Chapter 8  Earthfill and Rockfill
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Chapter 8  Earthfill and Rockfill

<table>
<thead>
<tr>
<th>Contents</th>
<th>645.0800 Introduction</th>
<th>8–1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>645.0801 Installation</td>
<td>8–1</td>
</tr>
<tr>
<td>(a)</td>
<td>Materials</td>
<td>8–1</td>
</tr>
<tr>
<td>(b)</td>
<td>Foundation preparation</td>
<td>8–5</td>
</tr>
<tr>
<td>(c)</td>
<td>Placement and processing</td>
<td>8–6</td>
</tr>
<tr>
<td>(d)</td>
<td>Moisture control</td>
<td>8–8</td>
</tr>
<tr>
<td>(e)</td>
<td>Compaction</td>
<td>8–10</td>
</tr>
<tr>
<td></td>
<td>645.0802 Sampling and testing</td>
<td>8–16</td>
</tr>
<tr>
<td>(a)</td>
<td>Determining frequency of testing</td>
<td>8–16</td>
</tr>
<tr>
<td>(b)</td>
<td>Testing location</td>
<td>8–17</td>
</tr>
<tr>
<td>(c)</td>
<td>Sampling</td>
<td>8–17</td>
</tr>
<tr>
<td>(d)</td>
<td>Testing</td>
<td>8–17</td>
</tr>
<tr>
<td>(e)</td>
<td>Evaluating test results</td>
<td>8–22</td>
</tr>
<tr>
<td></td>
<td>645.0803 Records and reports</td>
<td>8–27</td>
</tr>
<tr>
<td></td>
<td>645.0804 References</td>
<td>8–28</td>
</tr>
</tbody>
</table>
Chapter 8
Earthfill and Rockfill
Part 645
National Engineering Handbook

Figures

| Figure 8–1 | Disk penetrating into preceding lift | 8–6 |
| Figure 8–2 | Proctor curve | 8–8 |
| Figure 8–3 | Standard and Modified Proctor effort as specified in ASTM D698 and ASTM D1557 | 8–9 |
| Figure 8–4 | Compaction moisture's effect on soil strength and permeability | 8–9 |
| Figure 8–5 | Water requirements for compaction | 8–11 |
| Figure 8–6 | Selection of compactor type | 8–13 |
| Figure 8–7 | Sand cone apparatus | 8–18 |
| Figure 8–8 | Apparatus for the rubber balloon method | 8–19 |
| Figure 8–9 | Drive cylinder apparatus | 8–20 |
| Figure 8–10 | Typical family of curves | 8–23 |
| Figure 8–11 | Proctor and ZA\(V\) curves | 8–24 |
| Figure 8–12 | 70% ZA\(V\) curve, 90% ZA\(V\) curve, and ZA\(V\) curve | 8–25 |

Tables

| Table 8–1 | Engineering use of earthfill | 8–3 |
| Table 8–2 | Compaction characteristics of soils | 8–12 |
| Table 8–3 | Summary of compaction classes defined in NEH 642, Construction Specification 23 | 8–14 |
Chapter 8  Earthfill and Rockfill

645.0800  Introduction

Earthfills and rockfills are widely used in NRCS work for berms, dikes, levees, various types of embankments, and structural backfills. Many NRCS projects contain soil and/or rock as the primary structural component.

The quality of available material and the foundation conditions are major factors in determining the type of structure that can be economically constructed at a given location. The inherent variability of earth and rock materials requires a greater tolerance in design and construction than for most other construction materials. Materials range from fine-grained soils (50% or more passing a No. 200 sieve) to rocky soils (predominantly gravel and cobbles) or combinations of these. The availability of materials at the site, their engineering properties, and the purpose of the structure determine what can be designed.

The proper use of earth and rock as construction materials requires special attention to investigation, testing, and appropriate design procedures and assumptions. Onsite use of the materials in installation requires proper selection from a borrow source, control of placement and processing, moisture control, and adequate compaction. Inspection of earth and rock construction requires knowledge, experience, and judgment to ensure compliance with the specifications and a quality finished job.

Prior to earthfill and rockfill operations, the inspector is responsible for:

- reviewing and understanding the drawings and specifications related to earthfill and rockfill
- verifying diversion, dewatering, and drainage systems are in place
- verifying access and haul roads are constructed
- verifying safety aspects of earthfill and rockfill operations are addressed
- verifying required excavations can be accomplished without adversely affecting buried utilities
- verifying required permits are obtained and the work can adhere to permit requirements

645.0801  Installation

(a) Materials

(1) Earthfill and earth backfill

Earthfill is composed of natural earth materials that can be placed and compacted by construction equipment operated in a conventional manner. Earth backfill is also composed of natural earth materials placed and compacted in confined spaces or adjacent to structures (including pipes) by hand tamping, manually directed power tampers or vibrating plates, or their equivalent.

