr>
<tr>
<td>No. 10</td>
<td>2.00</td>
<td>608</td>
<td>30.4</td>
<td>53.7</td>
<td>46.3</td>
</tr>
<tr>
<td>No. 40</td>
<td>0.435</td>
<td>659</td>
<td>32.6</td>
<td>86.5</td>
<td>13.5</td>
</tr>
<tr>
<td>No. 100</td>
<td>0.150</td>
<td>224</td>
<td>11.2</td>
<td>97.5</td>
<td>2.5</td>
</tr>
<tr>
<td>No. 200</td>
<td>0.075</td>
<td>42</td>
<td>2.1</td>
<td>99.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Pan</td>
<td>—</td>
<td>8</td>
<td>0.4</td>
<td>100.0</td>
<td>—</td>
</tr>
</tbody>
</table>

**Required**
A grain-size distribution curve for this soil sample.

**Solution**
To plot the gradation curve, one must first calculate the percentage retained on each sieve, the cumulative percentage retained, and the percentage passing through each sieve, then tabulate the results, as shown in Table 2–3.

Total sample weight = 2000 g

1. The percentage retained on each sieve is obtained by dividing the weight retained on each sieve by the total sample weight. Thus,

   Percentage retained on ¼-in. sieve = \( \frac{0 \text{ g}}{2000 \text{ g}} \times 100\% = 0\% \)

   Percentage retained on ¾-in. sieve = \( \frac{158 \text{ g}}{2000 \text{ g}} \times 100\% = 7.9\% \)

   Percentage retained on No. 4 sieve = \( \frac{308 \text{ g}}{2000 \text{ g}} \times 100\% = 15.4\% \)

   Therefore,

   \[ \text{Column (4)} = \frac{\text{Column (3)}}{\text{Total sample weight}} \times 100\% \]

2. The cumulative percentage retained on each sieve is obtained by summing the percentage retained on all coarser sieves. Thus,

   Cumulative percentage retained on ¼-in. sieve = 0%

   Cumulative percentage retained on ¾-in. sieve = 0% + 7.9% = 7.9%

   Cumulative percentage retained on No. 4 sieve = 7.9% + 15.4% = 23.3%

   Cumulative percentage retained on No. 10 sieve = 23.3% + 30.4% = 53.7%

   Therefore, column (6) = 100% - column (5).

3. The percentage passing through each sieve is obtained by subtracting from 100% the cumulative percentage retained on the sieves. Thus,

   Percentage passing through ¼-in. sieve = 100% - 0% = 100%

   Percentage passing through ¾-in. sieve = 100% - 7.9% = 92.1%

   Percentage passing through No. 4 sieve = 100% - 23.3% = 76.7%

   Therefore, column (6) = 100% - column (5).

4. Upon completion of these calculations, the grain-size distribution curve is obtained by plotting column (2), sieve opening (mm), versus column (6), percentage passing through, on semilog paper. The percentage passing is always plotted as the ordinate on the arithmetic scale and the sieve opening as the abscissa on the log scale (see Fig. 2–2).

![Figure 2-2 Grain-size distribution curve for Example 2–1.](image-url)
Particle Shapes

- Very Angular
- Angular
- Subangular
- Subrounded
- Rounded
- Well Rounded
Clay Formation

- Clay particles < 2 µm

- Compared to Sands and Silts, clay size particles have undergone a lot more “chemical weathering”! 
Clay vs. Sand/Silt

- Clay particles are generally more platy in shape (sand more equi-dimensional)
- Clay particles carry surface charge
- Amount of surface charge depends on type of clay minerals
- Surface charges that exist on clay particles have major influence on their behavior (for e.g. plasticity)
Clay Minerals

- Kaolinite family
  - Kaolinite (ceramic industry, paper, paint, pharmaceutical)
- Smectite family
  - Montmorillonite (weathered volcanic ash, Wyoming Bentonite, highly expansive, used in drilling mud)
- Illite family
Elements of Earth

8-35 km crust

12500 km dia

% by weight in crust

- O = 49.2
- Si = 25.7
- Al = 7.5
- Fe = 4.7
- Ca = 3.4
- Na = 2.6
- K = 2.4
- Mg = 1.9
- other = 2.6

82.4%
Atomic Structure
Basic Structural Units

Clay minerals are made of two distinct structural units.

