Soil Compaction:
Densification of soil by the removal of air.

Figure courtesy of *Soil Compaction: A Basic Handbook* by MultiQuip.
WHY COMPACT SOILS?

- Basement & Pool Cracks & Leaks
- Slab Cracks
- Pipe Leakage & Breaks
- Foundation Erosion
- Erosion Gullies Under Abutments
- Utility Trench Settling

Figure courtesy of *Soil Compaction: A Basic Handbook* by MultiQuip.
Soil Compaction

Moist Unit Weight ($\gamma$) vs. Moisture Content ($w$)

Conceptual (Figure 4.1. Das FGE (2005))

\[ \gamma = \frac{\text{Weight (W)}}{\text{Volume (V)}} \]

Silty Clay (LL=37, PI =14) Example
(from Johnson and Sallberg 1960, taken from TRB State of the Art Report 8, 1990)
LABORATORY COMPACtion TESTS (i.e. PROCTORS)

Typical Proctor Test Equipment
(Figure courtesy of test-llc.com)
# Laboratory Compaction Test Summary

<table>
<thead>
<tr>
<th>Test</th>
<th>ASTM/AASHTO</th>
<th>Hammer Weight (lb)</th>
<th>Hammer Drop (in)</th>
<th>Compaction Effort (kip-ft/ft³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard (SCDOT)</td>
<td>D698 T-99</td>
<td>5.5</td>
<td>12</td>
<td>12.4</td>
</tr>
<tr>
<td>Modified</td>
<td>D1557 T-180</td>
<td>10</td>
<td>18</td>
<td>56</td>
</tr>
</tbody>
</table>

---

14.330 Soil Mechanics

Soil Compaction
# Laboratory Compaction Test Summary

<table>
<thead>
<tr>
<th>Test</th>
<th>STANDARD ASTM D698/AASHTO T-99</th>
<th>MODIFIED ASTM D1557/AASHTO T-180</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Material</td>
<td>≤ 20% Retained by #4 Sieve</td>
<td>&gt;20% Retained on 3/8 in</td>
</tr>
<tr>
<td>Use Soil Passing Sieve</td>
<td>#4</td>
<td>3/8 in</td>
</tr>
<tr>
<td>Mold Dia. (in)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>No. of Layers</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
**LAboratory Compaction Test Summary**

**Proctor Test**
A small soil sample is taken from the jobsite. A standard weight is dropped several times on the soil. The material is weighed and then oven-dried for 12 hours in order to evaluate the water content.

- Soil sample
  - 1/30 cubic feet
  - 3 layers
- Compaction force: 12,400 ft. lbs.
- 25 blows per layer
- 12 inches

**Modified Proctor Test**
This is similar to the Proctor test except a hammer is used to compact material for greater impact. This test is normally preferred in testing materials for higher shearing strength.

- Soil sample
  - 1/30 cubic feet
  - 5 layers
- Compaction force: 56,200 ft. lbs.
- 25 blows per layer
- 18 inches

Figure courtesy of *Soil Compaction: A Basic Handbook* by MultiQuip.
LABORATORY COMPACTION TESTS (i.e. PROCTORS)

Automated Proctor Equipment
(Figure courtesy of Humboldt)

Manual Proctor Test
(“What you WILL be doing”)
(Figure courtesy of westest.net)
14.330 SOIL MECHANICS
Soil Compaction

Maximum Dry Density
MDD or \( \gamma_{d,\text{max}} = 112.2 \text{ pcf} \)

From Soil Composition notes:

\[ \gamma_d = \frac{\gamma}{1 + w} \]

Optimum Moisture Content
OMC = 11.5%

SP-SM
% Fines = 6%

Zero Air Voids (ZAV) Line
\( G_s = 2.6 \)
**ZERO AIR VOIDS LINE**

**Dry Unit Weight ($\gamma_d$) (i.e. no water):**

$$\gamma_d = \frac{\text{Weight of Solids} (W_s)}{\text{Volume} (V)} = \frac{\gamma}{1 + w}$$

$\gamma_{zav}$ = **Zero Air Void Unit Weight:**

$$\gamma_{zav} = \frac{G_s \gamma_w}{1 + e} = \frac{G_s \gamma_w}{1 + wG_s} = \frac{\gamma_w}{w + \frac{1}{G_s}}$$
FACTORS AFFECTING SOIL COMPACTION

