4 SOIL COMPACTION

4.1 Introduction

In designing a steel or concrete structure, the engineer specifies a suitable grade of the material to meet the requirements.

When it comes to soils, we do not have that luxury and the structure is designed to suit the soil conditions. In some circumstances, it is necessary to improve the ground conditions so that better economies can be achieved in the design of the structure.

The poor soil conditions include loose granular deposits, soft clays, collapsible soils, expansive soils, organic soils, and contaminated soils. The ground improvement is generally well worth the expenditure and reduces the overall cost of the project.

4.2 Ground Improvement Techniques

When construction is carried out in, on, or with soils, the natural soil needs to be modified by densification, reinforcement, drainage, cementation, or by drying.
Some of these techniques were developed several centuries ago and have evolved with time. There are several methods available to improve the soil conditions. The appropriate method is selected based on the soil type, project constraints, and the budget.
Mechanical compaction discussed in this chapter is one of the oldest, simplest, and economical methods widely used for ground improvement. Some of the other ground improvement methods are:
a. Soil replacement;
b. Preloading with or without vertical drains;
c. Mass stabilization using lime, cement or fly-ash;
d. Vibroflotation;
e. Stone columns;
f. Semi-rigid inclusions;
g. Electro-osmotic consolidation/dewatering;
h. Jet grouting;
i. Dynamic compaction; and
j. Deep soil mixing.

These ground improvement methods can be implemented during the early works or at the design stage, during construction (e.g., unexpected soft soils), or post construction (e.g., as remedial measures).

Compaction is an economical and popular technique for improving soils. The soil fabric is forced into a dense configuration by the expulsion of air using mechanical effort with or without the assistance of water. The benefits of compaction are:

1. Increased soil strength.
2. Increased load-bearing capacity.
3. Reduction in settlement (lower compressibility).
4. Reduction in the flow of water (water seepage).
5. Reduction in soil swelling (expansion) and collapse (soil contraction).
6. Increased soil stability.
7. Reduction in frost damage.

Improper compaction can lead to:

1. Structural distress from excessive total and differential settlements.
2. Cracking of pavements, floors, and basements.
3. Structural damage to buried structures, water and sewer pipes, and utility conduits.
4. Soil erosion.

4.3 Compaction Curve

When a site is cleared prior to the construction, there is generally a need for cut and fill and earth moving work in preparing the site for the proposed structure (Fig. 4.1). During the cut and fill operation, the soil is loosened (Fig. 4.1a), and therefore requires densification through mechanical compaction (Fig. 4.1b).

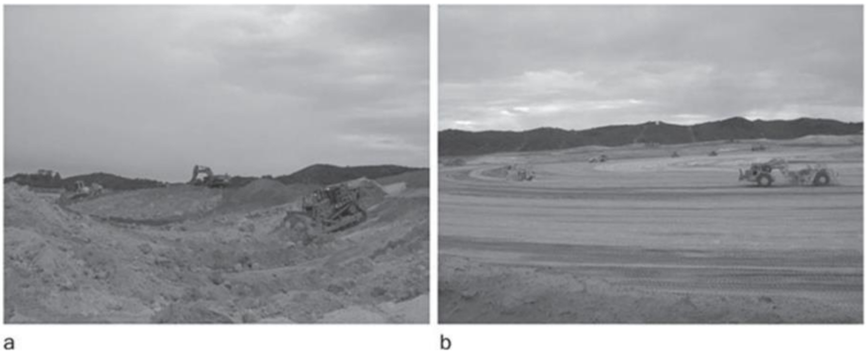


FIGURE 4.1 Site preparation: (a) before, (b) after.

When a weak soil is compacted, the void ratio is reduced and the dry density is increased. This generally makes the soil stronger, less permeable, and prone to lesser deformations while in service.

When the soil is compacted, water is added to act as a lubricant between the soil grains, facilitating the compaction process.

The properties of the compacted soil are mainly influenced by (a) the moisture content and (b) the effort used in compaction, known as compaction effort or compaction energy, quantified in N·m (same as Joules) per cubic meter of compacted soil.

Figure 4.2 shows the phase diagrams for five mixes (1–5) of the same soil compacted using the same energy but at different moisture contents, increasing from mix 1 to mix 5. In the phase diagrams, the volume of the soil grains is taken as the same for all five mixes, so that the relative changes in the other two phases can be compared.

The variations of the dry unit weight (γ_d) and the void ratio (e) with the moisture content (w) are also shown in the figure.

While the dry unit weight increases and decreases with the moisture content, the trend is opposite for the void ratio.

The moisture content at which the dry unit weight is the maximum is known as the optimum moisture content. The plot of dry unit weight (or dry density) against the moisture content is the compaction curve.

