3. Soil Compaction

Soil Mechanics
2010 - 2011

Soil Compaction

- Is the application of mechanical energy to densify the soil by reducing the volume of air, and thus reducing the total volume.
- Applications (examples):
  - Soil replacement
  - Earth dams
  - Pavement structures
- Benefits of compaction:
  - Increase soil’s strength
  - Reduce soil settlement
  - Reduce soil permeability
- The dry density of the soil changes due to compaction, where:
  \[ \gamma_{dry} = \frac{W}{V_T} \]
Factors controlling compaction

1. Water content
2. Energy of compaction
3. Soil type

Effect of water content

- The dry density – water content relationship (Compaction Curve) passes through 4 phases during compaction:
  1. **Hydration**
     - soil particles absorb water to saturate particles + provide minor lubrication, \( \gamma_{dry} \) increases
  2. **Lubrication**
     - water forms thin films around particles, acts as lubricant, \( \gamma_{dry} \) increases, densest packing
Effect of water content

- The dry density – water content relationship (Compaction Curve) passes through 4 phases during compaction:
  3. **Swelling**
     adding more water causes solid particles to move away from each other, $\gamma_{\text{dry}}$ decreases
  4. **Saturation**
     adding more water fills most of the voids between particles, $\gamma_{\text{dry}}$ decreases, sample is close to saturation

‡ The dry density – water content relationship (Compaction Curve) passes through 4 phases during compaction:

From compaction curve, get:
- $\gamma_{\text{dry, max}} = \text{maximum dry density}$
- $\text{OMC} = \text{optimum moisture content}$
As the compaction energy increases:
1. $\gamma_{\text{dry, max}}$ increases
2. OMC decreases

Compaction curve is the relationship between dry density ($\gamma_d$) and water content ($w$) for a specific soil compacted at constant energy. Determined in the laboratory.

Compaction curves for different energies never intersect.
Effect of soil type

- Different soil types compacted at the same energy:

\[ \text{Gravel} \quad \text{Sand} \quad \text{Silt} \quad \text{Clay} \]

\[ \gamma_{\text{dry}}^{(\text{t/m}^3)} \]

Water Content (%)

Effect of soil type

- \( \text{OMC}_{\text{clay}} > \text{OMC}_{\text{silt}} > \text{OMC}_{\text{sand}} > \text{OMC}_{\text{gravel}} \)
  (remember: OMC at end of lubrication stage. Lubrication is directly proportional to the surface area of solid particles)

- Curvature of compaction curve for clay > silt > sand > gravel.
  As the curvature increases, the effect of water content on \( \gamma_{\text{dry}} \) increases.
Saturation Curve

- Saturation curve is the relationship between dry density ($\gamma_d$) and water content (w) for a specific soil compacted at constant degree of saturation (S).

\[
\gamma_d = \frac{W_s}{\gamma_s} = \frac{w}{\gamma_w}
\]

\[
V_s = \frac{W_s}{\gamma_s} = \frac{w}{\gamma_w}
\]

\[
V_r = \frac{V_s}{S} = \frac{w}{\gamma_w S}
\]

\[
\gamma_d = \frac{V_r}{V_s} = \frac{1}{\gamma_w S} \left( \frac{1}{\gamma_s G_v} \right)
\]

- Calculated, not measured in lab.

- Find $\gamma_d$ in terms of $w$, $G_s$, and $S$:

Assume $W_s = 1$
Saturation Curve

\[ \gamma_d = \frac{1}{\gamma_w} \left( \frac{1}{w} + \frac{1}{\gamma_w G_s} \right) \]

- To draw 100% saturation curve, substitute \( S = 1 \). To draw 50% saturation curve, use \( S = 0.5 \).
- 100% saturation curve never intersect compaction curve.

Laboratory compaction tests

1. **Standard Proctor Test**
2. **Modified Proctor Test**

Determine compaction curves
### Standard Proctor Test

- **Volume of compaction mold (V)** = 1/30 ft³
- **Weight of hammer (W)** = 5.5 lb
- **Hammer drop (H)** = 12 inches = 1 ft
- Four to five soil samples are mixed at different water contents.
- Each sample is compacted in the mold in 3 equal layers, each layer is hit by **N = 25** blows with the hammer, which is falling freely (drop = 1 ft).
- Compaction energy (E) = WHN x no. of layers/V
  
  \[ E = \frac{5.5 \times 1 \times 25 \times 3}{1/30} \approx 12000 \text{ lb ft/ft}^3 \]
Standard Proctor Test

- After compacting each specimen, get the weight of the compacted wet soil in the mold (W).
- Calculate $\gamma_{\text{wet}} = \frac{W}{V_{\text{mold}}}$
- Measure the water content (w) of the wet soil sample in the mold
- Given: w, $\gamma_{\text{wet}}$. Calculate: $\gamma_{\text{dry}}$
  
  $$\gamma_{\text{dry}} = \frac{W_s}{V_T} = \frac{1}{1 + w} \gamma_{\text{wet}}$$
  
  $$\gamma_{\text{dry}} = \frac{\gamma_{\text{wet}}}{1 + w}$$

- Plot $\gamma_{\text{dry}}$ versus w, and get $\gamma_{\text{dry, max}}$ and OMC.