1. Soil Type
   Grain Size Distribution
   Shape of Soil Grains
   Specific Gravity of Soil Solids

2. Effect of Compaction Effort
   More Energy – Greater Compaction
Types of Compaction Curves

Lee and Suedkamp (1972)

A. Single Peak
   (Most Soils)

B. 1 ½ Peak
   Cohesive Soils LL<30

C. Double Peak
   Cohesive Soils LL<30
   or
   Cohesive Soils LL>70

D. No Definitive Peak
   Uncommon
   Cohesive Soils LL>70

after Figure 4.5. Das FGE (2005)
Effect of Compaction Energy

Table 4.1 Compaction energy for tests shown in Figure 4.6

<table>
<thead>
<tr>
<th>Curve number in Figure 4.6</th>
<th>Number of blows/layer</th>
<th>Compaction energy (kN-m/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>473.0</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>591.3</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>709.6</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>1182.6</td>
</tr>
</tbody>
</table>

In general:

\[ \text{Compaction Energy} = \gamma_{d,\text{max}} \]

\[ \text{Compaction Energy} = \text{OMC} \]

Figure 4.6. Das FGE (2005).
Effect of Compaction on Cohesive Soils

Dry Side Particle Structure
Flocculent

Wet Side Particle Structure
Dispersed

Figure 4.22. Das FGE (2005).
Effect of Compaction on Cohesive Soils

Hydraulic Conductivity ($k$): Measure of how water flows through soils

In General:

Increasing $w$ = Decreasing $k$

Until $\sim$ OMC, then increasing $w$ has no significant affect on $k$
Effect of Compaction on Cohesive Soils

Unconfined Compression Strength ($q_u$): Measure of soil strength

In General:

Increasing $w = \text{Decreasing } q_u$

Related to soil structure:
Dry side – Flocculent
Wet Side – Dispersed

Dry unit weight, $\gamma_d$

Moisture content (%)

Unconfined compression strength, $\sigma_{failure} = q_u$

Moisture content (%)
FIELD COMPACTION EQUIPMENT

4 Common Types:

1. Smooth Drum Roller
2. Pneumatic Rubber Tired Roller
3. Sheepsfoot Roller (Tamping Foot)
4. Vibratory Roller (can be 1-3)
FIELD COMPACTION EQUIPMENT

Photographs courtesy of:

myconstructionphotos.smugmug.com

http://cee.engr.ucdavis.edu/faculty/boulanger/

Holtz and Kovacs (1981)
FIELD COMPACTION EQUIPMENT

Fine Grained Soils

Course Grained Soils

MT-76D Diesel-Powered Rammer

MVC-77H Vibratory Plate

MVH-402DS Reversible Plate

Course Grained Soils

Fine Grained Soils
FIELD COMPACTION EQUIPMENT

COMPACTOR ZONES OF APPLICATION

100% Clay
Sheepsfoot

100% Sand
Vibratory
Smooth steel drums
Multitired pneumatic
Heavy pneumatic
Towed tamping foot
High-speed tamping foot

COMPACTIVE EFFORT

Rock
Grid
Static wt, kneading
Static wt, kneading
Static wt, vibration
Static wt
Static wt, kneading
Static wt, kneading
Static wt, kneading
Static wt, kneading
Static wt, kneading, impact, vibration

from Holtz and Kovacs (1981)
FIELD COMPACTION TESTING

Relative Compaction (R or C.R.):

\[ R(\%) = \frac{\gamma_{d(field)}}{\gamma_{d,\text{max}}} \times 100 \]

5 Common Field Test Methods:

1. Sand Cone (ASTM D1556)
2. Rubber Balloon Method (D2167)
3. Nuclear Density (ASTM D2922)
4. Time Domain Reflectometry (D6780)
5. Shelby Tube (not commonly used)
# Field Compaction Testing

## Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand Cone</td>
<td>• Large Sample&lt;br&gt;• Accurate</td>
<td>• Time consuming&lt;br&gt;• Large area required</td>
<td>• Void under plate&lt;br&gt;• Sand bulking&lt;br&gt;• Sand compacted&lt;br&gt;• Soil pumping</td>
</tr>
<tr>
<td>(ASTM D1556)</td>
<td>• Large Sample&lt;br&gt;• Direct Reading Obtained&lt;br&gt;• Open graded material</td>
<td>• Slow&lt;br&gt;• Balloon breakage&lt;br&gt;• Awkward</td>
<td>• Surface not level&lt;br&gt;• Soil pumping&lt;br&gt;• Void under plate</td>
</tr>
<tr>
<td>Balloon</td>
<td>• Fast&lt;br&gt;• Easy to re-perform&lt;br&gt;• More Tests</td>
<td>• No sample&lt;br&gt;• Radiation&lt;br&gt;• Moisture suspect</td>
<td>• Miscalibration&lt;br&gt;• Rocks in path&lt;br&gt;• Surface prep req.</td>
</tr>
<tr>
<td>(ASTM D2167)</td>
<td></td>
<td></td>
<td>• Under research</td>
</tr>
<tr>
<td>Nuclear</td>
<td></td>
<td>• Under research</td>
<td></td>
</tr>
<tr>
<td>(ASTM D2922 &amp; ASTM D3017)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TDR (ASTM D6780)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Advantages
- Large Sample
- Accurate
- Direct Reading Obtained
- Open graded material
- Fast
- Easy to re-perform
- More Tests
- Fast
- Easy to re-perform
- More Tests

## Disadvantages
- Time consuming
- Large area required
- Slow
- Balloon breakage
- Awkward
- No sample
- Radiation
- Moisture suspect
- Under research

## Errors
- Void under plate
- Sand bulking
- Sand compacted
- Soil pumping
- Surface not level
- Soil pumping
- Void under plate
- Miscalibration
- Rocks in path
- Surface prep req.
- Backscatter
- Under Research

---

*Revised 02/2013*  
*Photographs courtesy of Durham Geo/Slope Indicator and myconstructionphotos.smugmug.com.*
FIELD COMPACTATION TESTING

Sand Cone Method
(D1556-07)

Balloon Method
(D2167-08)

Nuclear Method
(D2922-05 & D3017-05)

## Field Compaction: Test Frequency

<table>
<thead>
<tr>
<th>Reference</th>
<th>City of Lynchburg</th>
<th>SCDOT QC</th>
<th>SCDOT QA</th>
<th>USBR Earth Manual</th>
<th>NAVFAC DM7.02</th>
<th>FM 5-410</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roads</td>
<td></td>
<td>1 per lift per 300 LF</td>
<td>1 per lift per 500 LF</td>
<td>1 per lift per 2500 LF</td>
<td>1 per lift per 250 LF</td>
<td>1 per lift per 250 LF</td>
</tr>
<tr>
<td>Buildings or Structures</td>
<td></td>
<td>1 per lift per 5000 SF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Airfields</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Embankment Mass Earthwork</td>
<td></td>
<td>1 per lift per 500 LF</td>
<td>1 per lift per 2500 LF</td>
<td>2000 CY</td>
<td>500 CY</td>
<td></td>
</tr>
<tr>
<td>Canal/Reservoir Linings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1000 CY</td>
<td>500-1,000 CY</td>
</tr>
<tr>
<td>Trenches &amp; Around Structures</td>
<td></td>
<td>1 per lift per 300 LF</td>
<td></td>
<td>200 CY</td>
<td>200-300 CY</td>
<td>1 per lift per 50 LF</td>
</tr>
<tr>
<td>Parking Areas</td>
<td></td>
<td>1 per lift per 10000 SF</td>
<td></td>
<td></td>
<td></td>
<td>1 per lift per 250 SY</td>
</tr>
<tr>
<td>Misc.</td>
<td></td>
<td></td>
<td></td>
<td>1 per areas of doubtful compaction</td>
<td>1 per areas of doubtful compaction</td>
<td></td>
</tr>
</tbody>
</table>
### Field Compaction: Left Heights

<table>
<thead>
<tr>
<th>State DOTs</th>
<th>Maximum Lift Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maryland, <strong>Massachusetts</strong>, Montana, North Dakota, Ohio, Oklahoma</td>
<td>Max. 0.15 m (6 in) lift before compaction</td>
</tr>
<tr>
<td><strong>Connecticut</strong>, Kentucky</td>
<td>Max. 0.15 m (6 in) lift after compaction</td>
</tr>
<tr>
<td>Alabama, Arizona, California, Delaware, Florida, Idaho, Illinois, Indiana, Iowa, Kansas, <strong>Maine</strong>, Minnesota, Mississippi, Missouri, Oregon, South Carolina, South Dakota, <strong>Vermont</strong>, Virginia, Washington, Wisconsin</td>
<td>Max. 0.2 m (8 in) lift before compaction</td>
</tr>
<tr>
<td>Louisiana, <strong>New Hampshire</strong>, New Jersey, Texas, Wyoming</td>
<td>Max. 0.3 m (12 in) lift before compaction</td>
</tr>
<tr>
<td>New York</td>
<td>Depends on Soil &amp; Compaction Equipment</td>
</tr>
</tbody>
</table>