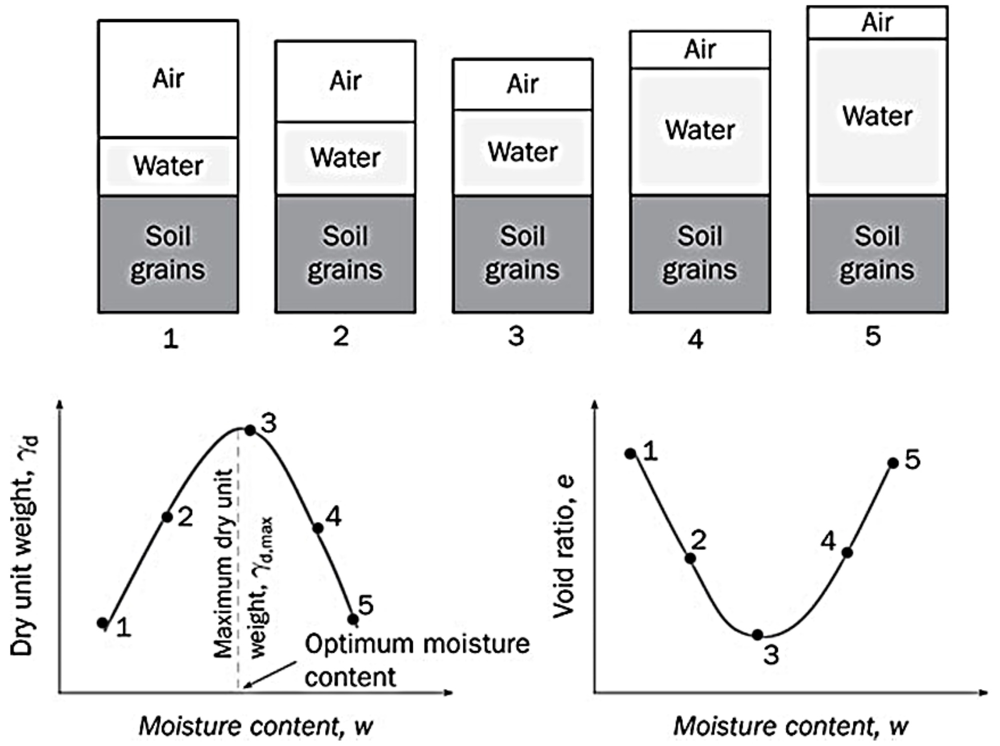


FIGURE 4.2 Effects of moisture content on dry unit weight and void ratio.

The dry unit weight can be written as

$$\gamma_d = \frac{G_s \gamma_w}{1 + e} \qquad (4.1)$$

It can be deduced from Eq. (4.1) that when void ratio decreases, dry unit weight increases and vice versa. When the dry unit weight is the maximum, the void ratio is the minimum.

The soils are generally compacted at moisture content close to the optimum moisture content, where they have the best engineering properties and a dense matrix.

Compacting a soil at moisture content less than the optimum moisture content is called “compacting dry of optimum” and compacting at moisture content greater than the optimum moisture content is known as “compacting wet of optimum.”

The compaction curve, the optimum moisture content, and the maximum dry unit weight depend on the type of soil and the compaction energy.

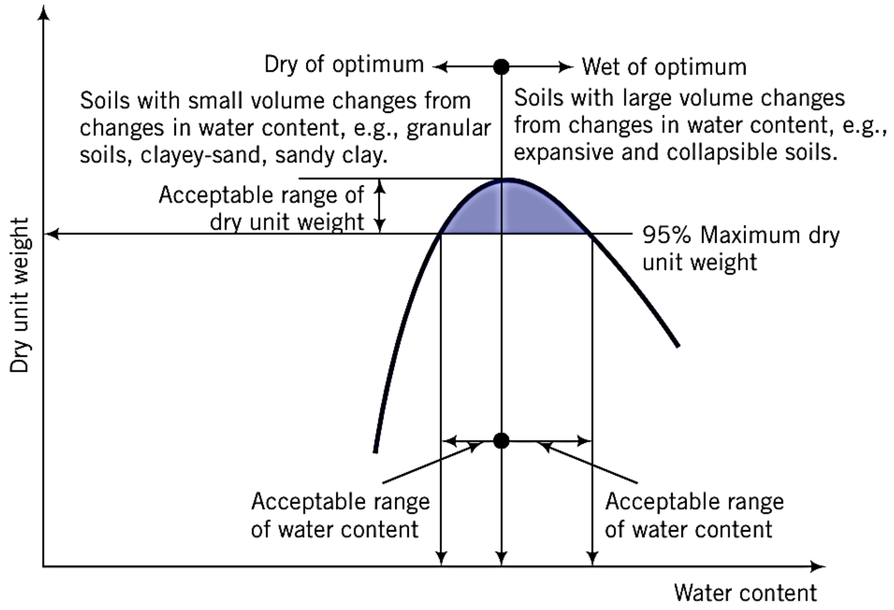


Figure 4.3: Illustration of compaction specification of soils in the field.

4.4 Proctor Compaction Test (Laboratory Test)

1. Standard Proctor test

➢ The standard Procter test developed to simulate field compaction in the lab.
➢ The purpose of test is to find the wopt and γd,max.
➢ ASTM (D-698) and AASHTO (T-99).
➢ For each test, the moist unit weight of compaction, γ is:

$$\gamma = \frac{W}{V_m} \qquad (4.2)$$

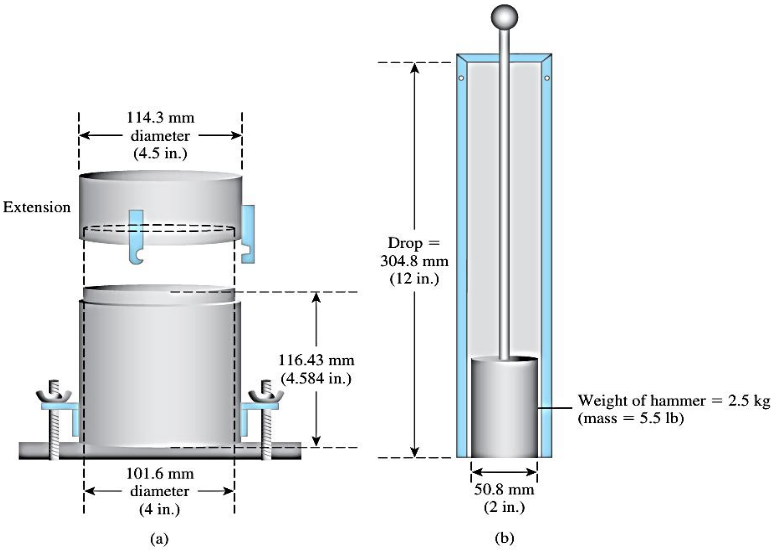
where

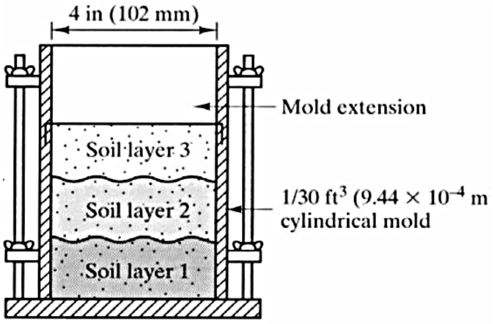
W = weight of the compacted soil in the mold.

Vm = volume of the mold.

Equipment

- ➢ Mold of volume 944 cm3 (1/30 ft^3), the diameter of the mold is 101.6 mm (4inch), the soil sample placed in three layers;
- ➢ Hammer of weight 5.5 lb (2.49 kg) and drop distance of 12inch (305 mm); with 25 blows/layer.
- ➢ The compaction effort (energy) is 600 kN-m/m3 (12400 lb-ft/ft^3).