Normally, earthfills are constructed from the most suitable materials available at or near the site after removal of rock particles that are larger than the maximum size specified. Physical properties of these materials such as permeability, strength, and compressibility must be assessed; preferably determined from prior laboratory and field test results. These laboratory and field test results are interpreted to predict the suitability of the material for the type of structure planned.

Earthfill and earth backfill details in the construction drawings and specifications are generally based on the laboratory tests of samples taken from the foundation and borrow areas at the site. These details identify the types of material to be used and their location in the installation according to their Unified Soil Classification System (USCS) designation. The USCS, developed by Cassagrande in 1952, was adopted by most U.S. Federal agencies as a standard for all engineering work. It is the recognized classification standard for all engineering work in the NRCS. The system is currently published as a standard in ASTM D2487. ASTM D2488 provides the field methods for classifying soils in accordance with the USCS.

All NRCS engineers and inspectors working on construction should be familiar with the USCS and the procedures outlined in both of the above ASTM practice standards. The NRCS provides soil mechanics training courses and modules for engineers and inspectors. It is recommended that inspectors take advantage of these and other available resources for improving knowledge, skills, and abilities in understanding engineering characteristics of various soil conditions.
groups and how they can best be used in construction of conservation measures. Additional information on the USCS can be found in chapter 7 of this handbook. Appendix B contains Worksheet 7.1, which could be helpful in performing a visual classification of the soil.

Examples of how the USCS can be applied to a variety of engineering uses of earthfill are shown in table 8–1. The four properties used for evaluation are permeability, resistance to piping, compressibility, and workability. A numerical rating from 1 (most suitable) to 14 (least suitable) is used to determine the relative suitability of soil materials in rolled earth embankments, channel sections, and foundations.

Earth backfill may be constructed from the same materials as earthfill; however, the specified maximum particle size is usually smaller than that specified for earthfill. Earth backfill may be composed of plastic materials with low permeability for sealing off the movement of water. Common classifications of these types of backfill materials are CL, ML, SC, SM, CH, and MH.

Earth backfill may also be nonplastic materials such as clean sands and gravels which are often selected over plastic soils because of the ease and economy of placing (particularly in confined areas), good stability, and low settlement potential. They cannot be used where impermeability is required. These nonplastic, granular soils can be made to flow under a pipe or other structure and be compacted with little effort if they do not contain excessive amounts of fines (i.e., particles smaller than the No. 200 sieve size). Sands and gravels classified as GW, GP, SW, and SP make the best granular backfill because, by definition, these soils contain less than 5 percent fines. Proper selection of granular materials is important for successful results. Excessive amounts of fines tend to plug the voids between the coarse-grained soils and inhibit drainage necessary for the consolidation process.

Gravels and sands with up to 12 percent fines may be suitable for some backfill applications. These include gravels and sands with a dual classification: GW–GM, GW–GC, GP–GM, GP–GC, SW–SM, SP–SM, SP–SC, and SW–SC. These gravels and sands by definition contain 5 to 12 percent fines. They would not be suitable for applications where free drainage is necessary. For more on gravels and sands used for drains and filters see NEH 645, Chapter 11, Drains and Filters.

In addition to being used for backfill, nonplastic granular materials are often used for structure foundations to improve the bearing capacity by removing and replacing soft soils with free draining coarse-grained soils.

Classifying soils according to the USCS alone does not always provide enough information to predict soil performance. Gravelly and stony soils used in compacted embankments have been classified by the NRCS in three groups on the basis of the durability of the coarse rock and soil materials. The details of this classification and its use are explained in NRCS Technical Release No. 26, The Use of Soils Containing More Than 5 Percent Rock Larger Than the No. 4 Sieve.

Most earthfills and earth backfills are designed as homogeneous fills. Larger structures, such as embankments for flood control dams, or sites that have limited quantities of impermeable soils may be designed as zoned fills. Zoned fills will have the less permeable material placed as a cutoff or core zone and the more permeable material placed at less strategic points such as the outside sections of the embankment. The inspector, in such cases, must be familiar with the quantity and quality of the borrow materials to verify the selection and placement of them in the embankment to produce the zones specified in the design. Any changes to zone locations or limits must be approved by the design engineer.