*After Hoppe (1999), Lenke (2006), and Kim et al. (2009).*
FIELD COMPACtion: ONE POINT PROCTOR

SC-T-29: Standard Method of Test for Field Determination of Maximum Dry Density and Optimum Moisture Content of Soils by the One-Point Method

General Procedure:

- Run one (1) Proctor Test DRY of OMC.
- Plot Test on Family of Curves
- Match to a specific curve: Take MDD and OMC Values from Table.

<table>
<thead>
<tr>
<th>CURVE NO.</th>
<th>MAXIMUM DRY DENSITY</th>
<th>OPTIMUM MOISTURE CONTENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>126.5</td>
<td>7.9</td>
</tr>
<tr>
<td>2</td>
<td>127.2</td>
<td>8.8</td>
</tr>
<tr>
<td>3</td>
<td>125.0</td>
<td>8.9</td>
</tr>
<tr>
<td>4</td>
<td>123.9</td>
<td>9.8</td>
</tr>
<tr>
<td>5</td>
<td>122.4</td>
<td>10.2</td>
</tr>
<tr>
<td>6</td>
<td>120.0</td>
<td>10.9</td>
</tr>
<tr>
<td>7</td>
<td>119.1</td>
<td>11.4</td>
</tr>
<tr>
<td>8</td>
<td>117.6</td>
<td>12.1</td>
</tr>
<tr>
<td>9</td>
<td>115.6</td>
<td>12.8</td>
</tr>
<tr>
<td>10</td>
<td>115.9</td>
<td>13.3</td>
</tr>
<tr>
<td>11</td>
<td>112.5</td>
<td>14.4</td>
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<tr>
<td>12</td>
<td>110.0</td>
<td>15.4</td>
</tr>
<tr>
<td>13</td>
<td>107.6</td>
<td>16.4</td>
</tr>
<tr>
<td>14</td>
<td>105.6</td>
<td>17.5</td>
</tr>
<tr>
<td>15</td>
<td>104.5</td>
<td>18.0</td>
</tr>
<tr>
<td>16</td>
<td>103.0</td>
<td>18.7</td>
</tr>
<tr>
<td>17</td>
<td>101.6</td>
<td>19.2</td>
</tr>
<tr>
<td>18</td>
<td>100.0</td>
<td>21.7</td>
</tr>
<tr>
<td>19</td>
<td>98.0</td>
<td>22.8</td>
</tr>
<tr>
<td>20</td>
<td>96.0</td>
<td>23.9</td>
</tr>
<tr>
<td>21</td>
<td>94.0</td>
<td>24.7</td>
</tr>
<tr>
<td>22</td>
<td>93.0</td>
<td>25.5</td>
</tr>
<tr>
<td>23</td>
<td>92.0</td>
<td>26.1</td>
</tr>
<tr>
<td>24</td>
<td>90.0</td>
<td>26.8</td>
</tr>
<tr>
<td>25</td>
<td>88.0</td>
<td>27.4</td>
</tr>
<tr>
<td>26</td>
<td>87.0</td>
<td>28.0</td>
</tr>
<tr>
<td>27</td>
<td>85.0</td>
<td>28.5</td>
</tr>
</tbody>
</table>
## Compaction Characteristics & Ratings: USCS Soils

<table>
<thead>
<tr>
<th>USCS Sym.</th>
<th>Compaction Equipment</th>
<th>$\gamma_{d,max}^{D698}$ (lb/ft$^3$)</th>
<th>Evaluation for Use as Fill</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Compression &amp; Expansion</td>
<td>Embankment</td>
</tr>
<tr>
<td>GW</td>
<td>Rubber Tired Smooth Drum Vibratory Roller</td>
<td>125 – 135</td>
<td>Almost None</td>
</tr>
<tr>
<td>GP</td>
<td>Rubber Tired Smooth Drum Vibratory Roller</td>
<td>115 – 125</td>
<td>Almost None</td>
</tr>
<tr>
<td>GM</td>
<td>Rubber Tired Sheepsfoot</td>
<td>120 – 135</td>
<td>Slight</td>
</tr>
<tr>
<td>GC</td>
<td>Rubber Tired Sheepsfoot</td>
<td>115 - 130</td>
<td>Slight</td>
</tr>
</tbody>
</table>

*after U.S. Army Engineer Waterways Experiment Station (now ERDC). (1960). “The Unified Soil Classification System,” Technical Memorandum No. 3-357, Vicksburg, MS.*
### Compaction Characteristics & Ratings: USCS Soils

<table>
<thead>
<tr>
<th>USCS Sym.</th>
<th>Compaon Equipment</th>
<th>$\gamma_{d,\text{max}}$ D698 (lb/ft$^3$)</th>
<th>Evaluation for Use as Fill</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Compression &amp; Expansion</td>
</tr>
<tr>
<td>SW</td>
<td>Rubber Tired Vibratory Roller</td>
<td>110-130</td>
<td>Almost None</td>
</tr>
<tr>
<td>SP</td>
<td>Rubber Tired Vibratory Roller</td>
<td>100-120</td>
<td>Almost None</td>
</tr>
<tr>
<td>SM</td>
<td>Rubber Tired Sheepsfoot</td>
<td>110-125</td>
<td>Slight</td>
</tr>
<tr>
<td>SC</td>
<td>Rubber Tired Sheepsfoot</td>
<td>105-125</td>
<td>Slight to Medium</td>
</tr>
</tbody>
</table>

*after U.S. Army Engineer Waterways Experiment Station (now ERDC), (1960). “The Unified Soil Classification System,” Technical Memorandum No. 3-357, Vicksburg, MS.*
# Compaction Characteristics & Ratings: USCS Soils

<table>
<thead>
<tr>
<th>USCS Sym.</th>
<th>Compaction Equipment</th>
<th>$\gamma_{d,\text{max}}$ D698 (lb/ft³)</th>
<th>Evaluation for Use as Fill</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Compression &amp; Expansion</td>
</tr>
<tr>
<td>ML</td>
<td>Rubber Tired Sheepsfoot</td>
<td>95-120</td>
<td>Slight to Medium</td>
</tr>
<tr>
<td>CL</td>
<td>Sheepsfoot Rubber Tired</td>
<td>95-120</td>
<td>Medium</td>
</tr>
<tr>
<td>MH</td>
<td>Sheepsfoot Rubber Tired</td>
<td>70-95</td>
<td>High</td>
</tr>
<tr>
<td>CH</td>
<td>Sheepsfoot</td>
<td>80-105</td>
<td>Very high</td>
</tr>
</tbody>
</table>

after U.S. Army Engineer Waterways Experiment Station (now ERDC). (1960). “The Unified Soil Classification System,” Technical Memorandum No. 3-357, Vicksburg, MS.
DYNAMIC COMPACTION

Figure 1. FHWA-SA-95-037.

US44 Expansion
Carver, MA.

Figure courtesy of www.betterground.com
DYNAMIC COMPACTATION

<table>
<thead>
<tr>
<th>GRAVEL</th>
<th>SAND</th>
<th>SILT &amp; CLAY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coarse to medium</td>
<td>Fine</td>
</tr>
</tbody>
</table>

 FHWA ZONE III
Impervious Soils

 FHWA ZONE I
Pervious Soils

 FHWA ZONE II
Semi-Pervious Soils

after Figure 5 (FHWA-SA-95-037).
Dynamic Compaction: US 44
DYNAMIC COMPACTION: US 44

- FHWA ZONE III: Impervious Soils
- FHWA ZONE I: Pervious Soils
- FHWA ZONE II: Semi-Pervious Soils

Graph showing sieving analysis data from Yong (2005), UMass Dartmouth sieve analysis range, and FHWA ZONE boundaries (SA-95-037). (from Hajduk et al., 2004)
Dynamic Compaction: US 44

(from Hajduk et al., 2004)
14.330 SOIL MECHANICS
Soil Compaction

VIBROFLOTATION

Figure 4.18. Das FGE (2005) (after Brown, 1977).

Photograph courtesy of http://www.vibroflotation.com
Soil Compaction

VIBROFLOTATION

Stage 1

Stage 2

Stage 3

Stage 4

VIBROFLotation
PROBE SPACING

VIBROFLotation
EFFECTIVE GRAIN SIZE DISTRIBUTIONS

Figure 4.20. Das FGE (2005).

Figure 4.21. Das FGE (2005).
COMPACTION: ASSOCIATED COSTS

Figure courtesy of www.groundimprovement.ch.