3

Compaction Concepts

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Often in highway engineering, the soils at particular sections along the roadway alignment are less than ideal for embankment construction. It may appear reasonable in such instances to simply relocate the facility. However, considerations other than geotechnical conditions often govern the location of a highway, and the engineer is forced to design for and construct on the site at hand. One possibility may be to adapt the foundation of the structure to the geotechnical conditions existing at the site. A good example of this approach is the use of pile foundations for bridges. Another possibility is to try to stabilize or improve the properties of the soils at the site, and depending on the circumstances, this approach often is the most economical solution to the problem. Stabilization is usually mechanical or chemical, but even thermal and electrical stabilization have occasionally been used or considered.

In this chapter, adapted from Holtz and Kovacs (1981, Chapter 5), the primary concern is with mechanical stabilization or densification, also called compaction. Chemical stabilization involves the mixing or injecting of chemical substances into the soil. Portland cement, lime, asphalt, calcium chloride, sodium chloride, and paper mill wastes are common chemical stabilization agents (Winterkorn 1975; TRB 1987).

Other methods for stabilizing unsuitable foundation soils include dewatering, which is the removal or reduction of excess groundwater pressures, and preloading, in which foundation soils are surcharged with a temporary overload so as to increase the strength and decrease anticipated settlement. Details of these and other methods are described in textbooks on foundation and highway engineering (see also Chapter 6 of this guide).

Compaction and stabilization are very important when soil is used as an engineering material; that is, when the structure itself is constructed of soil. Earth dams and highway embankments are typical examples of earth structures. If soils are dumped or otherwise placed at random in a fill, the result will be an embankment with low stability and high settlement.

Before the 1930s, highway and railroad fills were usually constructed by end-dumping soils from wagons or trucks. There was little attempt to compact or densify the soils, and failures of even moderately high embankments were common. As noted in Chapter 2, earthworks such as dams and levees are almost as old as man, but these structures, for example, in ancient China or India, were constructed by people carrying small baskets of soil and dumping them into the embankment. People walking over the dumped materials compacted and thus strengthened the soils. Even elephants have been used in some countries to compact soils, but research has shown that they are not very effective (Meehan 1967).

COMPACTION

As previously mentioned, compaction is the densification of soils by the application of mechanical energy. It may also involve modification of water content and gradation of the soil. Cohesionless soils are efficiently compacted by vibration. In the field, hand-operated vibrating plates and motorized vibratory rollers of various sizes are quite efficient for compacting shallow deposits of sand and gravel soils. Rubber-tired equipment can also be used efficiently to compact sands. Even large free-falling weights are used to dynamically compact loose granular deposits and fills. Some of these techniques are discussed in Chapters 6 and 9, as well as by Holtz (1989).

Fine-grained and cohesive soils may be compacted in the laboratory by falling weights and hammers, by special "kneading" compactors, and even statically. In the field, common compaction equipment includes hand-operated tampers, sheepsfoot rollers, rubber-tired rollers, vibratory rollers, and other types of heavy compaction equipment. Considerable compaction can also be obtained by proper routing of the hauling equipment over the embankment during construction (see Chapter 4, section on Compaction).

The objective of compaction is to improve the engineering properties of the soil mass; by compaction

- Detrimental settlements can be reduced or prevented;
- Soil strength can be increased and slope stability improved;
- Bearing capacity of pavement subgrades can be improved; and
- Undesirable volume changes, for example, caused by frost action, swelling, and shrinkage, may be controlled.

THEORY OF COMPACTION

The fundamentals of compaction of cohesive soils were developed by R. R. Proctor in the early 1930s. Proctor published a series of articles in *Engineering News-Record* (Proctor 1933) on the principles of compaction, and in his honor, the standard laboratory compaction test that he developed is called the Proctor test.

Proctor noted that compaction is a function of four variables: (a) dry density, ρ_d; (b) water content, w; (c) compactive effort; and (d) soil type. Compactive effort is a measure of the mechanical energy applied to a soil mass. In the field, compactive effort is the number of passes or "coverages" of the roller of a certain type and weight on a given volume of soil. In the laboratory impact compaction test, a hammer is dropped several times on a soil sample in a mold. The mass of the hammer, height of drop, number of drops, number of layers of soil, and the volume of the mold are specified. For example, in the standard Proctor test (also standard AASHTO T 99 and ASTM D 698), the mass of the hammer is 5.5 lb and the height of fall is 1 ft. The soil is placed in three layers into a $^1/_{30}$ ft^3 mold, and each layer is tamped 25 times. Compactive effort can be calculated to be 12,375 ft-lbf/ft^3.

The process of compaction for cohesive soils can best be illustrated by the Proctor test. Several samples of the same soil, but at different water contents, are compacted according to the standard Proctor test specifications given earlier. The total or wet density and the actual water content of each compacted sample are measured. Then the dry density for each sample can be calculated from

$$\text{Wet density, } \rho = \frac{\text{total mass or weight, } M_t}{\text{total volume, } V_t} \tag{3-1}$$

$$\text{Dry density, } \rho_d = \frac{\text{wet density, } \rho}{1 + \text{water content, } w} \tag{3-2}$$

When the dry densities of each sample are determined and plotted versus the water contents for each sample, then a curve called a compaction curve for standard Proctor compaction is obtained (Figure 3-1, Curve A). Each data point on the curve represents a single compaction test, and usually four or five individual tests are required to completely determine the compaction curve. This curve is unique for a given soil type, method of compaction, and (constant) compactive effort. The peak point of the curve determines the maximum dry density $\rho_{d\ max}$ at a water content

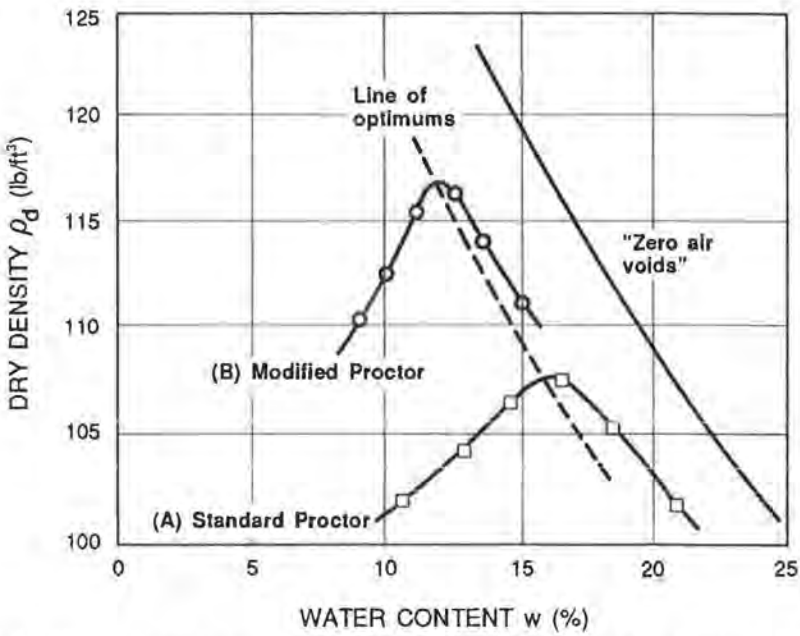

FIGURE 3-1 Standard and modified compaction curves for Crosby B till (Holtz and Kovacs 1981). *(Reprinted with permission from Prentice Hall, Inc.)*

known as the optimum water content w_{opt} [also called the optimum moisture content (OMC)]. Note that the maximum dry density is only a maximum for a specific compactive effort and method of compaction. This does not necessarily reflect the maximum dry density that can be obtained in the field.

Typical values of maximum dry density for inorganic cohesive soils are about 100 to 125 lb/ft^3 with the maximum range from about 80 to 150 lb/ft^3. Typical optimum water contents are between 10 and 20 percent, with an outside range of about 5 to 40 percent. Note that the compaction curve, even at high water contents, never actually reaches the zero air voids curve. This is true even for higher compactive efforts, for example, Curve B of Figure 3-1. Curve B is the compaction curve obtained by the modified Proctor compaction test (AASHTO T 180 and ASTM D 1557). This test uses a heavier hammer (10 lbf), a greater height of fall (1.5 ft), and five layers tamped 25 times into a standard Proctor mold. The compactive effort is 56,250 ft-lbf/ft^3.

The modified test was developed during World War II by the U. S. Army Corps of Engineers to better represent the compaction required for airfields to support heavy aircraft. The point is that increasing the compactive effort tends to increase the maximum dry density, as expected, but it also decreases the optimum water content. A line drawn through the peak points of several compaction curves for the same soil at different compactive efforts will be almost parallel to the zero air voids curve.

Typical compaction curves for different types of soils are shown in Figure 3-2. Note how sands that are well graded (SW soils, top curve) have a higher dry density than most uniform soils (SP soils, bottom curve). For clay soils, the maximum dry density tends to decrease as plasticity increases.

Why do we get compaction curves such as those shown in Figures 3-1 and 3-2? Starting at low water contents, as the water content increases,

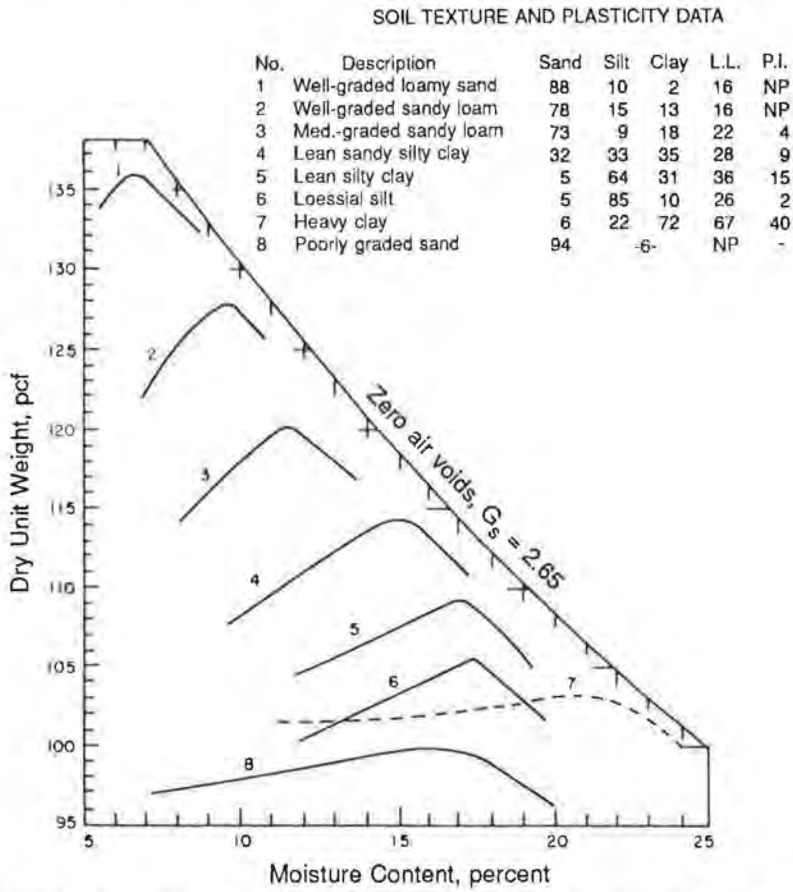

FIGURE 3-2 Water content–dry density relationships for eight soils compacted according to the standard Proctor method (Johnson and Sallberg 1960; cited by Holtz and Kovacs 1981). *(Reprinted with permission from Prentice Hall, Inc.)*

the particles develop larger and larger water films around them, which tend to "lubricate" the particles and make them easier to be moved about and reoriented into a denser configuration. However, eventually a water content is reached at which the density does not increase any further. At this point, water starts to replace soil particles in the mold, and because the density of water is much less than the density of the mineral grains, the dry density curve starts to fall off, as shown in Figure 3-3. Note that no matter how much water is added, the soil never becomes completely saturated by compaction.

Compaction behavior of cohesive soils as described in the preceding paragraph is typical for both field and laboratory compaction. The curves obtained will have different shapes and positions on the ρ_d versus w plot, but in general, the response will be similar to that shown in Figure 3-4, where the same soil is compacted under different conditions. The shapes of the curves are different because the types or modes of compaction in the laboratory are different from those in the field. Additional information on the properties of compacted soils can be found in soil mechanics textbooks and the references given in Chapter 1.

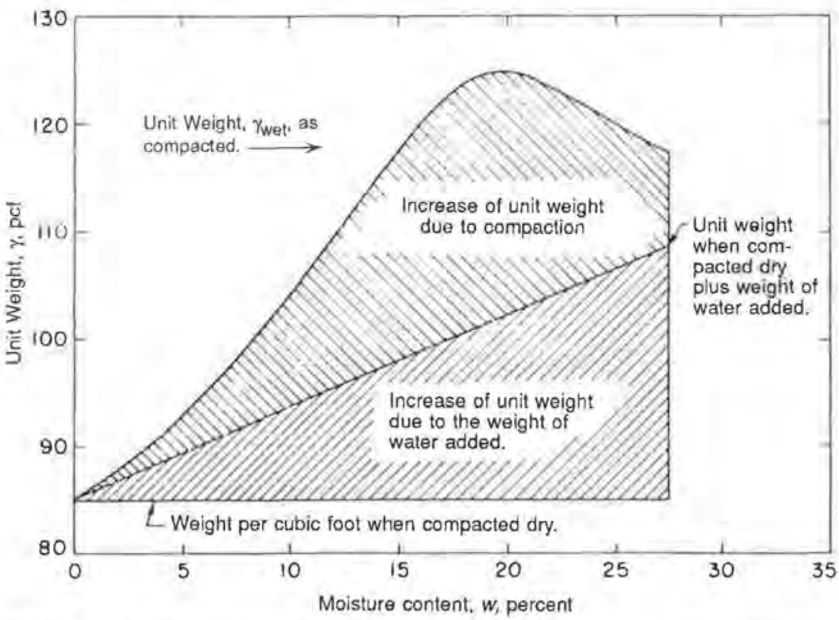

FIGURE 3-3 Water content–density relationship indicating the increased density resulting from the addition of water and the applied compaction effort. Soil is a silty clay, LL = 37, PI = 14, standard Proctor compaction (Johnson and Sallberg 1960; cited by Holtz and Kovacs 1981). (*Reprinted with permission from Prentice Hall, Inc.*)

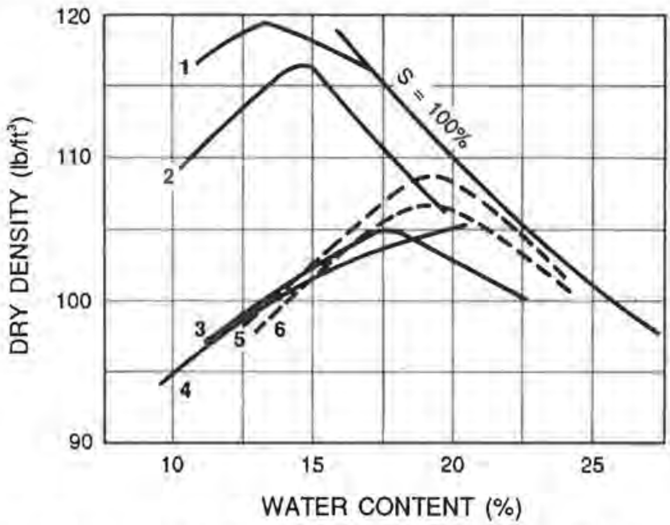

FIGURE 3-4 Comparison of field and laboratory compaction. (1) Laboratory static compaction, 2000 psi; (2) modified Proctor; (3) standard Proctor; (4) laboratory static compaction, 200 psi; (5) field compaction, rubber-tired load, six coverages; (6) field compaction, sheepsfoot roller, six passes.

Note: Static compaction from top and bottom of soil sample (Turnbull 1950, cited by Lambe and Whitman 1969 and Holtz and Kovacs 1981). (*Reprinted with permission from Prentice Hall, Inc.*)

SPECIFICATIONS AND COMPACTION CONTROL

Because the objective of compaction is to stabilize soils and improve their engineering behavior, many inspectors often forget that the desired engineering properties of the fill are important, not just its dry density and water content. Dry density and water content do reflect quite well the engineering properties, and thus they are convenient to use for construction control, but they are not the primary objective of compaction.

The usual design-construct procedure is as follows. Laboratory tests are conducted on samples of the proposed soil materials to be used to define the engineering properties required for design. After the embankment is designed, the appropriate compaction specifications are selected, field compaction control tests are specified, and the results of these tests become the standard for controlling the project. Construction control inspectors then conduct these tests to ensure that the contractor actually adheres to the compaction specifications.

The reasons for conducting such tests are outlined in the panel discussion in ASTM (1964, pp. 80–135); comments by Johnson and Sallberg (pp. 101–104) and Turnbull (pp. 104–106; 126–127) are particularly relevant.

Specifications

There are basically two types of earthwork specifications: (a) method specifications, and (b) end-product specifications. With method specifications, the type and weight of rollers, number of passes, lift thickness, and the like, are completely specified, and the responsibility for the quality of the earthwork rests with the owner or agency and owner's or agency's engineer. Although method specifications often provide considerable savings in unit costs for earthwork construction, they require such a large investment in preconstruction engineering and testing that they are generally used for large compaction projects such as earth dams.

End-product specifications are commonly used for highways and building foundations. A certain relative or percent compaction is specified. Relative or percent compaction is defined as the ratio of the field dry density, $\rho_{d\,\text{field}}$, to the laboratory maximum dry density, $\rho_{d\,\max}$, according to some specified standard test, for example, the standard Proctor or the modified Proctor test; or

$$\text{Relative or percent compaction} = \frac{\rho_{d\,\text{field}}}{\rho_{d\,\max}} \times 100(\%) \qquad (3\text{-}3)$$

How is relative or percent compaction determined? First, the test site is selected. It should be representative or typical of the compacted lift and soil material. Typical specifications call for a new field test for every 1,000 to 3,000 yd^3 or so, or when the soils change significantly. It is also advisable, if possible, to conduct the field test at least one or two compacted lifts below the already-compacted ground surface, especially when sheepsfoot rollers are used, or in granular soils, to be sure that loose materials near the surface are not included in the tested volume. Also, it is necessary to ensure that the materials the contractor has compacted are acceptable for the particular district or region according to the standard agency specifications or special provisions for the project.

Compaction Control Tests

Field control tests can either be destructive or nondestructive. Destructive tests involve excavation and removal of some of the fill material, whereas nondestructive tests indirectly determine by nuclear means the density and water content of the fill.

The steps required for the common destructive field tests are as follows:

1. Excavate a hole in the compacted fill at the desired sampling elevation (the size will depend on the maximum size of material in the fill). Determine the weight of the excavated material.
2. Determine the water content.
3. Measure the volume of the excavated material. Techniques commonly used to measure volume include the sand cone and balloon methods, or for rock fill and large holes, pouring water or oil of known density into the hole (Figure 3-5). In the sand cone method (AASHTO T 191; ASTM D 1556), dry sand of known dry density is allowed to flow through a cone-shaped pouring device into the hole. The volume of the hole can then easily be determined from the weight of sand in the hole and its dry density. In the balloon method (AASHTO T 205; ASTM D 2167), the volume of the excavated material is determined directly by the expansion of a balloon in the hole.
4. Compute the total density. If the total weight of the material excavated from the hole and the volume of the hole are known, the wet density can be computed. Because the water content is also known, the dry density of the fill can be determined.
5. Compare the field dry density with the Proctor density for that soil and calculate relative or percent compaction (see Equation 3-3).

There are several problems associated with the common destructive field density test. First, it is difficult and expensive to conduct a sufficient number of tests for a statistical analysis of the compaction test results. The volume of material involved in each test is an extremely small percentage of the total volume of fill being controlled (typically, one part in 100,000 or less). Second, oversize particles (gravel, cobbles, etc.) common in some soil deposits must be correctly accounted for, otherwise the laboratory test results will be less than those achieved in the field.

Oversize corrections are discussed in AASHTO T 224 and in ASTM D 698 and D 1557. Ideally, it is desirable to have the complete compaction curve for each field test, but this is time-consuming and expensive. Consequently, the laboratory maximum density may not be known exactly. It is not uncommon in highway construction for a series of laboratory compaction tests to be conducted on representative samples of the soil materials for the highway. Then, when the field test is conducted, its result is compared with the results of one or more of these standard soils from the project site. If the soils at the site are highly variable, this is a poor procedure.

Alternatively, a "family of curves" or a "one-point method" (AASHTO T 272) is often used. In this approach, a family of curves is

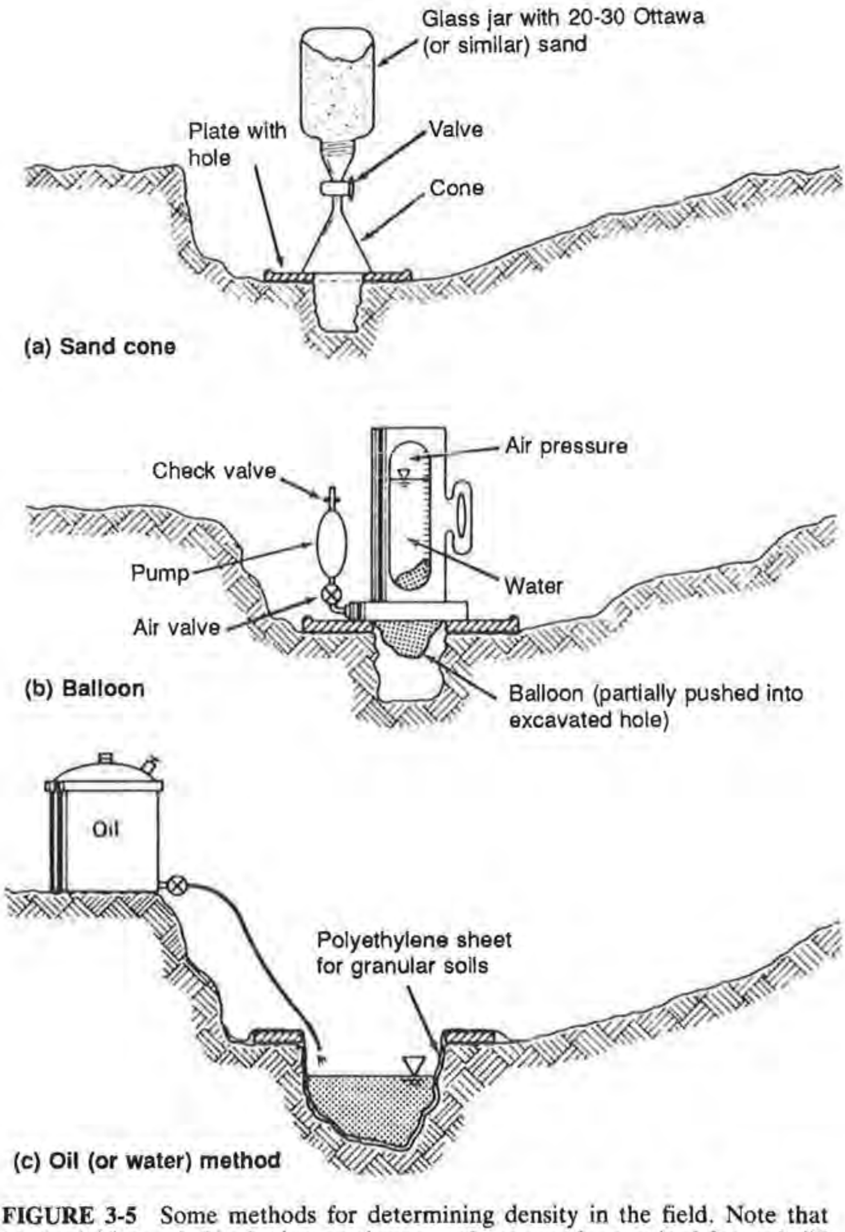

FIGURE 3-5 Some methods for determining density in the field. Note that Method (c) is suitable for large volumes, only as may be required for rock fill (Holtz and Kovacs 1981). (*Reprinted with permission from Prentice Hall, Inc.*)

developed by combining a series of Proctor curves for the various soil types common to a large area. One-point Proctor tests are conducted on the project soils and the results plotted on the family of curves. A Proctor curve having the same shape as the other curves is "fitted" into the family of curves by going through the one-point test results. Then the maximum density and optimum moisture for this one-point Proctor curve are determined, and the percent compaction is then calculated as usual by Equation 3-3.