It is common for borrow areas to contain layers or lenses of materials that vary in texture and moisture. The contractor, by selecting the materials at the time of loading and by proper routing and control of the haul equipment, should place the materials in the designated zones where they are suitable for use. On some jobs, compaction moisture is controlled by selecting borrow materials with a moisture content within the specified range. Thus, material suitability is contingent on both texture and moisture content.
### Table 8–1  Engineering use of earthfill

<table>
<thead>
<tr>
<th>Typical names of soil groups</th>
<th>Group symbols</th>
<th>Permeability when compacted</th>
<th>Shearing strength when compacted and saturated</th>
<th>Compressability when compacted and saturated</th>
<th>Workability as a construction material</th>
<th>Rolled earth dams</th>
<th>Canal sections</th>
<th>Foundations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Homogeneous embankment</td>
<td>Core</td>
<td>Shell</td>
</tr>
<tr>
<td>Well-graded gravels, gravel-sand mixtures, little or no fines</td>
<td>GW</td>
<td>Pervious</td>
<td>Excellent</td>
<td>Negligible</td>
<td>Excellent</td>
<td>—</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>Poorly graded gravels, gravel-sand mixtures, little or no fines</td>
<td>GP</td>
<td>Very pervious</td>
<td>Good</td>
<td>Negligible</td>
<td>Good</td>
<td>—</td>
<td>2</td>
<td>—</td>
</tr>
<tr>
<td>Silty gravels, poorly graded gravel-sand-silt mixtures</td>
<td>GM</td>
<td>Semipervious to impervious</td>
<td>Good</td>
<td>Negligible</td>
<td>Good</td>
<td>2</td>
<td>4</td>
<td>—</td>
</tr>
<tr>
<td>Clayey gravels, poorly graded gravel-sand-clay mixtures</td>
<td>GC</td>
<td>Impervious</td>
<td>Good to fair</td>
<td>Very low</td>
<td>Good</td>
<td>1</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>Well-graded sands, gravelly sands, little or no fines</td>
<td>SW</td>
<td>Pervious</td>
<td>Excellent</td>
<td>Negligible</td>
<td>Excellent</td>
<td>—</td>
<td>—</td>
<td>3 if gravelly</td>
</tr>
<tr>
<td>Poorly graded sands, gravelly sands, little or no fines</td>
<td>SP</td>
<td>Pervious</td>
<td>Good</td>
<td>Very low</td>
<td>Fair</td>
<td>—</td>
<td>—</td>
<td>4 if gravelly</td>
</tr>
<tr>
<td>Silty sands, poorly graded sand-silt mixtures</td>
<td>SM</td>
<td>Semipervious to impervious</td>
<td>Good</td>
<td>Low</td>
<td>Fair</td>
<td>4</td>
<td>5</td>
<td>—</td>
</tr>
<tr>
<td>Clayey sands, poorly graded sand-clay mixtures</td>
<td>SC</td>
<td>Impervious</td>
<td>Good to fair</td>
<td>Low</td>
<td>Good</td>
<td>3</td>
<td>2</td>
<td>—</td>
</tr>
<tr>
<td>Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity</td>
<td>ML</td>
<td>Semipervious to impervious</td>
<td>Fair</td>
<td>Medium</td>
<td>Fair</td>
<td>6</td>
<td>6</td>
<td>—</td>
</tr>
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</table>
### Table 8–1  Engineering use of earthfill—continued

<table>
<thead>
<tr>
<th>Typical names of soil groups</th>
<th>Group symbols</th>
<th>Permeability when compacted</th>
<th>Shearing strength when compacted and saturated</th>
<th>Compressibility when compacted and saturated</th>
<th>Workability as a construction material</th>
<th>Relative desirability for various uses</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
<td>Rolled earth dams</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Homogeneous embankment</td>
</tr>
<tr>
<td>Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays</td>
<td>CL</td>
<td>Impervious</td>
<td>Fair</td>
<td>Medium</td>
<td>Good to fair</td>
<td>5</td>
</tr>
<tr>
<td>Organic silts and organic silt-clays of low plasticity</td>
<td>OL</td>
<td>Semipervious to impervious</td>
<td>Poor</td>
<td>Medium</td>
<td>Fair</td>
<td>8</td>
</tr>
<tr>
<td>Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts</td>
<td>MH</td>
<td>Semipervious to impervious</td>
<td>Fair to poor</td>
<td>High</td>
<td>Poor</td>
<td>9</td>
</tr>
<tr>
<td>Inorganic clays of high plasticity fat clays</td>
<td>CH</td>
<td>Impervious</td>
<td>Poor</td>
<td>High</td>
<td>Poor</td>
<td>7</td>
</tr>
<tr>
<td>Organic clays of medium to high plasticity</td>
<td>OH</td>
<td>Impervious</td>
<td>Poor</td>
<td>High</td>
<td>Poor</td>
<td>10</td>
</tr>
<tr>
<td>Peat and other highly organic soils</td>
<td>P</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
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</table>
With respect to earthfill and earth backfill materials, the inspector is responsible for verifying:

- adequate knowledge and competency in the field use of the USCS
- materials being used are properly identified and do not differ significantly from those materials specified in design
- materials are routed to specified locations in the earthfill
- frozen materials are not used in any earthfill or earth backfill
- moisture content of borrow materials is within the specified range or will be adjusted to comply with specification requirements before compaction
- significant changes in materials are promptly reported to the responsible engineer

(2) Rockfill

Rockfill will generally be natural materials that are hard, durable, and larger than gravel size. Rockfill may contain only trace amounts of sand or fine-grained soil materials; however, various amounts of sand and fine-grained materials may be allowed by some specifications. Riprap materials differ from rockfill in that they are generally clean materials of a specified gradation. Rockfill materials may be from a source on the construction site or from offsite sources. On some occasions, rockfill materials may be of less durable onsite materials that are more weathered, but are being used as a zoned fill for purposes of economy. These types of materials will breakdown during the processing and compaction, so close attention needs to be given to specified methods and field test results.

Borrow sources (onsite or offsite), gradation, quality of rockfill materials, processing, and compaction need to be clearly designated in the drawings and specifications.

With respect to rockfill materials, the inspector is responsible for verifying:

- only rockfill materials meeting the job specifications are approved for installation

(b) Foundation preparation

The purpose of careful foundation preparation for earthfill placement is two-fold. The first is to remove topsoil, loose materials, organic materials, standing water, or any unsuitable materials that would compromise the integrity of the contact area between the earthfill and the foundation. The second is to prepare the foundation to allow good bonding of materials at the contact area. The project specifications will provide the necessary details for preparing the foundation.

Prior to placing earthfill or rockfill, foundations should be prepared by removing vegetation and other unsuitable material or excavating as specified. Dewatering must be accomplished to facilitate placement, processing, and compaction.

Rockfill foundations must be cleaned in a similar fashion as for earthfill. Bonding at the contact area is not a concern as long as the contact is clean and moist. Some contouring may be called for with regard to overhangs and vertical surfaces.

Occasional rock outcrops in earth foundations for earthfill may require special treatment if they interfere with foundation preparation, the initial layers of the fill or the bond between the foundation and the fill. In dams and other structures designed to restrain the movement of water, special treatment of rock outcrops is generally required. Otherwise, occasional rock outcrops should not require special treatment.

For dams and other structures designed to impound water, it is important that the foundation be prepared to achieve a good bond with the earthfill to prevent a future seepage path or a slippage surface due to weak shear strength properties. Earth foundations should be compacted to the specified density with the soil at the specified moisture content. See Construction Specification 23—Earthfill, NEH 642. Rock foundations, in the same situation, must be clean, moist, and contoured to eliminate overhangs, vertical surfaces, and excessively steep surfaces. This treatment is well represented in NEH 645, chapter 7, section 645.0701.

Some foundation soils, when left exposed to the sun and wind for any length of time, will shrink and begin...
to crack. Careful inspection is needed to assure that these soils are removed and the surface reworked to restore a competent foundation.

Care must be exercised to prevent the placement of frozen materials or the placement of material on a frozen surface. When all foundation surfaces are approved as meeting the specifications, the fill operations can begin.

Abutment and sloping surfaces for both kinds of fill should be cleared of all loose material by hand or other effective means and should be free of standing water when fill is placed upon them. Foundation and abutment surface steepness should be as specified for the job. Fill material should not be placed until the specified foundation preparation has been approved.

For more on foundation preparation, see NEH 642.07, Excavation, Dewatering, and Foundation Preparation.

With respect to foundation preparation, the inspector is responsible for verifying that:

- the foundation is prepared as specified prior to any placement of materials
- surface and subsurface drainage features are in place to control water during earth or rockfill operations
- clearing and foundation preparation operations comply with safety standards

(c) Placement and processing

(1) Earthfill

During the placement of earthfill, the inspection of borrow materials coming to the work area is most important. The compaction of earthfill, which follows the placement process, is dependent on clean materials that will allow a consistent compactive effort to produce a uniformly dense material. Any material that interferes with this compaction process is detrimental to the operation. Debris; sticks; stones; roots and other organic material; soil that is too wet to compact; and frozen soil all interfere with this process.

Good earthfill placement and processing that results in fill meeting the quality defined by job specifications, requires the proper selection of borrow materials, the use of proper equipment, and a systematic routing of this same equipment. This scenario provides a repeatable process that will produce a consistent quality fill. Inspectors should understand this process and be alert to contractors taking shortcuts in any aspect of this sequence of operations.

It is important to determine if the contractor understands the selection of borrow materials and has the proper equipment to haul the fill to the work site and spread it in the required lift thicknesses. The placement of the earthfill to the required precompaction lift thickness is an important first step.

After initial placement and spreading, all roots, vegetative growth, oversize rocks, and other debris that may have been brought to the fill site from the designated borrow sources must be separated and removed to the specified waste areas. This may require a root rake or possibly handpicking.

Large, hard lumps or masses of soil must be pulverized by disking, harrowing, or other means. When water is added at the time of placement, it is essential that it becomes thoroughly and uniformly mixed into the entire lift. The disk or plow that is used to mix and incorporate water into the soil must be able to penetrate completely through the current lift and into the preceding (previously placed) lift as depicted in figure 8–1. This will promote good bonding to the lower lift. When disking is specified, if applicable, the disk must meet the size and type specified and be capable of pen-
etrating and mixing the full depth of the lift. When the disk or plow cannot penetrate completely through the current lift, the alternatives are to get a bigger, heavier disk or reduce the lift thickness until this requirement can be met with the equipment being used.

During construction of an embankment, the top surface must be maintained approximately level with just enough slope for the drainage. Unless otherwise specified, when building a dam embankment, this slope should drain upstream toward the sediment pool area. This procedure is designed to minimize erosion on the back slope and the resulting sedimentation that would be transported downstream.

(2) Earth backfill
Earth backfill refers to fill placed adjacent to structures or in confined spaces. This fill is placed in thinner lift thickness with more strict requirements for removal of oversize particles. The inspector should be well aware of the specification requirements for this operation. The height of the earth backfill adjacent to a structure should be maintained at approximately the same level on all sides of the structure. The idea is to prevent overloading of a structure and allow the structure to assume the loads from the earth backfill gradually and in a uniform manner. For more on earth backfill, see Construction Specification 23 – Earthfill, NEH 642.

For earthfill and earth backfill placement and processing, the inspector is responsible for verifying:

- earthfill zones are properly staked out
- earthfill is installed at locations designated on the drawings and specifications
- foundation and/or embankment surfaces are conditioned for bonding and comply with the specified grades and density
- oversize stones, roots, and debris are removed before compaction
- type of earthfill materials comply with specification requirements
- earthfill placed in an embankment has a top surface that is maintained approximately horizontal and properly sloped for drainage
- earthfill has been placed, moisture adjusted, and processed in a manner consistent with the job drawings and specifications
- frozen materials have not been placed nor have materials been placed on any frozen foundation or fill surface

(3) Rockfill
Rockfill needs to be staked out and placed in those zones or areas designated on the drawings.

The preferred method for rockfill placement is to dump on the surface of the layer being placed and then to spread to the desired thickness with a crawler tractor by pushing the material over the advancing faces of the layer. This procedure creates segregation with the larger rocks in the bottom of the lift and the smaller rock, spalls, and finer materials in the upper part. The main advantage of this technique derives from the relatively smooth upper surface resulting from pushing the dumped rock a short distance on top of each layer being placed such that depressions and voids between larger rocks become progressively filled with the smaller materials. This approach also facilitates maintaining the desired lift thickness because the dozer operator is always advancing the lift ahead upon the smooth surface at its proper elevation. The smooth layer also reduces tire wear, allows higher truck speeds, and provides a better surface upon which to operate the compaction equipment.

Lift thickness is generally controlled by the maximum size of the material that is being used for rockfill.

The inspector needs to make sure rock materials are of the size range anticipated in design. When this is not the case, the inspector needs to notify the responsible engineer and see that changes are made in the lift thickness to fit the size range of the rockfill.

With respect to rockfill placement, the inspector is responsible for verifying:

- rockfill zones or areas are properly staked out
- rockfill is installed at locations designated on the drawings and specifications
prescribed placement methods are followed to produce a competent rockfill

- lift thicknesses are appropriate for the material being placed

(d) Moisture control

Earthfill and earthen backfill

Compaction moisture is the water content of soil at the time of compaction. Its importance cannot be overstated. In 1933, R.R. