c. Well-graded sand (SW). Optimum moisture content = 10 percent
d. Well-graded gravel (GW). Optimum moisture content = 7 percent

Some soils may be relatively insensitive to compaction water content. For example, open-graded gravels and clean coarse sands are so permeable that water simply drains out of the soil or is forced out of the soil during the compaction process. These types of soil can often be placed in a dry state and then vibrated into dense particle arrangements.

4. *Compaction effort (or energy).* The compaction effort is a measure of the mechanical energy applied to the soil. Usually the greater the amount of compaction energy applied to a soil, the denser the soil will become. There are exceptions, such as pumping soils (discussed in Sec. 15.2.5) that cannot be densified by an increased compaction effort. Compactors are designed to use one or a combination of the following types of compaction effort:
   a. Static weight or pressure
   b. Kneading action or manipulation
   c. Impact or a sharp blow
   d. Vibration or shaking

15.2.2 Relative Compaction

The most common method of assessing the quality of the field compaction is to calculate the *relative compaction* (RC) of the fill, defined as

$$RC = \frac{100\,\rho_d}{\rho_{d\max}} \tag{15.1}$$

where $\rho_{d\max}$ is the laboratory maximum dry density (pcf or Mg/m^3) and ρ_d is the field dry density (pcf or Mg/m^3).

In California, the typical mass grading specification for structural fill is a minimum relative compaction of 90 percent using the modified Proctor laboratory compaction test. In some cases, such as for the compaction of roadway base or for the lower portions of deep fill, a higher compaction of a minimum relative compaction of 95 percent is often specified.

As discussed in Sec. 3.6, the maximum dry density $\rho_{d\max}$ is obtained from the laboratory compaction tests, such as by using the modified Proctor test procedures (ASTM D 1557-02, 2004) or the standard Proctor test procedures (ASTM D 698-00, 2004). The objective of the laboratory compaction test is to obtain the compaction curve, with the peak point of the compaction curve corresponds to the laboratory maximum dry density (e.g., see Fig. 3.52).

In addition to the maximum dry density, the field dry density of the compacted soil must also be determined in order to calculate the relative compaction. Field dry density tests are discussed in the next section.

15.2.3 Field Density Tests

In order to determine ρ_d for Eq. 15.1, a field density test must be performed. Field density tests can be classified as either destructive or nondestructive tests (Holtz and Kovacs, 1981).

Probably the most common destructive method for determining the field dry density is through the use of the sand cone apparatus (ASTM D 1556-00, 2004). The test procedure consists of excavating a hole in the ground, filling the hole with sand using the sand cone apparatus, and then determining the volume of the hole based on the amount of sand required to fill the hole. By knowing the wet mass of soil removed from the hole divided by the volume of the hole, the wet density of the fill can be calculated. The water content w of the soil extracted from the hole can be determined and thus the dry density ρ_d can then be calculated.

Another type of destructive test for determining the field dry density is the drive cylinder (ASTM D 2937-00, 2004). This method involves the driving of a steel cylinder of known volume into the soil. Based on the mass of soil within the cylinder, the wet density can be calculated. Once the water content w of the soil is obtained, the dry density ρ_d of the fill can be calculated.

Probably the most common type of nondestructive field test is the nuclear method described in ASTM D 2922-01, 2004, "Standard Test Methods for Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow Depth)." In this method, the wet density is determined by the attenuation of gamma radiation. The water content is often determined by the thermalization or slowing of fast neutrons, described in ASTM D 3017-01, 2004, "Standard Test Method for Water Content of Soil and Rock in Place by Nuclear Methods (Shallow Depth)." The most common approach is to use the *backscatter method*, where the source and detector remain on the ground surface. In general, the nuclear method is much quicker than any of the destructive tests. However, disadvantages of this test are that special equipment is required and the equipment is much more expensive than the equipment required for the other types of field density tests. In addition, the equipment uses radioactive materials that could be hazardous to the health of the user. There are special governmental regulations concerning the storage, transportation, and use of this equipment and these safety requirements are beyond the scope of this book. A final disadvantage is that the equipment is subject to long-term aging of radioactive materials that may change the relationship between count rate and soil density. Hence, the equipment will need to be periodically calibrated (usually a block of material of known density is used as a calibration device). Because of these limitations, sand cone tests or drive cylinder tests should be used as a check on the results from the nuclear method.

NAVFAC DM-7.2 (1982) presents guidelines on the number of field density tests for different types of grading projects, as follows:

- One test for every 500 yd^3 (380 m^3) of material placed for embankment construction
- One test for every 500 to 1000 yd^3 (380 to 760 m^3) of material for canal or reservoir linings or other relatively thin fill sections
- One test for every 100 to 200 yd^3 (75 to 150 m^3) of backfill in trenches or around structures, depending upon total quantity of material involved
- At least one test for every full shift of compaction operations on mass earthwork
- One test whenever there is a definite suspicion of a change in the quality of moisture control or effectiveness of compaction

There are many other guidelines concerning the number of field density tests for specific grading activities.

It is rare for the licensed geotechnical engineer to perform field density testing on a daily basis because of the repetitive and time-consuming nature of such work. For large mass grading operations, it is common to have technicians performing the field density testing. The technician will have to be able to perform the field density tests, classify different soil types (based on visual and tactile methods), and insist on remedial measures when compaction falls below the specifications.

As indicated earlier, the number of field density tests per volume of compacted fill is often very low (e.g., one field density test per 500 yd^3 of fill). It is important that the field technician perform the density tests on areas where compaction is suspect. For example, the technician should not perform field compaction tests in the haul road area, because this path receives continuous traffic and will usually be in a dense compacted state. Likewise, testing in the wheel paths of the compaction equipment will yield high values. Often the field technician uses a metal rod to probe for possible poorly compacted fill zones. Field density tests would then be performed in these areas of possible poor compaction.

15.2.4 Types of Structural Fill

There are four general types of structural fill, as follows:

1. *Select import.* Select import refers to a processed material. The material may be derived from several different sources, then screened and mixed to provide a material of specified gradation. Table 15.3 presents different methods that can be used to produce a select import material. A common type of select import is granular base material, which may have to meet specifications