4

Soil Compaction and Stabilization

4–1 DEFINITION AND PURPOSE OF COMPACTION

The general meaning of the verb *compact* is "to press closely together." In soil mechanics, it means to press the soil particles tightly together by expelling air from the void space. Compaction is normally produced deliberately and proceeds rapidly during construction, often by heavy compaction rollers. This is in contrast to *consolidation* (Chapter 7), which also results in a reduction of voids but which is caused by extrusion of water (rather than air) from the void space. Also, consolidation is not rapid.

Compaction of soil increases its density and produces three important effects: (1) an increase in the soil's shear strength, (2) a decrease in future settlement of the soil, and (3) a decrease in its permeability. These three effects are beneficial for various types of earth construction, such as highways, airfields, and earthen dams; and, as a general rule, the greater the compaction, the greater these benefits will be. Compaction is actually a rather cheap and effective way to improve the properties of a given soil.

Compaction is quantified in terms of a soil's dry unit weight, γ_d, which can be computed in terms of wet unit weight, γ, and moisture content, w (expressed as a decimal), by

$$\gamma_d = \frac{\gamma}{1 + w} \tag{4–1}$$

In most cases, dry soils can be best compacted (and thus a greater density achieved) if for each soil a certain amount of water is added to it. In effect, water acts as a lubricant and allows soil particles to be packed together better. If, however, too much water is added, a lesser density results. Thus, for a given compactive effort, there is a particular moisture content at which dry unit weight is greatest and compaction best. This moisture content is called the *optimum moisture content*, and the associated dry unit weight is known as the *maximum dry unit weight*.

Usual practice in a construction project is to perform laboratory compaction tests (covered in Section 4–2) on representative soil samples from the construction site to determine the soil's optimum moisture content and maximum dry unit weight. This maximum dry unit weight is used by the designer in specifying design shear strength, resistance to future settlement, and permeability characteristics. The soil is then compacted by field compaction methods (covered in Section 4–4) until the laboratory maximum dry unit weight (or an acceptable percentage of it) has been achieved. In-place soil unit weight tests (covered in Section 4–7) are used to determine if and when the laboratory maximum dry unit weight (or an acceptable percentage thereof) has been reached. Section 4–8 covers field control of compaction.

4–2 LABORATORY COMPACTION TESTS (ASTM D 698 AND D 1557)

As related in the preceding section, laboratory compaction tests are performed to determine a soil's optimum moisture content and maximum dry unit weight. Compaction test equipment, shown in Figure 4–1, consists of a baseplate, collar, and mold, in which soil is placed, and a hammer that is raised and dropped freely onto the soil in the mold. The mold's size and the hammer's weight and drop distance are standardized, with several variations in size and weight available.

Table 4–1 summarizes specifications for compaction testing equipment, compaction effort, and sample fractionation for six test designations. The three on the left side of the table are designated ASTM D 698. Method A under these designations is known as the original *Standard Proctor* compaction test. The three test designations on the right side of the table are designated ASTM D 1557. Method A under these designations is known as the original *Modified Proctor* compaction test and was developed subsequent to the Standard Proctor test to obtain higher values of dry unit weights or densities. It was developed in response to the need for higher unit weights or densities of airfield pavement subgrades, embankments, earthen dams, and so forth, and for compacted soil that is to support large and heavy structures. It can be noted from Table 4–1 that the Standard Proctor test (i.e., ASTM D 698) utilizes a 5.5-lb (24.5-N) hammer, which is dropped 12 in. (305 mm), whereas the Modified Proctor test (i.e., ASTM D 1557) uses a 10-lb (44.5-N) hammer, which is dropped 18 in. (457 mm).

To carry out a laboratory compaction test, the soils engineer allows a soil sample from the field to dry until it becomes friable under a trowel. The soil sample may be dried in air or a drying oven. If an oven is used, its temperature should not exceed 60°C (140°F). After drying, a series of at least four specimens is prepared by adding increasing amounts of water to each sample so that the moisture contents will bracket the optimum moisture content. After a specified curing period, each prepared specimen is placed, in turn, in a compaction mold (with collar attached) and compacted in layers by dropping the hammer onto the specimen in the mold a certain distance and specified number of uniformly distributed blows per layer. This results in a specific energy exertion per unit volume of soil. Upon completion of each compaction, the attached collar is removed and the compacted soil trimmed until it is even with the top of the mold. The compacted soil specimen's wet unit

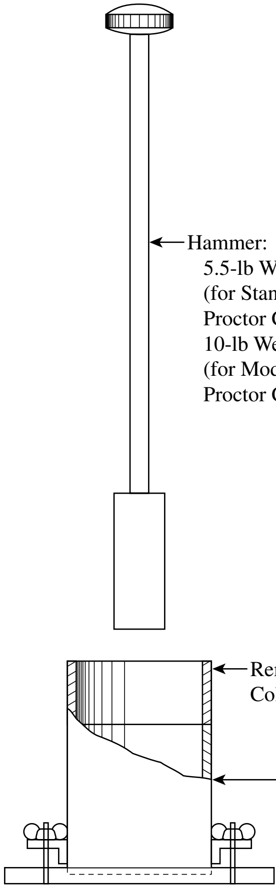


FIGURE 4–1 Compaction test equipment.
Source: B. K. Hough, *Basic Soils Engineering*, 2nd ed., The Ronald Press Company, New York, 1969. Copyright © 1969 by John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.

weight is then determined by dividing the weight of compacted soil in the mold by the soil specimen's volume, which is the volume of the mold. The compacted soil is subsequently removed from the mold and its moisture content determined. With the compacted soil's wet unit weight and moisture content known, its dry unit weight is computed using Eq. (4–1).

A plot made of the soil's moisture content versus dry unit weight for the data collected as described in the preceding paragraph will be of a form similar to the curve shown in Figure 4–2. The coordinates of the point at the curve's peak give the soil's maximum dry unit weight and optimum moisture content. Presumably, this gives the maximum expected dry unit weight—the dry unit weight to be used by the designer and to be striven for in the field compaction. To achieve this maximum dry unit weight, field compaction should be done at or near the optimum moisture content.

In Figure 4–2, the right side of the moisture content versus dry unit weight curve roughly parallels the dashed line labeled "Zero Air Voids." This line represents the dry

TABLE 4–1
Summary of Specifications for Compaction Testing Equipment, Compaction Effort, and Sample Fractionation[1]

	Test Designation					
	ASTM D 698			*ASTM D 1557*		
	Method A[2]	*Method B*	*Method C*	*Method A*[3]	*Method B*	*Method C*
Hammer weight (lb)	5.5	5.5	5.5	10	10	10
Drop (in.)	12	12	12	18	18	18
Size of mold						
Diameter (in.)	4	4	6	4	4	6
Height (in.)	4.584	4.584	4.584	4.584	4.584	4.584
Volume (ft^3)	$1/30$	$1/30$	$1/13.33$	$1/30$	$1/30$	$1/13.33$
Number of layers	3	3	3	5	5	5
Blows per layer	25	25	56	25	25	56
Fraction tested	−No. 4	$-3/8$ in.	$-3/4$ in.	−No. 4	$-3/8$ in.	$-3/4$ in.

[1] 1 lb = 4.448 N; 1 in. = 25.4 mm; 1 ft^3 = 0.02832 m^3.
[2] This is the original Standard Proctor test.
[3] This is the original Modified Proctor test.

unit weight when saturation is 100% (i.e., the soil's entire volume is water and solids). This line actually represents, in theory, the upper limit on unit weight at any moisture content. For this reason, the zero-air-voids line is often included on moisture content versus dry unit weight curves. It can be determined from the following equation:

$$\gamma_{ZAV} = \frac{G_s \gamma_w}{1 + wG_s} \tag{4–2}$$

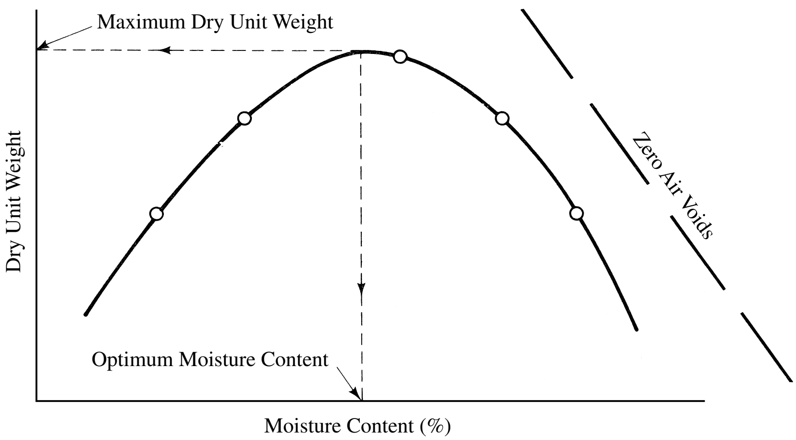


FIGURE 4–2 Compaction test results.

where γ_{ZAV} = dry unit weight at zero air voids
G_s = specific gravity of solids
γ_w = unit weight of water
w = moisture content (expressed as a decimal)

Example 4–1 illustrates computation of the unit weight of a specimen of a laboratory-compacted soil. Example 4–2 illustrates determination of the maximum dry unit weight and optimum moisture content, as the result of a laboratory compaction test.