The third major problem with the common destructive density test procedure is that determination of the water content takes time (several hours or overnight according to AASHTO T 265 and ASTM D 2216). Time is always of the utmost value on a compaction job, and if it takes a day or even several hours before the results are available, several lifts of fill may have been placed and compacted over the bad or failing test area. Then the engineer has to require the contractor to tear out possibly good fill to ensure that the relative compaction of the bad lift meets contract specifications. Contractors understandably are hesitant to do this, and yet how many zones of bad compaction should be allowed in an embankment? None, of course.

Because determination of water content takes the most time, several methods have been proposed to obtain it more rapidly. Pan drying or frying the sample over an open flame has been commonly used, but because it is difficult to control the temperature, this method gives poor results, especially for highly plastic clays.

Alternatively, a calcium carbide gas pressure meter (AASHTO T 217) can be used. The water in the soil reacts with carbide to produce acetylene gas; its pressure is proportional to the water content. Burning with methanol and the alcohol-hydrometer method are also sometimes used. For these methods, the correlation with standard oven drying is generally satisfactory for silts and lean clays.

If electricity is available at the field control laboratory, a microwave oven can be used to rapidly determine the water content. According to ASTM D 4643 (1989), microwave drying is not intended as a replacement for convection oven drying, but it can be used as a supplementary method when rapid results are required. The method appears to be satisfactory for most soils unless they contain significant amounts of halloysite, mica, montmorillonite, gypsum or other hydrated minerals, highly organic soils, or marine soils containing dissolved salts. Small, porous pebbles in the soil sample may explode when rapidly heated; therefore soil containers should be covered with heavy paper towels to prevent damage or injuries.

Another method for quickly and efficiently determining the relative compaction of cohesive soils was developed in the 1950s by the U. S.

Bureau of Reclamation (USBR 1974) and Hilf (1961) [see also Hilf (1975) and Holtz and Kovacs (1981)]. The procedure makes it possible to accurately determine the relative compaction of a fill as well as a close approximation of the difference between the optimum water content and the fill water content without actually oven drying the sample. Experience has shown that it is possible to obtain the values required for control of construction in about 1 hr from the time the field density test is performed.

Other problems with destructive field tests are associated with the determination of the volume of the excavated material. The sand cone method (AASHTO T 191, Figure 3-5a), often taken as the standard, is subject to errors. For example, vibration from nearby equipment will increase the density of the sand in the hole, making a larger hole volume; this results in a lower field density. A higher density will result if the technician stands too close to the hole and causes soil to squeeze into it during excavation. All of the common volumetric methods are subject to error if the compacted material is gravel or contains gravel particles.

Any unevenness in the walls of the hole causes significant error in the balloon method (AASHTO T 205, Figure 3-5b). If the soil is coarse sand or gravel, none of the liquid methods works well, unless the hole is very large and a polyethylene sheet is used to contain the water or oil (Figure 3-5c).

Density and Water Content by Nuclear Methods

Because of the problems with destructive field tests, nondestructive density and water content testing using radioactive isotopes has increased in popularity during the past few years. Nuclear methods (AASHTO T 238 and T 239; ASTM D 2922 and D 3017) have several advantages over traditional techniques. Tests can be conducted rapidly and results can be obtained within minutes. Erratic results can be easily and quickly double-checked. Therefore, the contractor and engineer know the results quickly, and corrective action can be taken before too much additional fill has been placed. Because more tests can be conducted, a better statistical control of the fill is provided. An average value of the density and water content is obtained over a significant volume of fill, and therefore the natural variability of compacted soils can be considered.

Disadvantages of nuclear methods include the relatively high initial cost of the equipment and the potential danger to field personnel of exposure to radioactivity. Strict radiation safety standards must be enforced when nuclear devices are used, and only properly trained and licensed operators are permitted to use nuclear density equipment.

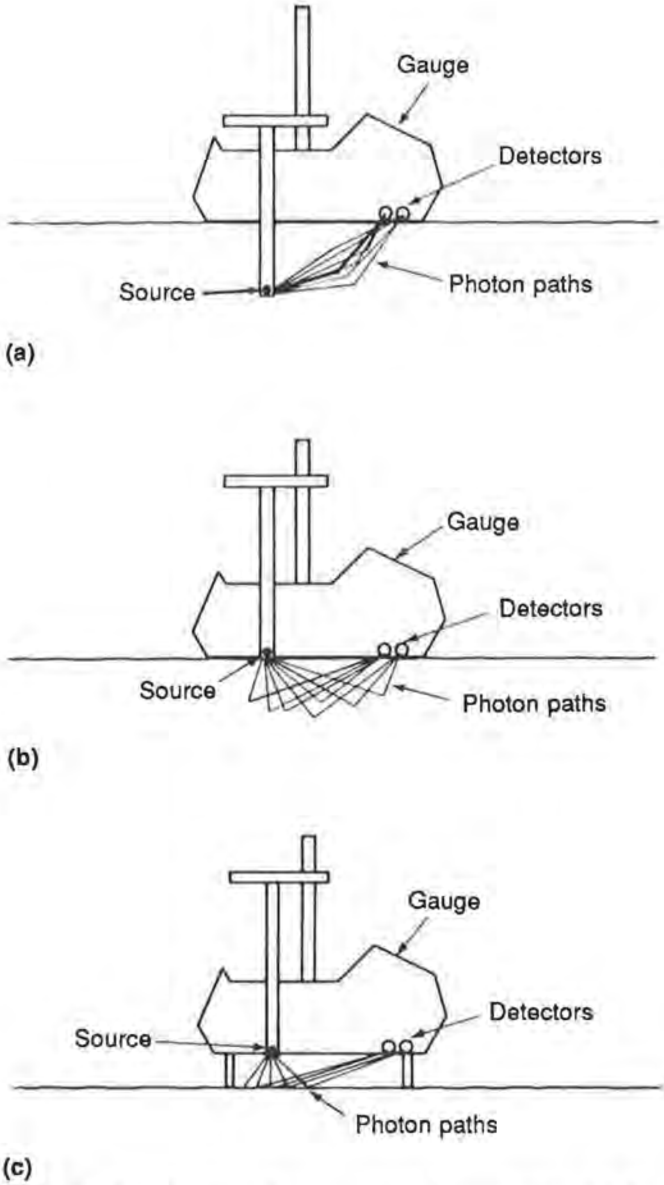

FIGURE 3-6 Nuclear density and water content determination: (a) direct transmission, (b) backscatter, (c) air gap (Troxler Electronic Laboratories, Inc.; cited by Holtz and Kovacs 1981). *(Reprinted with permission from Prentice Hall, Inc.)*

Two types of sources or emitters are necessary to determine both the density and the water content. Gamma radiation, as provided by radium or a radioactive isotope of cesium, is scattered by the soil particles; the amount of scatter is proportional to the total density of the material. The spacing between the source and the detector, which is usually a scintillation counter or a Geiger counter, is constant. Hydrogen atoms in water scatter neutrons, and this provides a means whereby water content can be determined. Typical neutron sources are americium-beryllium isotopes. Calibration against compacted materials of known density is necessary, and for instruments operating on the surface, the presence of an uncontrolled air gap can significantly affect the measurements. Filling the gap with dry sand helps reduce but does not eliminate this effect.

Three nuclear techniques are in common use. The direct transmission method is shown schematically in Figure 3-6a, and the backscatter technique is shown in Figure 3-6b. The less common air-gap method (Figure 3-6c) is sometimes used when the composition of the near-surface materials adversely affects the density measurement. For detailed test procedures, see AASHTO T 238 and 239 and ASTM D 2922 and D 3017.

REFERENCES

ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
USBR	U. S. Bureau of Reclamation

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