Procedure

1. Obtain 10 lbs of soil passing sieve No.4;

2. Record the weight of the Proctor mold without the base and the (collar) extension;

3. Assemble the compaction apparatus;

4. Place the soil in the mold in 3 layers and compact using 25 well distributed blows of the Proctor hammer;

5. Remove the collar and the base without disturbing the soil sample to determine the weight of the mold and compacted soil;

6. Take a sample (20-30) grams of soil to find the moisture content;

7. Place the remainder of the molded soil into the pan, break it down, and thoroughly remix it with the other soil, plus 100 additional grams of water.

For each test, the moisture content of the compacted soil is determined in the Lab., the dry unit weight is:

$$\gamma_d = \frac{\gamma}{1+w} \qquad (4.3)$$

The values of determined γd can be plotted against the corresponding moisture contents to obtain the maximum dry unit weight and the optimum moisture content for the soil.

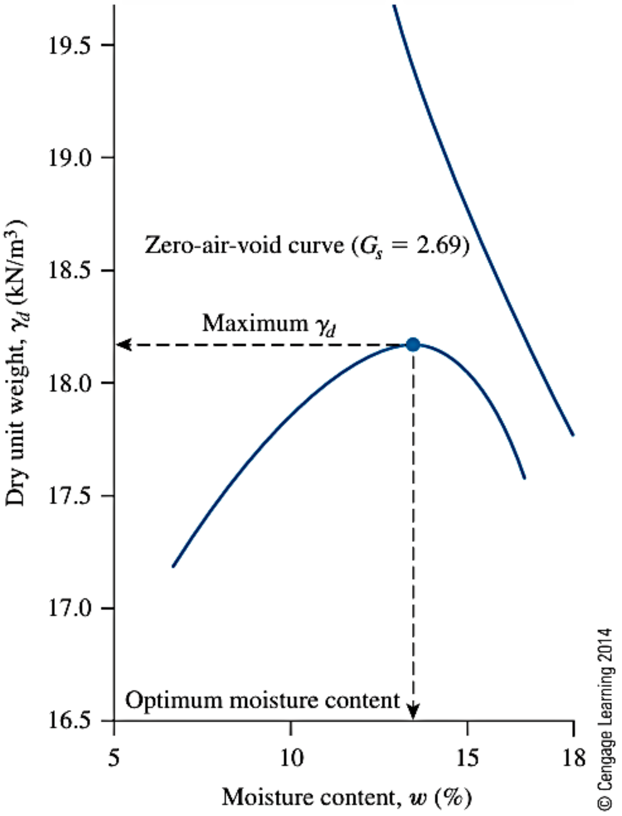


Figure 4-5: Standard Proctor compaction test (results for a silty clay)

2. Modified Proctor test

➢ The modified Procter test was developed to simulate larger compaction effort for more serious loads and bigger equipment.

➢ ASTM (D-1557) and AASHTO (T-180).

Equipment

1) Mold of volume 944 cm^3 (1/30 ft^3); the soil sample placed in five layers;

2) Hammer of weight 4.54 kg (10 lb) and drop distance of 457 mm (18 inch); with 25 blows/layer.

3) The compaction effort (energy) is 2700 kN-m/m^3 (56000 lb-ft/ft^3).

4) used in standard Procter test except placing soil in five layers instead of three layers.

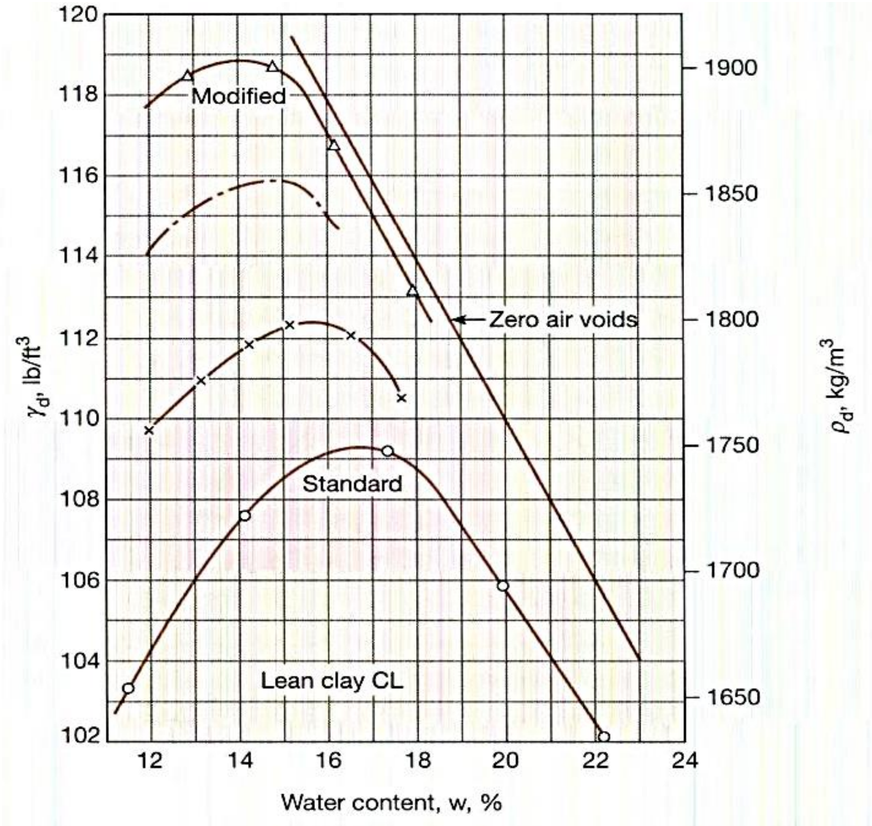


Figure 4.6: Effects of compaction effort on compaction curve.