Example

Mold data:

- The volume = 946 cm$^3$
- The weight = 4263 gm

<table>
<thead>
<tr>
<th>Test No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt. of Mold + Soil (gm)</td>
<td>5900</td>
<td>6045</td>
<td>6200</td>
<td>6230</td>
<td>6120</td>
<td>6050</td>
</tr>
<tr>
<td>Water Content (%)</td>
<td>5.1</td>
<td>6.3</td>
<td>7.1</td>
<td>8.2</td>
<td>9.8</td>
<td>12.8</td>
</tr>
</tbody>
</table>
Example

\[ \gamma_{\text{dry}} \ (t/m^3) \]

\[ \gamma_{d\text{max}} = 1.93 \ t/m^3 \]

\[ \text{O} \text{M} \text{C} = 7.65 \% \]

Example

\[ \gamma_{\text{dry}} \ (t/m^3) \]

Not Acceptable
Adjust your scale
Modified Proctor Test

- Volume of compaction mold ($V$) = $\frac{1}{30}$ ft$^3$
- Weight of hammer ($W$) = 10 lb
- Hammer drop ($H$) = 18 inches = 1.5 ft
- Four to five soil samples are mixed at different water contents.
- Each sample is compacted in the mold in 5 equal layers, each layer is hit by $N = 25$ blows with the hammer, which is falling freely (drop = 1.5 ft).
- Compaction energy ($E$) = $WHN \times \text{no. of layers}/V$
  $$= 10 \times 1.5 \times 25 \times 5 / (1/30)$$
  $$\approx 56000 \text{ lb ft/ft}^3$$

Standard versus modified Proctor tests

- $E_{\text{modified}} > E_{\text{standard}}$
- $\gamma_{\text{modified}} > \gamma_{\text{standard}}$
- $O\text{MC}_{\text{modified}} < O\text{MC}_{\text{standard}}$
Field Compaction

- Soil is compacted in layers, 20 to 50 cm thick.
- Based on laboratory defined compaction curves, target field water content is defined to obtain target field dry density.
- Equipment for field compaction
  - Smooth-wheel rollers (Static compaction)
  - Rubber-tired roller
  - Sheepsfoot rollers (Kneeding compaction)
  - Vibratory rollers
  - Vibratory plates

Field Compaction Equipment

Smooth-wheel roller → suitable for all types of soil
Field Compaction Equipment

Rubber-tired rollers \(\rightarrow\) suitable for all types of soil

Field Compaction Equipment

Sheepsfoot rollers \(\rightarrow\) suitable for fine-grained soil
Field Compaction Equipment

Vibratory rollers → suitable for coarse-grained soil (vibrators attached to smooth-wheel or rubber-tired rollers)

Field Compaction Equipment

Hand-held

Vibratory plate compactor → suitable for all types of soil

Mounted on machine
Specifications for field compaction

- In most specifications, it is required to achieve a dry density of 90 to 98% of maximum dry density obtained from standard or modified Proctor tests.

- This is a specification for relative compaction:

\[
\text{Relative Compaction} = \frac{\gamma_{d,\text{field}}}{\gamma_{d,\text{max}}} \times 100
\]

- Field dry density can be determined by conducting “Sand Cone Test”

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**Sand Cone Test**

[Diagram of Sand Cone Test apparatus]
For excavated soil, determine:
- Weight
- Water content

After test

$$W_2$$

Before test

$$W_1$$

$$W_1 - W_2 = \text{weight of standard sand that filled (cone + hole)}$$

Volume of (cone + hole) = $$\frac{W_1 - W_2}{\gamma_{\text{standard sand}}}$$

Volume of hole = Volume of (cone + hole) – Volume of cone
Sand Cone Test

\[ W_1 - W_2 = \text{weight of standard sand that filled cone + hole} \]

Volume of (cone + hole) = \( \frac{(W_1 - W_2)}{\gamma_{\text{standard sand}}} \)

Volume of hole = Volume of (cone + hole) - Volume of cone

Volume of hole = Volume of excavated soil = \( V_T \)

\[ \gamma_{\text{wet}} = \frac{W_T}{V_T} \]

\[ \gamma_{d, \text{field}} = \frac{\gamma_{\text{wet}}}{1 + W} \]

\[ RC = \frac{\gamma_{d, \text{field}}}{\gamma_{d, \text{max}}} \times 100 \]

Sand Cone Test

- Excavate of a hole in the ground.
- The hole is filled with standard sand using the sand cone apparatus.
- The volume of hole equals the volume of standard sand that filled the hole.
- \( \gamma_{\text{wet}} \) is calculated using weight of excavated soil divided by the volume of hole.
- The water content of the extracted soil is measured.
- \( \gamma_{\text{d,field}} \) is calculated.
- RC is calculated.
- The field compaction is compared to RC specification
- If RC < specified value, field compaction is rejected, recompaeted until RC meets the specification.