- **Silicon tetrahedron**
  - Aluminum or magnesium
  - Hydroxyl or oxygen
  - 0.26 nm

- **Aluminium Octahedron**
  - 0.29 nm
Tetrahedral Sheet

Several tetrahedrons joined together form a tetrahedral sheet.
Tetrahedral & Octahedral Sheets

For simplicity, let’s represent silica tetrahedral sheet by:

\[ \text{Si} \]

and alumina octahedral sheet by:

\[ \text{Al} \]
Different Clay Minerals

Different combinations of tetrahedral and octahedral sheets form different clay minerals:

1:1 Clay Mineral (e.g., kaolinite, halloysite):
Different Clay Minerals

Different combinations of tetrahedral and octahedral sheets form different clay minerals:

2:1 Clay Mineral (e.g., montmorillonite, illite)
Kaolinite

Typically 70-100 layers

joined by strong H-bond
∴ no easy separation

joined by oxygen sharing

0.72 nm
Kaolinite

- used in paints, paper and in pottery and pharmaceutical industries
- \((\text{OH})_8\text{Al}_4\text{Si}_4\text{O}_{10}\)

Halloysite

- kaolinite family; hydrated and tubular structure
- \((\text{OH})_8\text{Al}_4\text{Si}_4\text{O}_{10}.4\text{H}_2\text{O}\)
Montmorillonite

- also called **smectite**; expands on contact with water

\[
\begin{array}{cccc}
\text{Si} & \text{Al} & \text{Si} & \text{Si} \\
\text{Si} & \text{Al} & \text{Si} & \text{Si} \\
\text{Si} & \text{Al} & \text{Si} & \text{Si} \\
\text{Si} & \text{Al} & \text{Si} & \text{Si} \\
\end{array}
\]

\[0.96 \text{ nm}\]

\[\therefore\] easily separated by water

joined by **weak** van der Waal’s bond
Montmorillonite

- A highly reactive (expansive) clay
- \((\mathrm{OH})_4\mathrm{Al}_4\mathrm{Si}_8\mathrm{O}_{20}.n\mathrm{H}_2\mathrm{O}\)
  - swells on contact with water

Bentonite

- montmorillonite family
- used as drilling mud, in slurry trench walls, stopping leaks

- high affinity to water
Illite

joined by $K^+$ ions

fit into the hexagonal holes in Si-sheet

$0.96\ nm$
Others…

**Chlorite**
- A 2:1:1 (???) mineral.
  - Si
  - Al
  - Al or Mg

**Vermiculite**
- montmorillonite family; 2 interlayers of water

**Attapulgite**
- chain structure (no sheets); needle-like appearance
A Clay Particle

Plate-like or Flaky Shape
Clay Fabric

edge-to-face contact

face-to-face contact

Flocculated

Dispersed
Clay Fabric

- Electrochemical environment (i.e., pH, acidity, temperature, cations present in the water) during the time of sedimentation influence clay fabric significantly.

- Clay particles tend to align perpendicular to the load applied on them.
Identifying Clay Minerals
Scanning Electron Microscope

- common technique to see clay particles
- qualitative

plate-like structure
Others…

**X-Ray Diffraction (XRD)**
- to identify the molecular structure and minerals present

**Differential Thermal Analysis (DTA)**
- to identify the minerals present
Casagrande’s PI-LL Chart
Special Terms
Specific Surface

- surface area per unit mass (m²/g)
- smaller the grain, higher the specific surface

Example:

- e.g., soil grain with specific gravity of 2.7
- 10 mm cube
  - spec. surface = 222.2 mm²/g
- 1 mm cube
  - spec. surface = 2222.2 mm²/g
Isomorphous Substitution

- substitution of Si$^{4+}$ and Al$^{3+}$ by other lower valence (e.g., Mg$^{2+}$) cations
- results in charge imbalance (net negative)

Clay Particle with Net negative Charge
Cation Exchange Capacity (c.e.c)

- Capacity to attract cations from the water (i.e., measure of the net negative charge of the clay particle)

- Measured in meq/100g (net negative charge per 100g of clay)

- The replacement power is greater for higher valence and larger cations.

\[ \text{Al}^{3+} > \text{Ca}^{2+} > \text{Mg}^{2+} >> \text{NH}_4^+ > \text{K}^+ > \text{H}^+ > \text{Na}^+ > \text{Li}^+ \]
A Comparison

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Specific surface (m²/g)</th>
<th>C.E.C (meq/100g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaolinite</td>
<td>10-20</td>
<td>3-10</td>
</tr>
<tr>
<td>Illite</td>
<td>80-100</td>
<td>20-30</td>
</tr>
<tr>
<td>Montmorillonite</td>
<td>800</td>
<td>80-120</td>
</tr>
<tr>
<td>Chlorite</td>
<td>80</td>
<td>20-30</td>
</tr>
</tbody>
</table>
Cation Concentration in Water

- Cation concentration drops with distance from clay particle

![Diagram showing the cation concentration and double layer free water around a clay particle.](image)
Adsorbed Water

- A thin layer of water tightly held to particle; like a skin
- 1-4 molecules of water (1 nm) thick
- more viscous than free water
Clay Particle in Water

- Adsorbed water
- Double layer water
- Free water

1 nm
50 nm
Practical Significance
Summary - Clays

- Clay particles are like plates or needles. They are negatively charged.
- Clays are plastic; Silts, sands and gravels are non-plastic.
- Clays exhibit high dry strength and slow dilatancy.
Montmorillonites have very high specific surface, cation exchange capacity, and affinity to water. They form reactive clays.

Montmorillonites have very high liquid limit (100+), plasticity index and activity (1-7).

Bentonite (a form of Montmorillonite) is frequently used as drilling mud.