4.5 Zero Air Void Curve

$$\gamma_d = \frac{G_s \gamma_w}{1+e} \tag{4.4}$$

$$w = \frac{Se}{G_s} \tag{4.5}$$

From Eqs. (4.4) and (4.5)

$$\gamma_d = \frac{G_s \gamma_w}{1 + \frac{w G_s}{S}} \tag{4.6}$$

- From Eq. (4.6) it can be seen that in a specific soil (i.e., for a known value of Gs), every point on the $\gamma_d - w$ plane will have a specific value for the degree of saturation S. Therefore, Eq. (4.6) can be used to define the curves representing different values of degree of saturation.
- The curve representing S = 100% is called the zero air void curve (see Fig. 4.7a).
- The zero air void curve separates the $\gamma_d - w$ space into two regions where S < 100% and S > 100% (which is not possible). The regions to the left and right of the zero air void curve represent the points where S < 100% and S > 100%, respectively.

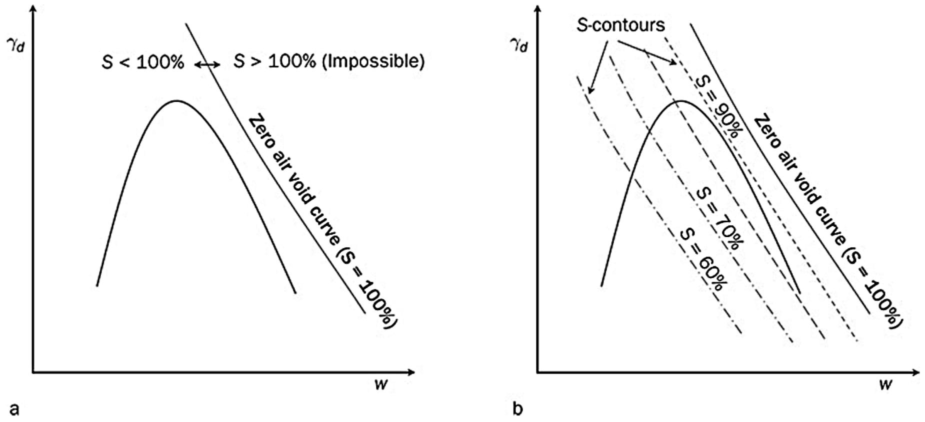


Figure 4.7 (a) Zero air void curve, (b) degree of saturation contours.

4.6 Factors Affecting Compaction

The preceding section showed that moisture content has a strong influence on the degree of compaction achieved by a given soil. Besides moisture content, other important factors that affect compaction are soil type and compaction effort (energy per unit volume).

a) Effect of Soil Type

The soil type—that is, grain-size distribution, shape of the soil grains, specific gravity of soil solids, and amount and type of clay minerals present—has a great influence on the maximum dry unit weight and optimum moisture content. Figure 4.8 shows typical compaction curves obtained from four soils.

- ➢ fine grain soil needs more water to reach wopt; and
- ➢ coarse grain soil needs less water to reach wopt.

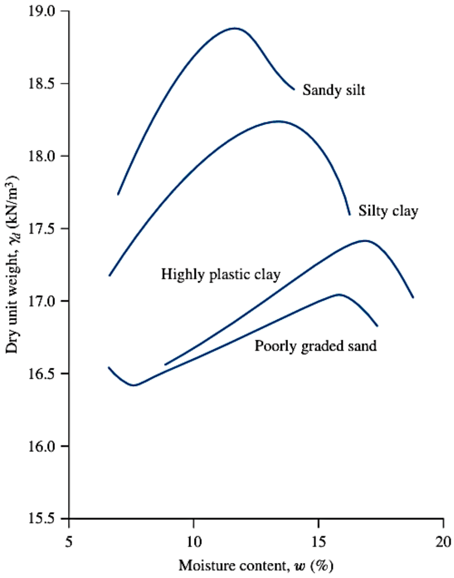


Figure 4.8 Typical compaction curves for four soils (ASTM D-698)

b) Effect of Compaction Effort

The compaction effort can be calculated as follows:

$$E = \frac{\begin{pmatrix}\text{Number}\\ \text{of blows}\\ \text{per layer}\end{pmatrix} \times \begin{pmatrix}\text{Number}\\ \text{of}\\ \text{layers}\end{pmatrix} \times \begin{pmatrix}\text{Weight}\\ \text{of}\\ \text{hammer}\end{pmatrix} \times \begin{pmatrix}\text{Height of}\\ \text{drop of}\\ \text{hammer}\end{pmatrix}}{\text{Volume of mold}}$$

From the Figure 4.9, we can see that

1. As the compaction effort is increased, the maximum dry unit weight of compaction is also increased.
2. As the compaction effort is increased, the optimum moisture content is decreased to some extent.

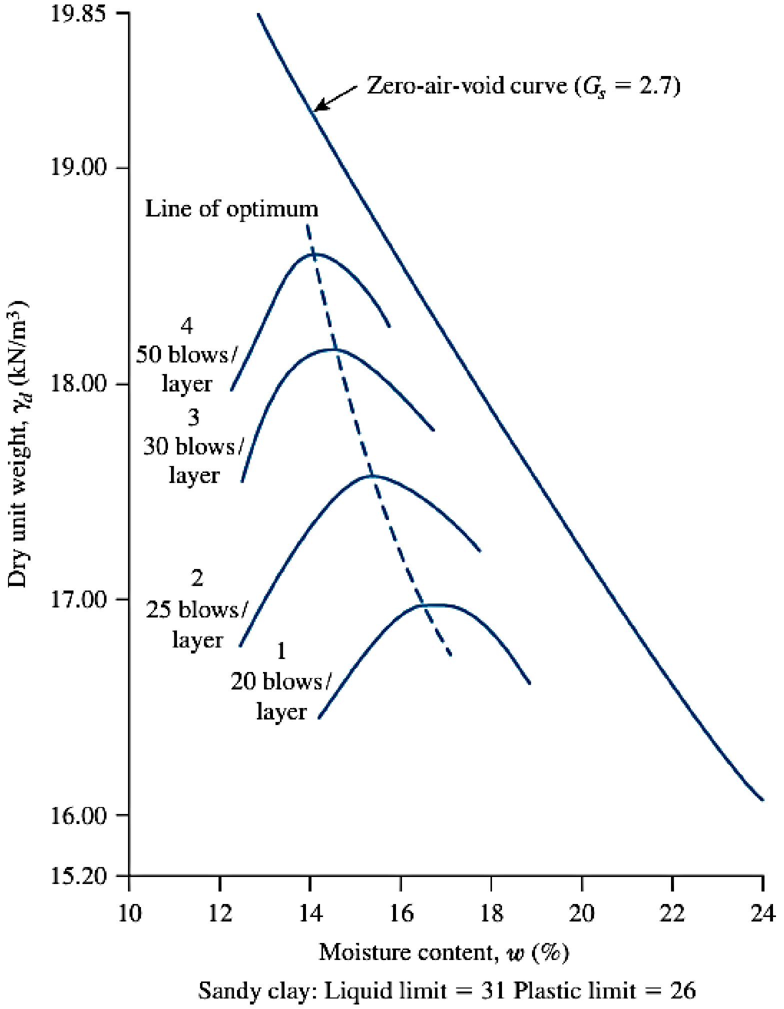


Figure 4.9 Effect of compaction energy on the compaction of a sandy clay

Example 4.1

The laboratory test results of a standard Proctor test are given in the following table.

Volume of mold (cm^3)	Weight of moist soil in mold (N)	Moisture content, w (%)
944	16.81	10
944	17.84	12
944	18.41	14
944	18.33	16
944	17.84	18
944	17.35	20

a. Determine the maximum dry unit weight of compaction and the optimum moisture content.

b. Calculate and plot γ_d versus the moisture content for degree of saturation, $S = 80$, 90, and 100% (i.e., γ_{zav}). Given: $G_s = 2.7$.

Solution

Part a

The following table can be prepared.

Volume of mold V_m (cm^3)	Weight of soil, W (N)	Moist unit weight, γ (kN/m^3)[a]	Moisture content, w (%)	Dry unit weight, γ_d (kN/m^3)[b]
944	16.81	17.81	10	16.19
944	17.84	18.90	12	16.87
944	18.41	19.50	14	17.11
944	18.33	19.42	16	16.74
944	17.84	18.90	18	16.02
944	17.35	18.38	20	15.32

[a] $$\gamma = \frac{W}{V_m}$$

[b] $$\gamma_d = \frac{\gamma}{1 + \frac{w\%}{100}}$$

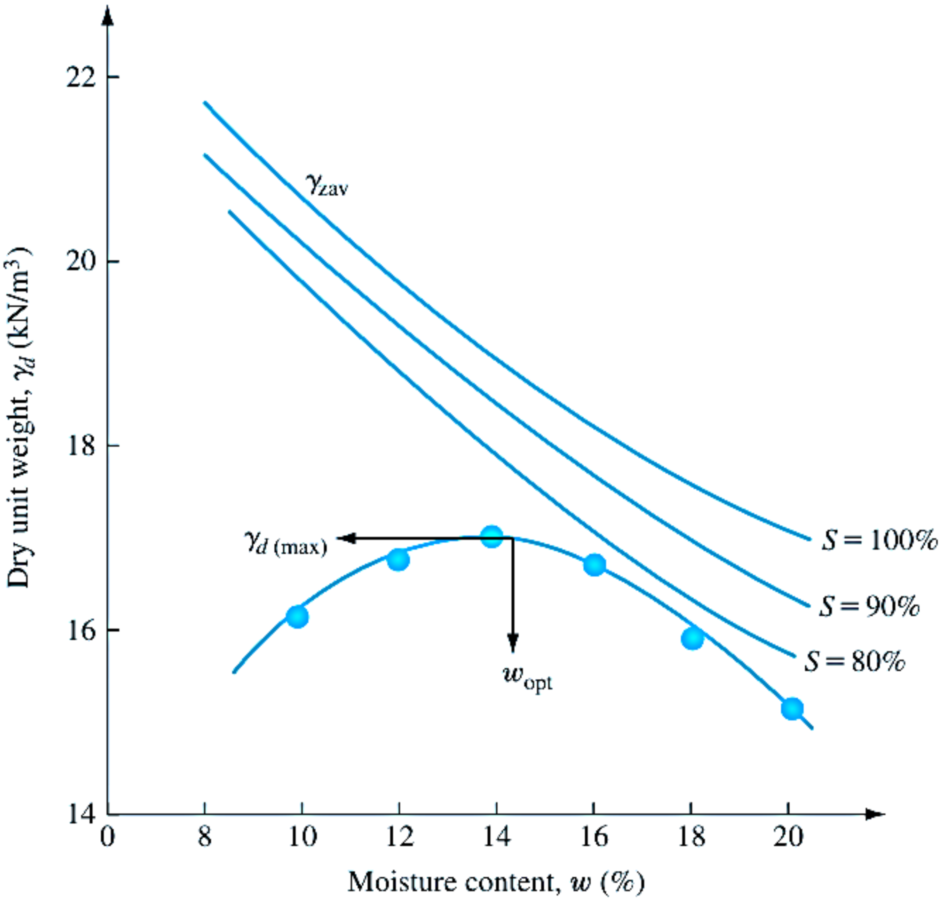
Part b

From Eq. (6.3),

$$\gamma_d = \frac{G_s \gamma_w}{1 + \frac{G_s w}{S}}$$

The following table can be prepared.

		γ_d (kN/m^3)		
G_s	w (%)	S = 80%	S = 90%	S = 100%
2.7	8	20.84	21.37	21.79
2.7	10	19.81	20.37	20.86
2.7	12	18.85	19.48	20.01
2.7	14	17.99	18.65	19.23
2.7	16	17.20	17.89	18.50
2.7	18	16.48	17.20	17.83
2.7	20	15.82	16.55	17.20



Example 4.2

In a standard Proctor compaction test, the soil is compacted in a cylindrical mold of 943.3 cm^3 volume in three equal layers, with 25 blows per layer. For each blow, the 2.495 kg hammer is dropped over 304.8 mm in delivering the blows. Determine the compaction energy per unit volume in kJ/m^3.

Solution

Work done per blow = (2.495 × 9.81 N) (0.3048 m) = 7.4603 N·m

No of blows for the sample = 3 × 25 = 75

Therefore, total work done on the soil in the mold = 7.4603 × 75 = 559.52 N·m

Volume of the compacted sample = 943.3 cm^3

Therefore, the compaction energy delivered to the soil = 559.52 N·m/(943.3 × 10^{-6} m^3)

= 593 kN·m/m^3or 593 kJ/m^3

4.7 Field Compaction

The common equipment used in field compaction are:

1. Smooth wheel rollers;
2. Pneumatic rubber-tired rollers;
3. Sheep foot rollers;
4. Vibratory rollers.

Smooth Wheel Rollers or Smooth Drum Rollers

- ➢ Are suitable for thin layers and for finishing operations;
- ➢ Suitable for sandy and clayey soils;
- ➢ Provide 100% coverage;
- ➢ Ground contact pressure range (310-380) kN/m^2.

Pneumatic Rubber-Tired Rollers

- ➢ Have a series of rubber tires side-by-side instead of a smooth drum. Compaction is achieved by a combination of weight and kneading action.
- ➢ Suitable for sandy and clayey soils;
- ➢ Provide (70-80) % coverage;
- ➢ Ground contact pressure range (600-700) kN/m^2.

Sheep foot Rollers

- ➢ Are drums with a large number of "sheep foot" projections. They are most effective in compacting clayey soils.
- ➢ Most effective in clayey soils;
- ➢ Ground contact pressure range (1400-7000) kN/m^2.

Vibratory Rollers

Vibratory rollers work well in compacting granular soils. Vibratory action can be attached to the all types of rollers.

Ramming

Rammers can be used for effective compaction of granular soils over a limited area.

Factors Affecting Field Compaction

1. Soil type; 2. Moisture content; 3. Thickness of lift; 4. Intensity of pressure applied by the equipment; 5. The area over which the pressure is applied.

4.8 Measurement of field compaction

In most specifications for earthwork, the contractor is instructed to achieve a compacted field dry unit weight of 90 to 95% of the maximum dry unit weight determined in the laboratory by either the standard or modified Proctor test.

a) Relative compaction

Relative compaction is a way of comparing compaction in the field with the laboratory compaction results. It is defined as:

$$R(\%) = \frac{\gamma_d(in\ the\ field)}{\gamma_{dmax.}(in\ the\ lab)} \times 100$$

R (%) = relative compaction.

- Relative Compaction value range (90 – 100%).
- If R > 100 % use Modified Proctor Test.

b) Relative density

For the compaction of granular soils, specifications sometimes are written in terms of the required relative density Dr or the required relative compaction. Relative density should not be confused with relative compaction. It indicates the in-situ denseness or looseness of granular soil.

$$\boldsymbol{D_r = \frac{e_{max} - e_{field}}{e_{max} - e_{min}}}$$

D_r: is the relative density, usually given as percentage;
e_{field} : is the in situ void ratio of the soil;
e_{max}: is the void ratio of the soil in the loosest state;
e_{min}: is the void ratio of the soil in the densest state.

- In terms of the porosity

$$\boldsymbol{D_r = \frac{(1 - n_{min})(n_{max} - n_{field})}{(n_{max} - n_{min})(1 - n_{field})}}$$

- In terms of unit weight

$$\boldsymbol{D_r = \left[\frac{\gamma_{d(field)} - \gamma_{d(\min)}}{\gamma_{d(\max)} - \gamma_{d(\min)}}\right]\left[\frac{\gamma_{d(\max)}}{\gamma_{d(field)}}\right]}$$

$\gamma_{d(min)}$: is the dry unit weight in the loosest condition (at a void ratio of e_{max});
$\gamma_{d(max)}$: is the dry unit weight in the densest condition (at a void ratio of e_{min});
$\gamma_{d(field)}$: is the in situ dry unit weight (at void ratio of e_{field}).

- In terms of density

$$D_r = \left[\frac{\rho_{d(field)} - \rho_{d(min)}}{\rho_{d(max)} - \rho_{d(min)}}\right]\left[\frac{\rho_{d(max)}}{\rho_{d(field)}}\right]$$

$$R = \frac{R_o}{1 - D_r(1 - R_o)}$$

$$R_o = \frac{\gamma_{d(\min)}}{\gamma_{d(\max)}}$$

Table 4.1: Qualitative description of granular soil deposits.

Relative Density %	Description
0-15	Very loose
15-50	Loose
50-70	Medium
70-85	Dense
85-100	Very dense

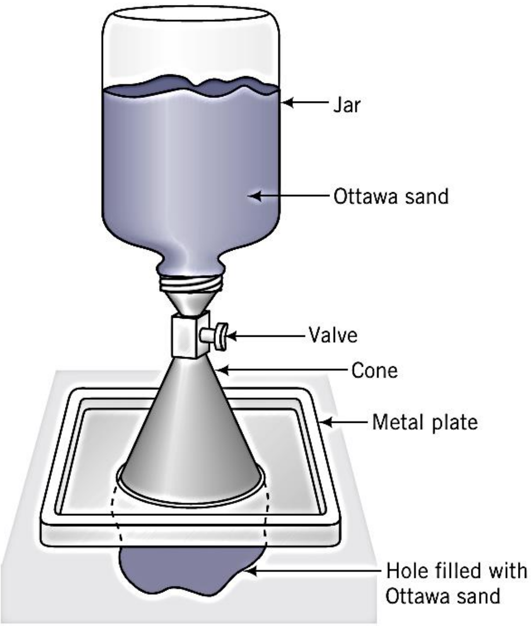
4.9 Determination of field unit weight

The common methods are:

a) Sand cone method (ASTM D-1556 or AASHTO T-191);
b) Rubber balloon method (ASTM D-2167 or AASHTO T-205);
c) Nuclear method (ASTM D-2922).

a) Sand cone method

The device consists of a glass or plastic jar with a metal cone attached at its top. The jar is filled with uniform dry Ottawa sand.



Procedure

1. Determine the combined weight of jar, cone and sand filling the jar, W_1;
2. Clean the area in the site of the compacted area, then excavate a small hole and measure the weight of excavated soil, W2, also determine the moisture content of excavated soil;
3. Determine the dry weight of soil;

$$W_3 = \frac{W_2}{1 + \frac{w\,(\%)}{100}}$$

4. After excavation the hole, place the inverted cone with jar over the hole. The sand is allowed to fill the hole, after determine the combined weight of jar, cone and remaining sand, W4;

$$W_5 = W_1 - W_4$$

   Where W5 is the weight of sand filled the hole.

5. Determine the volume of the excavated hole;

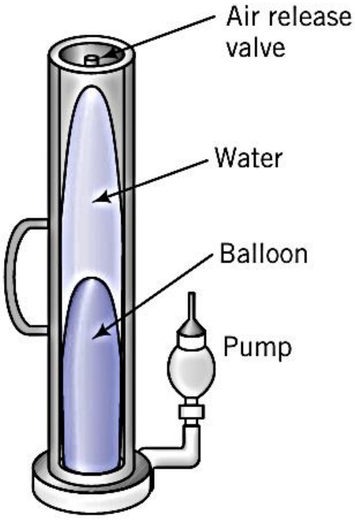
$$V = \frac{W_5 - W_c}{\gamma_{d(sand)}}$$

   Wc is the weight of sand to fill the cone only,
6. Determine the field dry unit weight of compacted soil

$$\gamma_{d(field)} = \frac{W_3}{V}$$

b) Rubber balloon method

It's similar to the sand cone method except the determination of volume of hole by introducing a balloon filled with water into the hole.

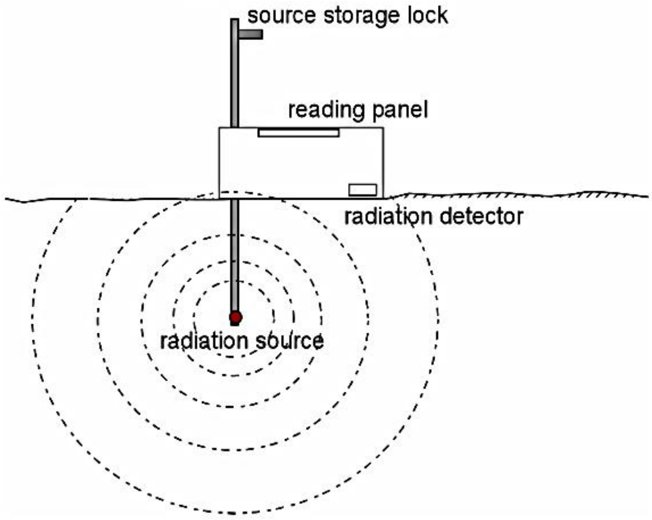


c) Nuclear method

➢ Operates either in drilled holes or from the ground surface.

➢ Measures the weight of wet soil per unit volume and the weight of water present in a unit volume of soil.

➢ The big disadvantage of this instrument is the safety precautions that have to be taken into account. It is even



Example 4.3

Laboratory compaction test results for a clayey silt are given in the following table.

Moisture content (%)	Dry unit weight (kN/m^3)
6	14.80
8	17.45
9	18.52
11	18.9
12	18.5
14	16.9

Following are the results of a field unit-weight determination test performed on the same soil by means of the sand cone method:

- Calibrated dry density of Ottawa sand = 1570 kg/m^3
- Calibrated mass of Ottawa sand to fill the cone = 0.545 kg
- Mass of jar + cone + sand (before use) = 7.59 kg
- Mass of jar + cone + sand (after use) = 4.78 kg
- Mass of moist soil from hole = 3.007 kg
- Moisture content of moist soil = 10.2%

Determine:

a. Dry unit weight of compaction in the field

b. Relative compaction in the field

Solution

Part a

In the field,

$$\text{Mass of sand used to fill the hole and cone} = 7.59\text{ kg} - 4.78\text{ kg} = 2.81\text{ kg}$$

$$\text{Mass of sand used to fill the hole} = 2.81\text{ kg} - 0.545\text{ kg} = 2.265\text{ kg}$$

$$\text{Volume of the hole } (V) = \frac{2.265\text{ kg}}{\text{Dry density of Ottawa sand}}$$

$$= \frac{2.265\text{ kg}}{1570\text{ kg/m}^3} = 0.0014426\text{ m}^3$$

$$\text{Moist density of compacted soil} = \frac{\text{Mass of moist soil}}{\text{Volume of hole}}$$

$$= \frac{3.007}{0.0014426} = 2.084.4\text{ kg/m}^3$$

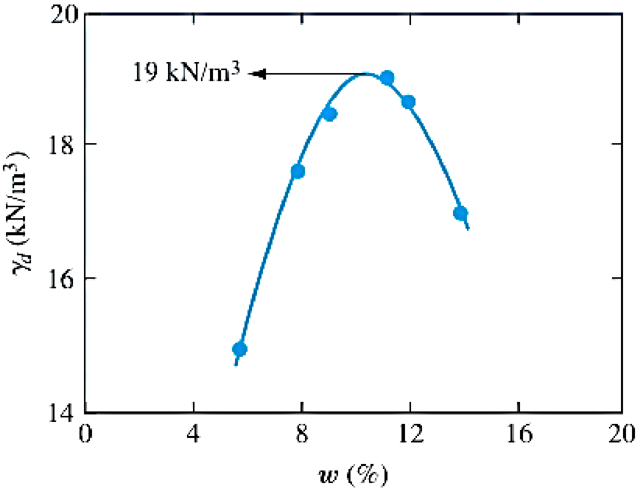
$$\text{Moist unit weight of compacted soil} = \frac{(2084.4)(9.81)}{1000} = 20.45\ \text{kN/m}^3$$

Hence,

$$\gamma_d = \frac{\gamma}{1 + \dfrac{w(\%)}{100}} = \frac{20.45}{1 + \dfrac{10.2}{100}} = \mathbf{18.56\ kN/m^3}$$

Part b

The results of the laboratory compaction test are plotted in Figure 6.27. From the plot, we see that $\gamma_{d(\max)} = 19\ \text{kN/m}^3$. Thus, from Eq. (6.19),



© Cengage Learning 2014

Figure 6.27 Plot of laboratory-compaction test results

$$R = \frac{\gamma_{d(\text{field})}}{\gamma_{d(\max)}} = \frac{18.56}{19.0} = \mathbf{97.7\%}$$

Example 4.4

For a given soil, following are the results of compaction tests conducted in the laboratory.

Moisture content (%)	Dry unit weight γ_d (kN/m³)
12	16.34
14	16.93
16	17.24
18	17.20
20	16.75
22	16.23

© Cengage Learning 2014

After compaction of the soil in the field, sand cone tests (control tests) were conducted at five separate locations. Following are the results:

Location	Moisture content (%)	Moist density, ρ (kg/m^3)
1	15.2	2055
2	16.4	2060
3	17.2	1971
4	18.8	1980
5	21.1	2104

The specifications require that:

a. γ_d must be at least 0.95 $\gamma_{d(\max)}$.

b. Moisture content w should be within ±2% of w_{opt}.

Make necessary calculations to see if the control tests meet the specifications.

Solution

From Eq. (6.4),

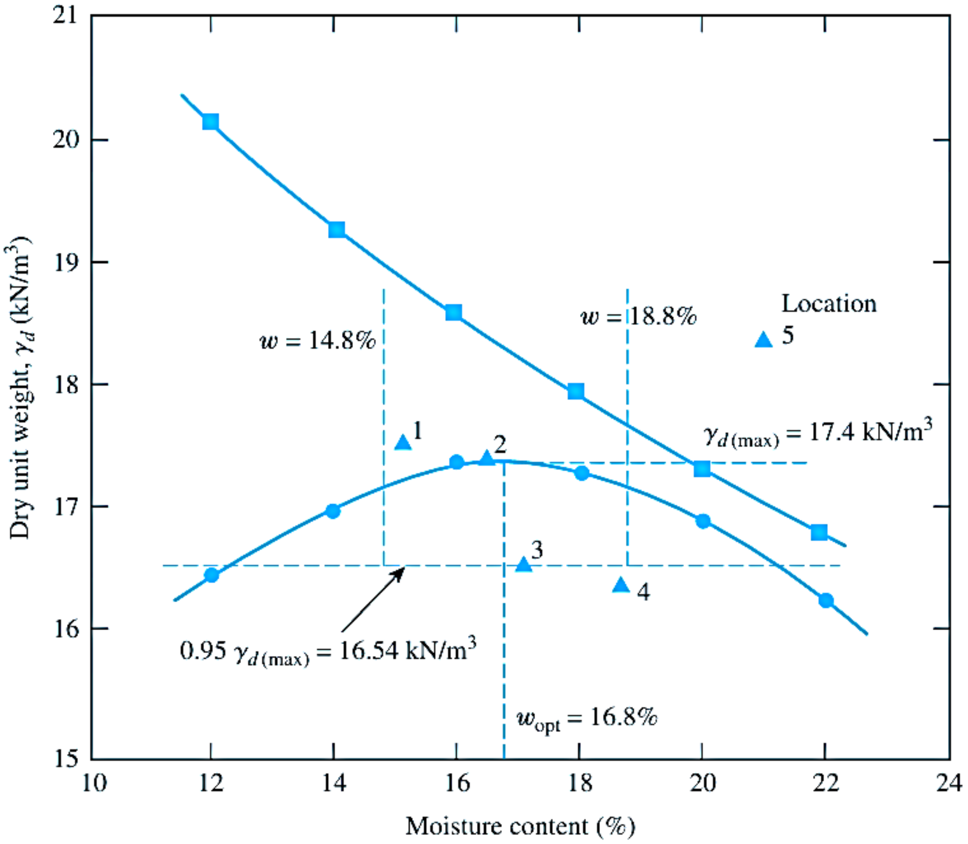
$$\gamma_{\text{zav}} = \frac{\gamma_w}{w + \dfrac{1}{G_s}}$$

Given: $G_s = 2.72$. Now the following table can be prepared.

w (%)	γ_{zav} (kN/m^3)
12	20.12
14	19.33
16	18.59
18	17.91
20	17.28
22	16.70

Figure 6.28 shows the plot of γ_d and γ_{zav}. From the plot, it can be seen that:

$$\gamma_{d(\max)} = 17.4 \text{ kN/m}^3$$
$$w_{\text{opt}} = 16.8\%$$



Based on the specifications, γ_d must be at least $0.95\gamma_{d(\max)} = (0.95)(17.4) = 16.54\ \text{kN/m}^3$ with a moisture content of 16.8% ± 2% = 14.8% to 18.8%. This zone is shown in Figure 6.28.

For the control tests, the following table can be prepared.

Location	**w (%)**	**ρ (kg/m^3)**	**γ_d^* (kN/m^3)**
1	15.2	2055	17.5
2	16.4	2060	17.36
3	17.1	1971	16.51
4	18.8	1980	16.35
5	21.1	2104	18.41

$$^{*}\ \gamma_d(\text{kN/m}^3) = \left[\frac{\rho(\text{kg/m}^3)}{1+\dfrac{w\ (\%)}{100}}\right]\left(\frac{9.81}{1000}\right)$$

The results of the control tests are also plotted in Figure 6.28. From the plot, it appears that the **tests at locations 1 and 2 meet the specifications**. The test at location 3 is a borderline case. Also note that there is some error for the test in location 5, since it falls above the zero-air-void line.

Example 4.5

The maximum and minimum possible void ratios of a sand determined in the laboratory are 0.89 and 0.42, respectively. Determine the moist unit weight of this sand when compacted to relative density of 70% and moisture content of 12%, assuming $G_s = 2.65$. Also, determine the maximum and minimum dry unit weights of this sand.

Solution

$e_{\max} = 0.89$, $e_{\min} = 0.42$

$$D_r(\%) = \frac{e_{\max} - e}{e_{\max} - e_{\min}} \times 100$$

$$70(\%) = \frac{0.89 - e}{0.89 - 0.42} \times 100$$

Therefore, at $D_r = 70\%$, $e = 0.56$

$$w = \frac{Se}{G_s}$$

$$S = \frac{wG_s}{e} = \frac{0.12 \times 2.65}{0.56} = 0.568$$

$$\gamma_m = \left(\frac{G_s + Se}{1 + e}\right)\gamma_w = \left(\frac{2.65 + 0.568 \times 0.56}{1 + 0.56}\right) \times 9.81 = \mathbf{18.66\ kN/m^3}$$

$$\gamma_d = \frac{G_{sw}}{1 + e}$$

At loosest state, with $e_{\max} = 0.89$,

$$\gamma_{d,\min} = \frac{2.65 \times 9.81}{1 + 0.89} = \mathbf{13.75\ kN/m^3}$$

At densest state, with $e_{\min} = 0.42$,

$$\gamma_{d,\max} = \frac{2.65 \times 9.81}{1 + 0.42} = \mathbf{18.31\ kN/m^3}$$