EXAMPLE 4–1

Given

1. The combined weight of a mold and the specimen of compacted soil it contains is 8.63 lb.
2. The mold's volume is 1/30 ft^3.
3. The mold's weight is 4.35 lb.
4. The specimen's water content is 10%.

Required

1. Wet unit weight of the specimen.
2. Dry unit weight of the specimen.

Solution

1. From Eq. (2–11),

$$\gamma = \frac{W}{V} \tag{2–11}$$

$$\gamma = \frac{8.63\text{ lb} - 4.35\text{ lb}}{\frac{1}{30}\text{ ft}^3} = 128.4\text{ lb/ft}^3$$

2. From Eq. (4–1),

$$\gamma_d = \frac{\gamma}{1 + w} \tag{4–1}$$

$$\gamma_d = \frac{128.4\text{ lb/ft}^3}{1 + 0.10} = 116.7\text{ lb/ft}^3$$

EXAMPLE 4–2

Given

A set of laboratory compaction test data and results is tabulated as follows. The test was conducted in accordance with the ASTM D 698 Standard Proctor test.

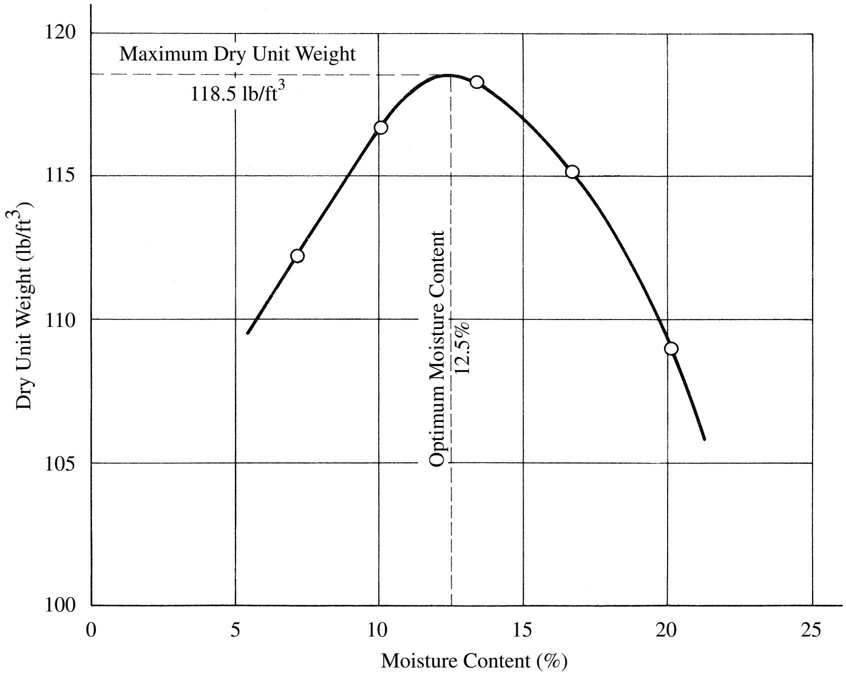


FIGURE 4–3 Proctor curve for Example 4–2.

Determination Number	1	2	3	4	5
Dry unit weight (lb/ft^3)	112.2	116.7	118.3	115.2	109.0
Moisture content (%)	7.1	10.0	13.4	16.7	20.1

Required

1. Plot a Proctor curve (i.e., dry unit weight versus moisture content).
2. Determine the soil's maximum dry unit weight and optimum moisture content.

Solution

1. See Figure 4–3.
2. From Figure 4–3,

$$\text{Maximum dry unit weight} = 118.5\ \text{lb/ft}^3$$

$$\text{Optimum moisture content} = 12.5\%$$

4–3 FACTORS AFFECTING COMPACTION OF SOIL

Several factors affect the compaction of soil. These might be categorized as moisture content, compaction effort, and type of soil. Section 4–2 covered the influence of moisture content on the degree of compaction achieved by a given soil sample. This section discusses the effect of compaction effort and soil type on the compaction of soil.

Compaction effort can be quantified in terms of the compaction energy per unit volume. A function of the number of blows per layer, number of layers, weight of the hammer, height of the drop of the hammer, and volume of the mold, compaction energy per unit volume is 12,400 ft-lb/ft^3 (600 kN · m/m^3) for the Standard Proctor test and 56,000 ft-lb/ft^3 (2700 kN · m/m^3) for the Modified Proctor test. Clearly, the greater the compaction energy per unit volume, the greater will be the compaction. In fact, if the compaction energy per unit volume is changed, the Proctor curve (moisture content versus unit weight, see Figure 4–2) will change. Figure 4–4 illustrates the influence of compaction energy on the compaction of a sandy clay; as the number of blows per layer increases (and therefore the compaction

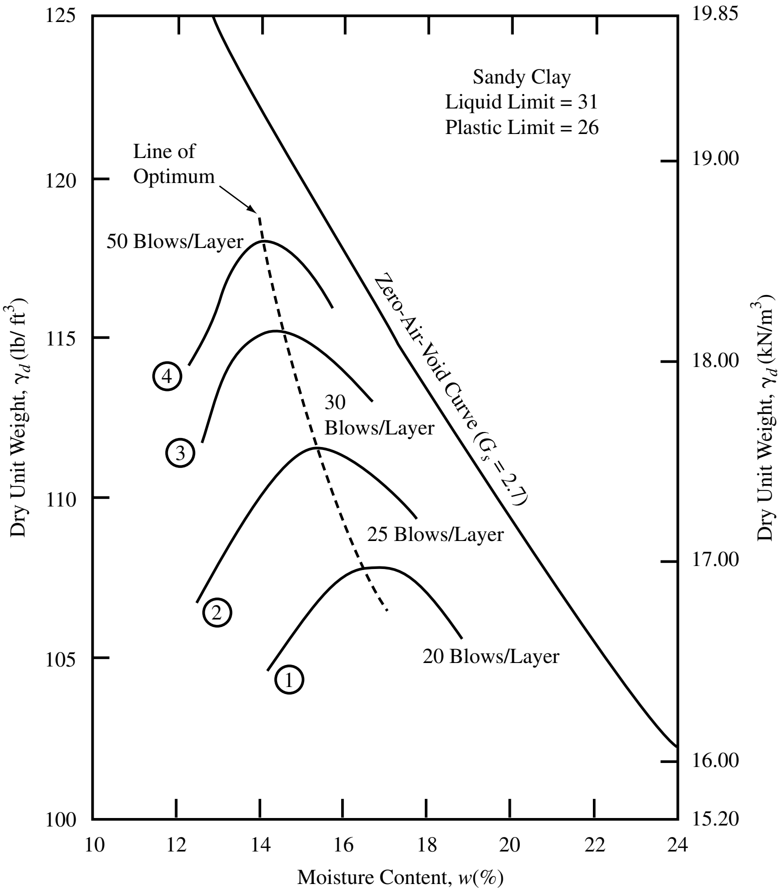


FIGURE 4–4 Effect of compaction energy on the compaction of a sandy clay.
Source: B. M. Das, *Principles of Geotechnical Engineering*, 3rd ed., PWS Publishing Company, Boston, 1994. Reprinted by permission.

energy per unit volume), the maximum dry unit weight increases and the optimum moisture content decreases.

Clearly, the type of soil will also affect the compaction of soil. The grain-size distribution of soil, and shape, and the specific gravity of solids, as well as the type and amount of clay minerals present, affect maximum dry unit weight and optimum moisture content for a given compactive effort and compaction method. Maximum dry unit weights may range from about 60 lb/ft^3 (9.42 kN/m^3) for organic soils to about 145 lb/ft^3 (22.78 kN/m^3) for well-graded granular material containing just enough fines to fill small voids. Optimum moisture contents may range from around 5% for granular material to about 35% for elastic silts and clays. Higher optimum moisture contents are generally associated with lower dry unit weights. Higher dry unit weights are associated with well-graded granular materials. Uniformly graded sand, clays of high plasticity, and organic silts and clays typically respond poorly to compaction.

Moisture versus density curves for various types of soils are given in Figure 4–5. These curves were determined by the Standard Proctor method (ASTM D 698). It should be noted that both the shapes and the positions of the curves change as the texture of the soils varies from coarse to fine.

Table 4–2 presents some general compaction characteristics of various soil types, along with their values as embankment, subgrade, and base material, for soils classified according to the Unified Soil Classification System (USCS). Table 4–3 gives

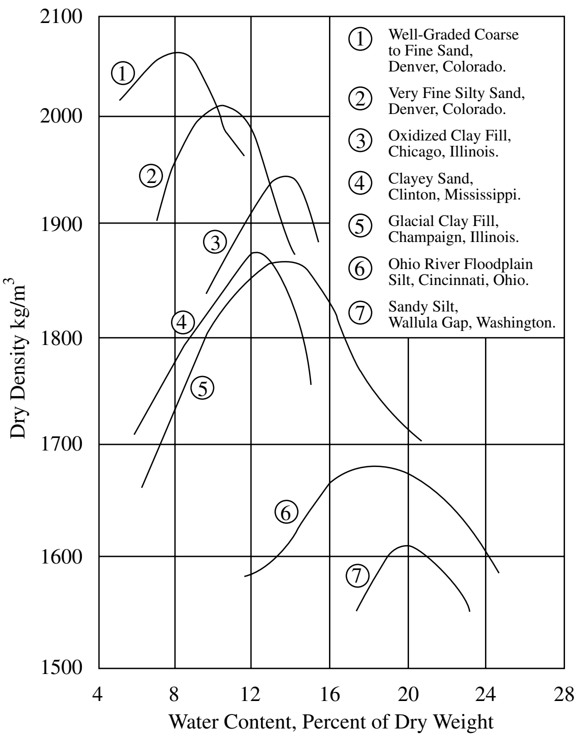


FIGURE 4–5 Moisture–density relations for various types of soils as determined by ASTM Method D 698.
Source: K. Terzaghi, R. B. Peck, and G. Mesri, *Soil Mechanics in Engineering Practice*, 3rd ed., John Wiley & Sons, Inc., New York, 1996. Copyright © 1996, by John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.

TABLE 4–2
Compaction Characteristics and Ratings of Unified Soil Classification System Classes for Soil Construction

Class	Compaction Characteristics	Maximum Dry Unit Weight Standard Proctor (lb/ft^3)[1]	Compressibility and Expansion	Value as Embankment Material	Value as Subgrade Material	Value as Base Course
GW	Good: Tractor, rubber-tired, steel wheel, or vibratory roller	125–135	Almost none	Very stable	Excellent	Good
GP	Good: Tractor, rubber-tired, steel wheel, or vibratory roller	115–125	Almost none	Reasonably stable	Excellent to good	Fair to poor
GM	Good: Rubber-tired or light sheepsfoot roller	120–135	Slight	Reasonably stable	Excellent to good	Fair to poor
GC	Good to fair: Rubber-tired or sheepsfoot roller	115–130	Slight	Reasonably stable	Good	Good to fair
SW	Good: Tractor, rubber-tired, or vibratory roller	110–130	Almost none	Very stable	Good	Fair to poor
SP	Good: Tractor, rubber-tired, or vibratory roller	100–120	Almost none	Reasonably stable when dense	Good to fair	Poor
SM	Good: Rubber-tired or sheepsfoot roller	110–125	Slight	Reasonably stable when dense	Good to fair	Poor
SC	Good to fair: Rubber-tired or sheepsfoot roller	105–125	Slight to medium	Reasonably stable	Good to fair	Fair to poor
ML	Good to poor: Rubber-tired or sheepsfoot roller	95–120	Slight to medium	Poor stability, high density required	Fair to poor	Not suitable
CL	Good to fair: Sheepsfoot or rubber-tired roller	95–120	Medium	Good stability	Fair to poor	Not suitable
OL	Fair to poor: Sheepsfoot or rubber-tired roller	80–100	Medium to high	Unstable, should not be used	Poor	Not suitable
MH	Fair to poor: Sheepsfoot or rubber-tired roller	70–95	High	Poor stability, should not be used	Poor	Not suitable
CH	Fair to poor: Sheepsfoot roller	80–105	Very high	Fair stability, may soften on expansion	Poor to very poor	Not suitable
OH	Fair to poor: Sheepsfoot roller	65–100	High	Unstable, should not be used	Very poor	Not suitable
PT	Not suitable	—	Very high	Should not be used	Not suitable	Not suitable

[1] $1\ lb/ft^3 = 0.1571\ kN/m^3$.

Source: "The Unified Soil Classification System," *Waterways Exp. Sta. Tech. Mem.* 3–357 (including Appendix A, 1953, and Appendix B, 1957), U.S. Army Corps of Engineers, Vicksburg, MS, 1953.

TABLE 4–3
General Guide to Selection of Soils on Basis of Anticipated Embankment Performance

AASHTO Classification	Visual Description	Maximum Dry Unit Weight Range (lb/ft³)[1]	Optimum Moisture Range (%)	Anticipated Embankment Performance
A-1-a	Granular material	115–142	7–15	Good to excellent
A-1-b				
A-2-4	Granular material	110–135	9–18	Fair to excellent
A-2-5	with soil			
A-2-6				
A-2-7				
A-3	Fine sand and sand	110–115	9–15	Fair to good
A-4	Sandy silts and silts	95–130	10–20	Poor to good
A-5	Elastic silts and clays	85–100	20–35	Unsatisfactory
A-6	Silt–clay	95–120	10–30	Poor to good
A-7-5	Elastic silty clay	85–100	20–35	Unsatisfactory
A-7-6	Clay	90–115	15–30	Poor to fair

[1] 1 lb/ft^3 = 0.1571 kN/m^3.

Source: R. D. Krebs and R. D. Walker, *Highway Materials,* McGraw-Hill Book Company, New York, 1971. Reprinted by permission of the author.

anticipated embankment performance for soils classified according to the American Association of State Highway and Transportation Officials (AASHTO) system.

4–4 FIELD COMPACTION

Normally, soil is compacted in layers. An approximately 8-in. (203-mm) loose horizontal layer of soil is often spread from trucks and then compacted to a thickness of about 6 in. (152 mm). The moisture content can be increased by sprinkling water over the soil if it is too dry and thoroughly mixing the water into the uncompacted soil by disk plowing. If the soil is too wet, its moisture content can be reduced by aeration (i.e., by spreading the soil in the sun and turning it with a disk plow to provide aeration and drying). Actual compaction is done by *tampers* and/or *rollers* and is normally accomplished with a maximum of 6 to 10 complete coverages by the compaction equipment. The surface of each compacted layer should be scarified by disk plowing or other means to provide bonding between layers. Various kinds of field compaction equipment (i.e., tampers and rollers) are discussed briefly in this section.

Tampers are devices that compact soil by delivering a succession of relatively light, vertical blows. Tampers are held in place and operated by hand. They may be powered either pneumatically or by gasoline-driven pistons. Tampers are limited in scope and compacting ability. Therefore, they are most useful in areas not readily

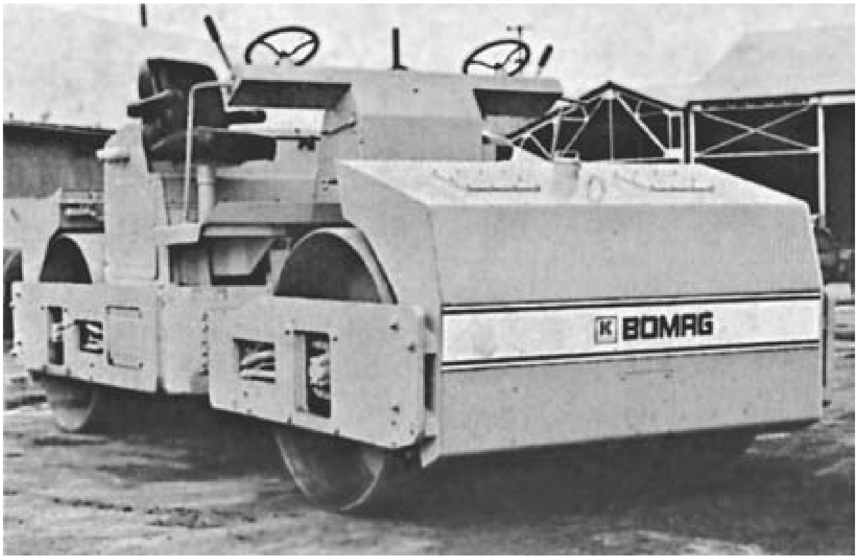


FIGURE 4–6 Smooth wheel roller.
Source: Reprinted by permission of the Koehring Compaction and General Equipment Group.

accessible to rollers, in which case soil may be placed in loose horizontal layers not exceeding 6 in. (152 mm) and then compacted with tampers.

Rollers come in a variety of forms, such as the smooth wheel roller, sheepsfoot roller, pneumatic roller, and vibratory roller. Some of these are self-propelled, whereas others are towed by tractors. Some are more suited to certain types of soil. Rollers can easily cover large areas relatively quickly and with great compacting pressures. Following are brief descriptions of the four types of rollers just mentioned.

A *smooth wheel roller* (see Figure 4–6) employs two or three smooth metal rollers. It is useful in compacting base courses and paving mixtures and is also used to provide a smooth finished grade. Generally, smooth wheel rollers are self-propelled and equipped with a reversing gear so that they can be driven back and forth without turning. A smooth wheel roller provides compactive effort primarily through its static weight.

A *sheepsfoot roller* (see Figure 4–7) consists of a drum with metal projecting "feet" attached. Because only the projecting feet come in contact with the soil, the area of contact between roller and soil is smaller (than for a smooth wheel roller), and therefore a greater compacting pressure results (generally more than 200 lb/in.^{2}). A sheepsfoot roller provides kneading action and is effective for compacting fine-grained soils (such as clays and silts).

A *pneumatic roller* (see Figure 4–8) consists of a number of rubber tires, highly inflated. They vary from small rollers to very large and heavy ones. Most large pneumatic rollers are towed, whereas some smaller ones are self-propelled. Some have boxes mounted above their wheels, to which sand or other material can be added

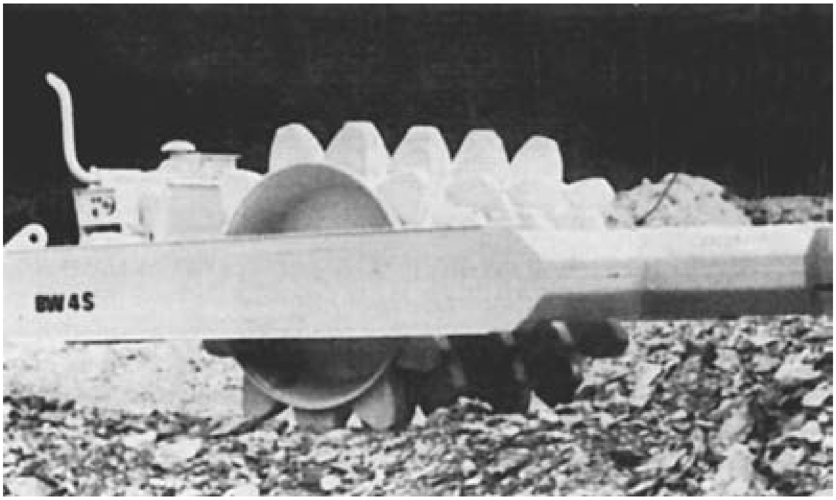


FIGURE 4–7 Sheepsfoot roller.
Source: Reprinted by permission of the Koehring Compaction and General Equipment Group.

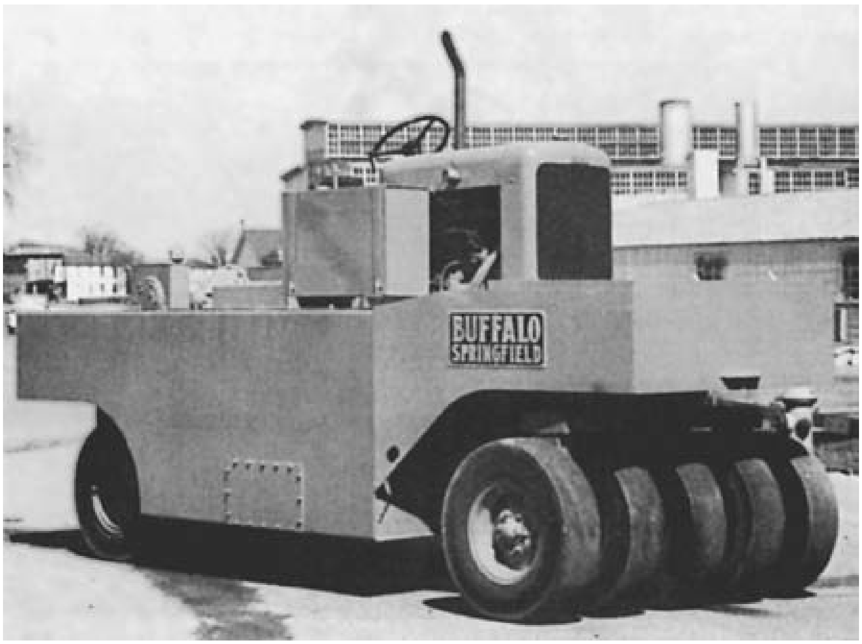


FIGURE 4–8 Pneumatic roller.
Source: Reprinted by permission of the Koehring Compaction and General Equipment Group.

FIGURE 4–9 Vibratory roller.
Source: Courtesy of Hyster Company, Construction Equipment Division.

for increased compacting pressure. Clayey soils and silty soils may be compacted effectively by pneumatic rollers. These rollers are also effective in compacting granular material containing a small amount of fines.

A *vibratory roller* (see Figure 4–9) contains some kind of vibrating unit that imparts an up-and-down vibration to the roller as it is pulled over the soil. Vibrating units can supply frequencies of vibration at 1500 to 2000 cycles per minute, depending on compacting requirements. They are effective in compacting granular materials—particularly clean sands and gravels.

Two means (or possibly a combination of the two) may be used to specify a particular compaction requirement. One is to specify the procedure to be followed by the contractor, such as the type of compactor (i.e., roller) to be used and the number of passes to be made. The other is to simply specify the compacted soil's required final dry unit weight. The first method has the advantage that little testing is required, but it has the disadvantage that the specified procedure may not produce the required result. The second method requires much field testing, but it ensures that the required dry unit weight is achieved. In effect, the second method specifies the required final dry unit weight but leaves it up to the contractor as to how that unit weight is achieved. This (i.e., the second) method is probably more commonly employed.

4–5 VIBROFLOTATION

Vibroflotation is one of several vibrocompaction methods that are useful for compacting thick [up to 75 ft (23 m)], *in situ* layers of loose cohesionless soils. The vibroflotation method utilizes simultaneous vibration and saturation.

Figure 4–10 illustrates the equipment used for vibroflotation. A Vibroflot® prode is a cylindrical vibrator 6 to 7 ft (1.8 to 2.1 m) long and 16 in. (400 mm) in diameter weighing around 2 tons (18 kN). The Vibroflot® is suspended from a crane (see Figure 4–10) and is then jetted to the depth where compaction is to begin by means of pressurized water jetting downward from the tip of the Viobroflot®. Lateral vibration of the Vibroflot® then causes the soil to compact horizontally. Next, the Vibroflot® is slowly raised while continuing to vibrate, thereby causing compaction horizontally from the lowest depth to the surface. During the process, additional sand is continually added from the ground surface into the area around the Vibroflot® to fill in the void space created as the sand is compacted horizontally. Figure 4–11 illustrate the process just described.

Because the compaction effect of the vibroflotation process extends radially outward 4 to 5 ft (1.2 to 1.5 m) from the Vibroflot®, in order to cover an entire area the process is normally repeated at a spacing of 10 ft (3 m) or so.

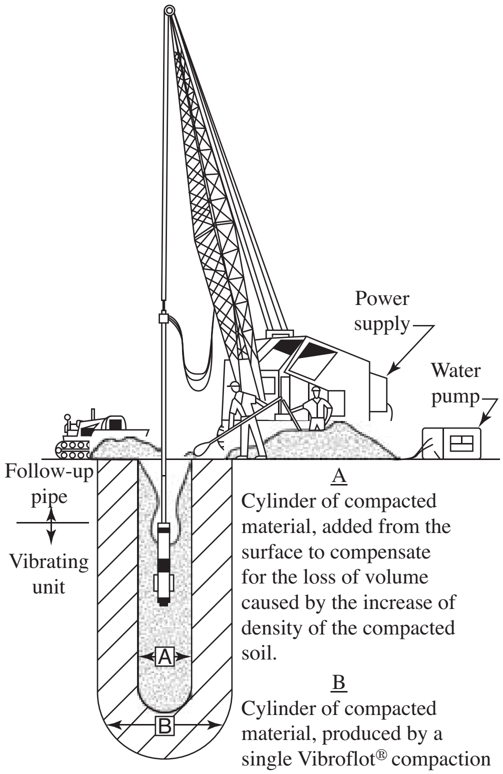


FIGURE 4–10 Vibroflotation Equipment
Source: R. E. Brown, "Vibroflotation Compaction of Cohesionless Soils," *J. Geotech Eng. Div. ASCE*, 103(GT12), 1437–1451 (1977). Reprinted by permission.

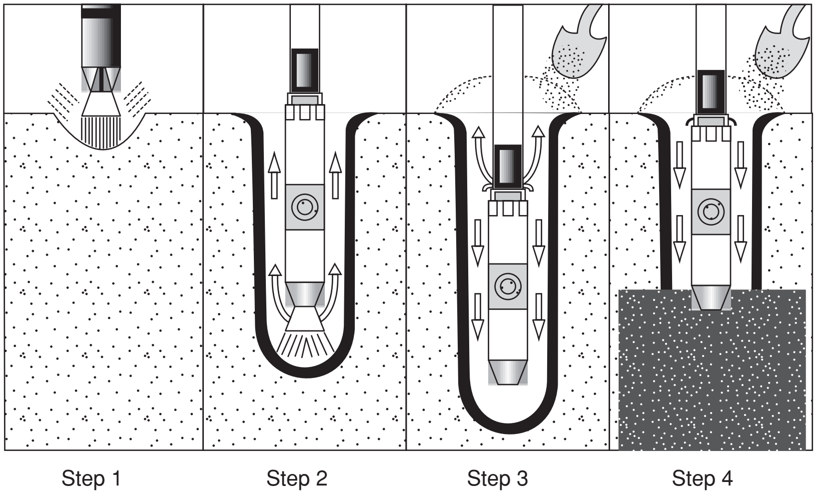


FIGURE 4–11 Vibroflotation compaction process.
Source: R. E. Brown, "Vibroflotation Compaction of Cohesionless Soils," *J. Geotech. Eng. Div. ASCE*, 103 (GT12), 1437–1451 (1977). Reprinted by permission.

Step 1. The Vibroflot® vibrates and water jets from the Vibroflot®.

Step 2. The Vibroflot® is lowered under its own weight to the depth where compaction is to begin. When this depth is reached, the flow is reduced and diverted from the lower jets to upper interior jets. Wash water from the upper interior jets flows from outlets immediately above the vibrating unit and upward along the outside of the follow-up pipe.

Step 3. The upward flow maintains an open channel along the sides of the Vibroflot®, permitting backfill material shoved from the surface to reach the tip and preventing the Vibroflot® from sticking.

Step 4. As the Vibroflot® is raised, workers constantly shove backfill material into the annular space to fill the void left as the Vibroflot® is raised. Backfill is periodically supplied to the workers by heaping it around the Vibroflot® with a front-end loader.

4–6 DYNAMIC COMPACTION

In cases where existing surface or near-surface soil is poor with regard to foundation support, a field procedure known as *dynamic compaction* may be employed to improve the soil's properties. This method is carried out essentially by repeatedly dropping a very heavy weight onto the soil from a relatively great height. The dropped weight may be an ordinary steel wrecking ball, or it may be a mass especially designed for the dynamic-compaction procedure. Typical weights range from 2 to 20 tons or higher, whereas dropping distances range from 20 to 100 ft.

Generally, the heavier the weight and the greater the dropping distance, the greater the compactive effort will be. For a given situation, however, the weight and dropping distance used may depend on the lifting equipment (such as a crane) available.

Dynamic compaction may be used for both cohesive and cohesionless soils. It can also be utilized to compact buried refuse fill areas. In cohesive soils, the reduction of settlements due to dynamic compaction is more distinct than the increase in bearing capacity. The tamping produces a true presettlement of the soil, well beyond the settlement that would have occurred as a result of construction weight only, without any preliminary consolidation (Menard and Broise, 1975). For cohesionless soils, dynamic compaction densifies loose soil.

Dynamic compaction should not be done by dropping weight randomly. Instead, a closely spaced grid pattern is selected for a given compaction site (see Figure 4–12). Preliminary work is done to determine grid spacing and weight, height, and number of drops. Typically, 5 to 10 drops are made on each grid point. Figure 4–13 shows a photograph of a dynamic-compaction site.

The approximate depth of influence of dynamic compaction (D) may be determined in terms of weight (W) and distance dropped (h). For cohesionless soils (Leonards et al., 1980),

$$D = 0.5\sqrt{Wh} \tag{4–3}$$

For cohesive soils (Menard and Broise, 1975),

$$D = \sqrt{Wh} \tag{4–4}$$

These equations give the depth of zone (D) receiving improvement in meters if W is in metric tons (1000 kg) and h in meters. The extent of improvement is greatest near

FIGURE 4–12 Drop pattern. *Source:* G. A. Leonards, W. A. Cutter, and R. D. Holtz, "Dynamic Compaction of Granular Soils," *J. Geotech. Eng. Div. ASCE*, 106 (GT1) 35–44 (1980).

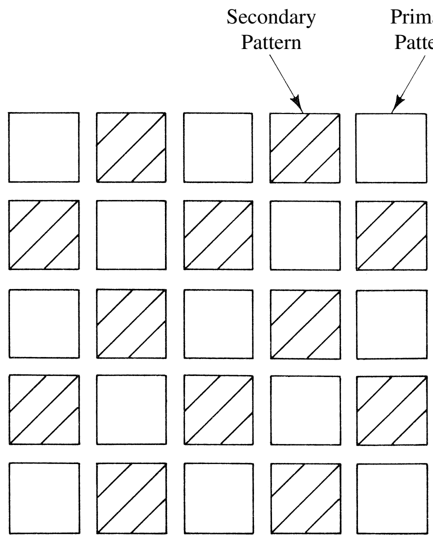


FIGURE 4–13 Dynamic-compaction site.
Source: Courtesy of Hayward Baker, Inc.

the surface and diminishes with depth. Improvement increases with the number of drops made up to some limit—typically from 5 to 10 drops—beyond which additional drops afford little or no additional improvement.

With saturated, fine-grained soils, satisfactory results may be obtained by performing a series of drops at intervals of one or several days, the purpose being to provide time for dissipation of pore water pressures created by the previous compaction.

It should be noted that a soil surface may become cratered as a result of dynamic compaction. This is particularly true of "loose" soils. When this happens, the craters must be backfilled and compacted by other means (such as those described in Section 4–4).

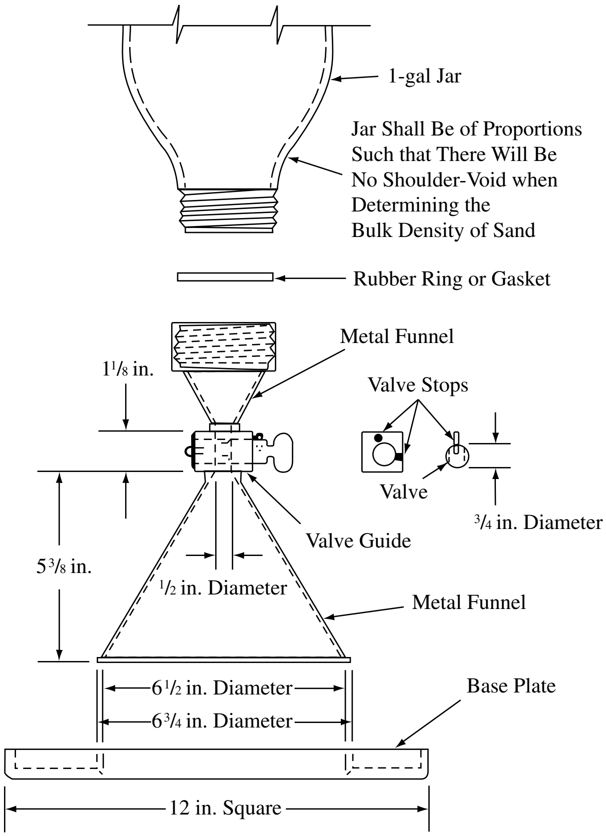
4–7 IN-PLACE SOIL UNIT WEIGHT TEST

As related previously, after a fill layer of soil has been compacted by the contractor, it is important that the compacted soil's in-place dry unit weight be determined in order to ascertain whether the maximum laboratory dry unit weight has been attained. If the maximum dry unit weight (or an acceptable percentage thereof) has not been attained, additional compaction effort is required.

There are several methods for determining in-place unit weight. As a general rule, the weight and volume of an in-place soil sample are determined, from which unit weight can be computed. Measurement of the sample's weight is straightforward, but there are several methods for determining its volume. For cohesive soils, a thin-walled cylinder may be driven into the soil to remove a sample. The sample's volume is known from the cylinder's volume. This method is known as *density of soil in-place by the drive cylinder method* and is designated as ASTM D 2937 or AASHTO T 204. The drive cylinder method is not applicable for very hard soil that cannot be easily penetrated. Neither is it applicable for low plasticity or cohesionless soils, which are not readily retained in the cylinder.

For low plasticity or cohesionless soils, a hole can be dug in the ground or compacted fill and the removed soil sample weighed and tested for water content. The volume of soil removed, which is the same as the volume of the hole, can be determined by filling the hole with loose, dry sand of uniform unit weight (such as Ottawa sand). By measuring the weight of sand required to fill the hole and knowing the sand's unit weight, one can find the volume of the hole. With the soil sample's weight, volume, and water content known, its dry unit weight can be easily computed. This method is carried out using a sand-cone apparatus, which consists of a large jar with an attached cone-shaped funnel (see Figures 4–14 and 4–15). With the jar inverted, sand is allowed to pass through the funnel into the hole until the hole is just filled with sand. The weight of sand required to fill the hole can then be determined, from which, with the sand's unit weight known, the soil sample's volume and subsequently its dry unit weight can be computed. Typically, Ottawa sand, a loose, dry sand of uniform unit weight approximating 100 lb/ft^3 (16 kN/m^3), is used in this test. This procedure is called *unit weight of soil in-place by the sand-cone method* and is designated as ASTM D 1556 and AASHTO T 191.

FIGURE 4–14 Density apparatus used in the sand-cone method.
Source: Annual Book of ASTM Standards, ASTM, Philadelphia, 1995. Copyright American Society for Testing and Materials. Reprinted with permission.



Metric Equivalents

in.	1/2	3/4	1 1/8	5 3/8	6 1/2	6 3/4	12
mm	12.7	19.1	28.6	136.5	165.1	171.5	304.8

Another method for determining *in situ* dry unit weight is known as *unit weight of soil in-place by the rubber-balloon method* (designated as ASTM D 2167 and AASHTO T 205). In this method, a hole is dug and the removed soil sample weighed and tested for water content as in the previous method. The volume of soil removed is determined using a balloon apparatus (Figures 4–16 and 4–17), which consists of a vertical cylinder with transparent sides and graduation marks on its side. A rubber membrane or balloon is stretched over the open bottom of the cylinder. In use, the apparatus is placed over the empty hole, and air is pumped into the top of the cylinder above the water level, forcing the balloon and water down into the hole, completely filling it. The volume of water required to fill the hole, which is easily determined by reading the water level in the cylinder before and after forcing the water into the

FIGURE 4–15 Density apparatus used in the sand-cone method.
Source: Courtesy of ELE International, Inc.

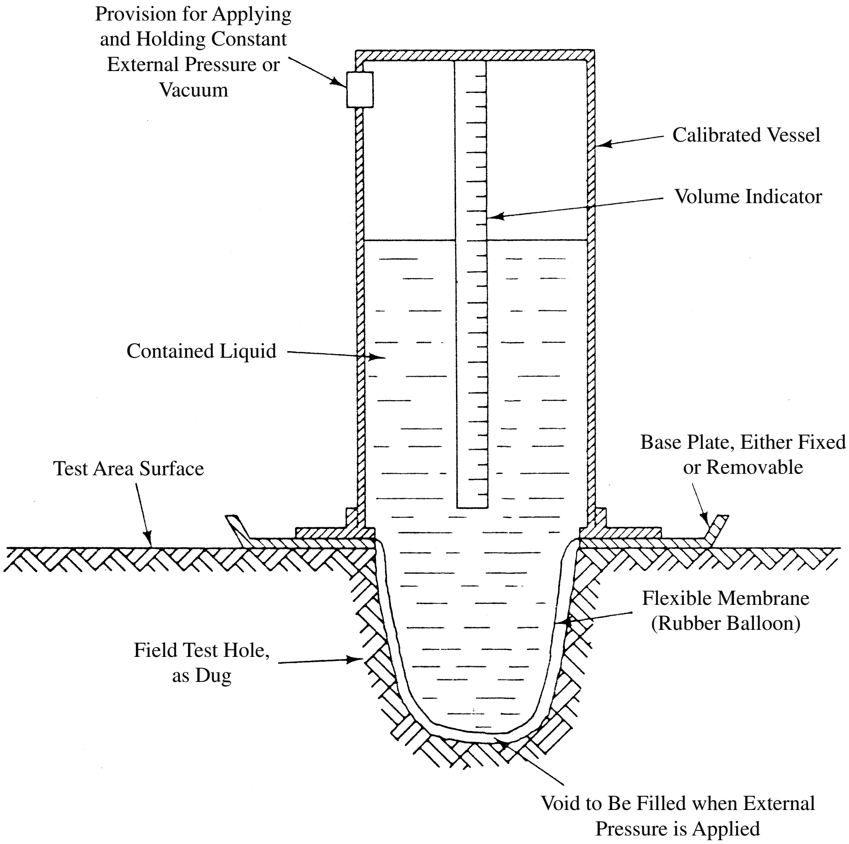
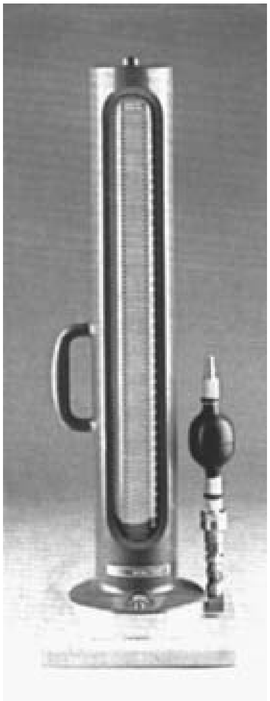


FIGURE 4–16 Schematic drawing of calibrated vessel, indicating the principle of the rubber-balloon method (not to scale).
Source: Annual Book of ASTM Standards, ASTM, Philadelphia, 1995. Copyright American Society for Testing and Materials. Reprinted with permission.

FIGURE 4–17 Rubber-balloon apparatus for determining unit weight of soil in-place.
Source: Courtesy of ELE International, Inc.



hole, is the same as the volume of the hole and of the soil removed from the hole. As in the previous method, with the soil sample's weight, volume, and water content known, its dry unit weight can be determined.

Although widely used, the sand-cone and rubber-balloon methods are *destructive* testing methods, in that a sizable hole must be dug in the ground or compacted fill. They are also fairly time consuming, a significant factor when numerous tests must be performed as quickly as possible at a construction site.

A *nondestructive* method for determining *in situ* dry unit weight utilizes a nuclear apparatus (see Figure 4–18). In use, this apparatus is placed on the ground or compacted fill and emits gamma rays through the soil. Some of the gamma rays will be absorbed; others will reach a detector. Soil unit weight is inversely proportional to the amount of radiation that reaches the detector. Through proper calibration, nuclear count rates received at the detector can be translated into values of soil (wet) unit weight. Calibration curves are normally provided by the manufacturer. The nuclear apparatus also determines moisture content by emitting alpha particles that bombard a beryllium target, causing the beryllium to emit fast neutrons. Fast neutrons that strike hydrogen atoms in water molecules lose velocity; the resulting low-velocity neutrons are thermal neutrons. Thermal neutron counts are made, from which—with proper correlation—soil moisture results (as weight of water per unit of volume) can be determined. (*Note:* Moisture determinations by this method can be in error in soils containing iron, boron, or cadmium.) The dry unit weight

FIGURE 4–18 Nuclear moisture–density apparatus. *Source:* Courtesy of Troxler Electronic Laboratories, Inc., North Carolina.

can then be found by subtracting this moisture result from the wet unit weight previously determined. Figure 4–19 illustrates several modes for using a nuclear apparatus. This method for determining *in situ* dry unit weight is known as *unit weight of soil and soil-aggregate in-place by nuclear methods* and is designated as ASTM D 2922.

The nuclear method is considerably faster to perform than the sand-cone and rubber-balloon methods. For this reason, it is now commonly used for determining *in situ* unit weight, replacing the sand-cone and rubber-balloon methods. It has the disadvantage, however, of potential hazards to individuals handling radioactive materials. The nuclear apparatus is also considerably more costly than the apparatuses used in the other two methods.

In addition to determining the in-place wet unit weight of soil (using the sand-cone or balloon method), it is necessary to determine the soil's moisture content in order to compute the compacted soil's dry unit weight. Although the moisture content can be determined by oven drying, this method is often too time consuming because test results are commonly needed quickly. Drying of a soil sample can be accomplished by putting it in a skillet and placing the skillet over the open flame of a camp stove. The Speedy Moisture Tester (ASTM D 4944) (see Figure 4–20) can also be used to determine moisture content quickly with fairly good results. Because of the rather small amount of sample utilized in this test, the Speedy Moisture Tester may not be appropriate for use in coarser materials.

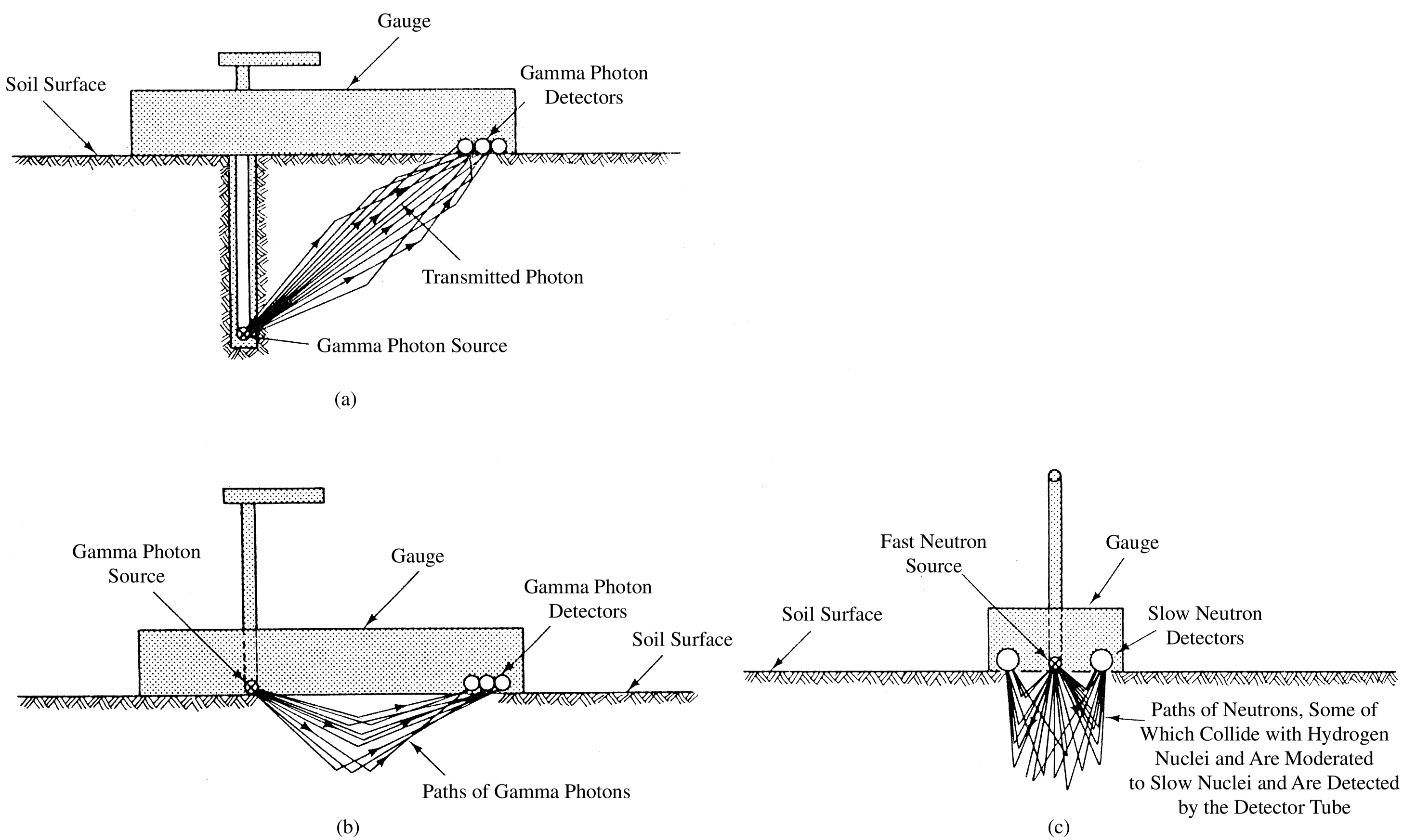


FIGURE 4–19 Different modes for measuring soil density and moisture content by nuclear methods: (a) direct transmission density measurement; (b) backscatter density measurement; (c) backscatter moisture measurement.
Source: Courtesy of Troxler Electronic Laboratories, Inc., North Carolina.

FIGURE 4–20 Speedy Moisture Tester.
Source: Courtesy of Soiltest, Inc.

Step-by-step details of all the aforementioned test procedures are given in *Soil Properties: Testing, Measurement, and Evaluation*, 5th edition, by Liu and Evett (2003).

EXAMPLE 4–3

Given

During construction of a soil embankment, a sand-cone in-place unit weight test was performed in the field. The following data were obtained:

1. Mass of sand used to fill test hole and funnel of sand-cone device = 867 g.
2. Mass of sand to fill funnel = 319 g.
3. Unit weight of sand = 98.0 lb/ft^3.
4. Mass of wet soil from the test hole = 747 g.
5. Moisture content of soil from test hole as determined by Speedy Moisture Tester = 13.7%.

Required

Dry unit weight of the compacted soil.

Solution

Weight of sand used in test hole

$$= \text{Mass of sand to fill test hole and funnel} - \text{Mass of sand to fill funnel}$$

$$= 867\ \text{g} - 319\ \text{g} = 548\ \text{g}$$

$$\text{Volume of test hole} = \frac{548\text{ g}/453.6\text{ g/lb}}{98.0\text{ lb/ft}^3} = 0.0123\text{ ft}^3$$

$$\text{Wet unit weight of soil in-place} = \frac{747\text{ g}/453.6\text{ g/lb}}{0.0123\text{ ft}^3} = 133.9\text{ lb/ft}^3$$

From Eq. (4–1),

$$\gamma_d = \frac{\gamma}{1 + w} \qquad \textbf{(4–1)}$$

$$\gamma_d = \frac{133.9\text{ lb/ft}^3}{1 + 0.137} = 117.8\text{ lb/ft}^3$$

4–8 FIELD CONTROL OF COMPACTION

As related previously, after a fill layer of soil has been compacted, an in-place soil unit weight test is usually performed to determine whether the maximum laboratory dry unit weight (or an acceptable percentage thereof) has been attained. It is common to specify a required percent of compaction, which is "the required in-place dry unit weight" divided by "the maximum laboratory dry unit weight" expressed as a percentage, in a contract document. Thus, if the maximum dry unit weight obtained from ASTM or AASHTO compaction in the laboratory is 100 lb/ft^3 and the required percent of compaction is 95% according to a contract, an in-place dry unit weight of 95 lb/ft^3 (or higher) would be acceptable. In theory, this is simple enough to do, but there are some practical considerations that must be taken into account. For example, the type of soil or compaction characteristics of soil taken from borrow pits may vary from one location to another. Also, the degree of compaction may not be uniform throughout.

To deal with the problem of nonuniformity of soil from borrow pits, it is necessary to conduct ASTM or AASHTO compaction tests in the laboratory to establish the maximum laboratory dry unit weight along with the optimum moisture content for each type of soil encountered in a project. Then, as soil is transported from the borrow pit and subsequently placed and compacted in the fill area, it is imperative that the results of each in-place soil unit weight test be checked against the maximum laboratory dry unit weight of the respective type of soil.

To deal with the problem of the variable degree of field compaction of a soil, it is common practice to specify a minimum number of field unit weight tests. For example, for a dam embankment, it might be specified that one test be made for every 2400 yd^3 (loose measure) of fill placed.

To ensure that the required field unit weight is achieved by the field compaction, a specifications contract between the owner and the contractor is prepared. The contract will normally specify the required percent of compaction and minimum number of field unit weight tests required. For compaction adjacent to a structure, where settlement is a serious matter, a higher percent of compaction and a higher minimum number of tests may be specified than for compaction, for example, of the foundation of a parking lot. The specifications contract may also include additional items, such as the maximum thickness of loose lifts (layers) prior to compaction, methods to obtain maximum dry unit weight (e.g., ASTM D 698 or AASHTO T 99), methods to determine in-place unit weight (e.g., ASTM D 1556 or AASHTO T 191), and so on.

As the owner's representative, an engineer is responsible for ensuring that contract provisions are carried out precisely and completely. He or she is responsible for the testing and must see that the required compacted dry unit weight is achieved. If a particular test indicates that the required compacted dry unit weight has not been achieved, he or she must require additional compaction effort, possibly including an adjustment in moisture content. In addition, he or she must be knowledgeable and capable of dealing with field situations that arise that may go beyond the "textbook procedure."

EXAMPLE 4–4

Given

1. Soil from a borrow pit to be used for construction of an embankment gave the following laboratory results when subjected to the ASTM D 698 Standard Proctor test (from Example 4–2):

$$\text{Maximum dry unit weight} = 118.5\ \text{lb/ft}^3$$

$$\text{Optimum moisture content} = 12.5\%$$

2. The contractor, during construction of the soil embankment, achieved the following (from Example 4–3):

$$\text{Dry unit weight reached by field compaction} = 117.8\ \text{lb/ft}^3$$

$$\text{Actual water content} = 13.7\%$$

Required

Percent of compaction achieved by the contractor.

Solution

Percent of Standard Proctor compaction achieved

$$= \frac{\text{In-place dry unit weight}}{\text{Maximum laboratory dry unit weight}} \times 100 = \frac{117.8\ \text{lb/ft}^3}{118.5\ \text{lb/ft}^3} \times 100 = 99.4\%$$

EXAMPLE 4–5

Given

1. A borrow pit's soil is being used as earth fill at a construction project.
2. The *in situ* dry unit weight of the borrow pit soil was determined to be $17.18\ \text{kN/m}^3$.

3. The soil at the construction site is to be compacted to a dry unit weight of $18.90\ \text{kN/m}^3$.
4. The construction project requires $15{,}000\ \text{m}^3$ of compacted soil fill.

Required

Volume of soil required to be excavated from the borrow pit to provide the necessary volume of compacted fill.

Solution

Total dry weight required to furnish the compacted fill

= Total dry weight of soil required to be excavated from the borrow pit

$$= (18.90\ \text{kN/m}^3)(15{,}000\ \text{m}^3) = 283{,}500\ \text{kN}$$

Volume of soil required to be obtained from the borrow pit

$$= \frac{283{,}500\ \text{kN}}{17.18\ \text{kN/m}^3} = 16{,}500\ \text{m}^3$$

EXAMPLE 4–6

Given

1. The *in situ* void ratio (e) of a borrow pit's soil is 0.72.
2. The borrow pit soil is to be excavated and transported to fill a construction site where it will be compacted to a void ratio of 0.42.
3. The construction project requires $10{,}000\ \text{m}^3$ of compacted soil fill.

Required

Volume of soil that must be excavated from the borrow pit to provide the required volume of fill.

Solution

Let subscript f denote soil in the fill. From Eq. (2–7),

$$e = \frac{V_v}{V_s} \tag{2–7}$$

$$0.42 = \frac{(V_v)_f}{(V_s)_f}$$

$$(0.42)(V_s)_f = (V_v)_f \tag{A}$$

$$(V_s)_f + (V_v)_f = 10{,}000\ \text{m}^3 \tag{B}$$

Substitute Eq. (A) into Eq. (B).

$$(V_s)_f + 0.42(V_s)_f = 10{,}000\ \text{m}^3$$

$$(V_s)_f = 7042\ \text{m}^3$$

Let subscript b denote soil in the borrow pit.

$$(V_s)_b = (V_s)_f = 7042 \text{ m}^3 \tag{C}$$

From Eq. (2–7),

$$0.72 = \frac{(V_v)_b}{(V_s)_b}$$

$$(0.72)(V_s)_b = (V_v)_b \tag{D}$$

From Eq. (C), $(V_s)_b = 7042 \text{ m}^3$; substitute into Eq. (D).

$$(0.72)(7042 \text{ m}^3) = (V_v)_b$$

$$(V_v)_b = 5070 \text{ m}^3$$

Total volume of soil from borrow pit $(V_b) = (V_v)_b + (V_s)_b = 5070 \text{ m}^3 + 7042 \text{ m}^3 = 12{,}112 \text{ m}^3$

4–9 SOIL STABILIZATION

Sections 4–4, 4–5, and 4–6 described physical means (field compaction, vibroflotation, and dynamic compaction) whereby a soil can have its physical properties improved to increase bearing capacity, increase soil shear strength, decrease settlement, and reduce soil permeability. *Soil stabilization* can also be used to improve the properties of a natural soil by preloading the soil or by adding other special soil (mechanical stabilization), chemical material (chemical stabilization), or some kind of fabric materials (geosynthetics) to the soil. These means of achieving soil stabilization are discussed in the remainder of this section.

Preloading

Preloading refers to adding an artificial load to a potential construction site prior to the time the structure is built (and loaded). The soil is improved by causing soil consolidation to occur prior to construction and loading, thereby decreasing subsequent settling of the structure.

Preloading is carried out simply by adding fill or other surcharge to the natural soil *in situ* and allowing the added weight to consolidate the soil naturally over a period of time. In general, the greater the added surcharge and the longer the time it is in place prior to construction, the better the consolidation will be and the better the bearing capacity of the soil will be. In most cases, the amount of material to be used as surcharge and the time available may be limited, however, by practical and/or economic considerations. Transporting soil is expensive, and in some cases suitable surcharge material may not be readily available. The time needed to effect soil improvement may be reduced by including vertical sand and/or gravel drains in the soil during the surcharge period. The amount of time needed varies from several months to several years.

Preloading works best in soft silty and clayey soils. Granular soils, where consolidation is an insignificant phenomenon, are not generally amenable to improvement by preloading.

Mechanical Stabilization

Mechanical stabilization is a relatively simple means of soil stabilization that is carried out by adding soil material to the naturally occurring soil. The added soil material is usually mechanically mixed with the natural soil and worked together, after which the mixture is compacted. Normally, a blending of coarse aggregate and fine-grained soil is achieved in order to get a soil mixture that possesses some internal friction and cohesion and will thereby be workable and subsequently stable when mixing and compaction have been completed.

Chemical Stabilization

Chemical stabilization is achieved by adding a cementing material or some kind of chemical to the soil. The chemical material may be mechanically mixed with the natural soil and the resulting mixture compacted, or the chemical material may be simply applied to the natural soil and allowed to penetrate the soil through the void space. Another process is to inject the stabilizing chemical into or through the soil under pressure; this is known as *grouting*. The procedure of grouting (i.e., injection stabilization) is generally performed where it is necessary to improve soil that cannot be disturbed. Grouting can be effective at relatively large depths of soil formation. Grouting and injection stabilization are generally performed by specialty contractors who have proper and adequate equipment and have developed experience over the years with one or more stabilization procedures.

Many different chemicals have been used for chemical stabilization—sodium chloride, calcium chloride, cement, and lime, to name a few of the more common ones. Sodium chloride and calcium chloride may be added to a soil when it is desired to hold soil water. Sodium chloride spread on the surface of dirt roads can help with dust control on rural highways. Various kinds of cement (Portland cement, asphalt cement) may be added to soil to bond the soil particles together. When Portland cement is added to soil in the presence of water, concrete is formed. In the construction of the soil-cement mixture, the soil needs to be at or near the optimum moisture content for maximum compaction as determined by a compaction test (i.e., ASTM D 698). In soil stabilization using Portland cement, the amount of cement added is quite small (on the order of 7% to 14% by weight for sandy to clayey soils, respectively), and the result is a stabilized soil that is stronger than the natural soil but not nearly as strong as concrete. Cement-stabilized soils may be used as road bases when traffic is relatively light and not of heavy weight. Lime and calcium chloride may be used as additives for high-plasticity, clayey soils where they serve to reduce plasticity. This technique can be effective in reducing volume changes associated with certain expansive clays. The construction of lime stabilization requires mixing lime with natural soil, curing for a few days, then remixing followed by compaction.

There are available additional chemical stabilizers that can be used for soil stabilization; some are marketed under their trade names. The chemical stabilizers described here are among the more common ones. Geotechnical engineers' practical experience may be invaluable in deciding what specific type of chemical stabilization to use in any give situation.

Geosynthetics

Geosynthetics refers to a family of manufactured materials (sheet or netlike products) made of plastics or fiberglass. Geosynthetics may be used to stabilize and reinforce soil masses, such as erosion control of earth slope surfaces, reinforcing backfill of retaining walls, reinforcing slopes or embankments, slope protection of open channels, and drainage control, to name a few. Figure 4–21 illustrates a number of examples of the use of geosynthetics. Geosynthetics may come in the form of *geotextiles*, *geogrids*, *geonets*, and *geomembranes*.

Geotextiles are similar to woven fabric, or textiles. Common usages for geotextiles are for strata separation, soil reinforcement, filtration, etc. In strata separation, the geotextile is simply placed between two different soil strata where it serves to retain the strata separation and to preserve each stratum's individual properties and function. A typical example is to place a geotextile between a fine-grained subgrade soil and aggregate base course to prevent the fine-grained soil from intruding into the aggregate base course. In reinforcement, the geotextile may be placed over a weak soil with a layer of "good" fill placed on the geotextile. In filtration, small openings in the geotextile allow water, but not soil particles, to move through the geotextile. For example, a geotextile may be used in this capacity to protect a drain from soil infiltration.

Geogrids have larger openings (1 to 4 in.) than geotextiles and therefore resemble nets. They are used (in conjunction with geotextiles) to reinforce relatively poor soils over which paved surfaces, such as roads and parking lots, are to be constructed. Geogrids can be used for improved slope stability (to prevent potential slip failure) and also as a reinforcement to construct an earth wall, similar to a reinforced wall.

Geonets are similar to geogrids but have intersecting ribs. They may be used for drainage purposes under roadways and landfills and behind retaining walls. They too are often used in conjunction with geotextiles. Geonets are usually installed on a slope toward a perforated drain pipe or a ditch.

Geomembranes are impervious, thin plastic sheets. They are used to prohibit, or greatly restrict, the movement of water within soil masses. A common example of their use is as landfill liners, to prevent the movement of wastewater (leachate) from within the landfill into surrounding soil strata.

The preceding covers only a few of numerous applications of geosynthetics in soil stabilization and other soil usages. Koerner (1990) gives extensive information about geosynthetics.

(a) (b)

(c) (d)

(e)

FIGURE 4–21 Examples of use of geosynthetics (Courtesy of C.F.P. Inc.). (a) Geotextile stabilization, (b) Geocomposite drainage panel, (c) High-strength geotextile (slide repair), (d) Geogrid reinforced steepened slope, and (e) Geosynthetic clay liner.

4–10 PROBLEMS

4–1. A compaction test was conducted in a soils laboratory, and the Standard Proctor compaction procedure (ASTM D 698) was used. The weight of a compacted soil specimen plus mold was determined to be 3815 g. The volume and weight of the mold were 1/30 ft^3 and 2050 g, respectively. The water content of the specimen was 9.1%. Compute both the wet and dry unit weights of the compacted specimen.

4–2. A soil sample was taken from the site of a proposed borrow pit and sent to the laboratory for a Standard Proctor test (ASTM D 698). Results of the test are as follows:

Determination Number	**1**	**2**	**3**	**4**	**5**
Dry unit weight (lb/ft^3)	107.0	109.8	112.0	111.6	107.3
Moisture content (%)	9.1	11.8	14.0	16.5	18.9

Plot a moisture content versus dry unit weight curve and determine the soil's maximum dry unit weight and optimum moisture content.

4–3. Using the results of the Standard Proctor test as given in Problem 4–2, determine the range of water content most likely to attain 95% or more of the maximum dry unit weight.

4–4. A laboratory compaction test was performed on a soil sample taken from a proposed cut area. The maximum dry unit weight and optimum moisture content were determined to be 104.8 lb/ft^3 and 20.7%, respectively. Estimate the possible type (or classification) of soil for this sample.

4–5. During construction of a highway project, a soil sample was taken from compacted earth fill for a sand-cone in-place density test. The following data were obtained during the test:

1. Weight of sand used to fill test hole and funnel of sand-cone device = 845 g.
2. Weight of sand to fill funnel = 323 g.
3. Unit weight of sand = 100 lb/ft^3.
4. Weight of wet soil from test hole = 648 g.
5. Moisture content of soil from test hole = 16%.

Calculate the dry unit weight of the compacted earth fill.

4–6. A soil sample was taken from a proposed cut area in a highway construction project and sent to a soils laboratory for a compaction test, using the Standard Proctor compaction procedure. Results of the test are as follows:

$$\text{Maximum dry unit weight} = 112.6\ \text{lb/ft}^3$$
$$\text{Optimum moisture content} = 15.5\%$$

The contractor, during construction of the soil embankment, achieved the following:

$$\text{Dry unit weight reached by field compaction} = 107.1\ \text{lb/ft}^3$$
$$\text{Actual water content} = 16.0\%$$

Determine the percent compaction achieved by the contractor.

4–7. Soil having a void ratio of 0.68 as it exists in a borrow pit is to be excavated and transported to a fill site where it will be compacted to a void ratio of 0.45. The volume of fill required is 2500 m^3. Find the volume of soil that must be excavated from the borrow pit to furnish the required volume of fill.

4–8. A field procedure of dynamic compaction is employed to improve the soil properties of cohesionless soils in the field. The weight of the hammer is 20 metric tons (20,000 kg). The drop distance is 10 m. Determine the approximate depth of influence of dynamic compaction.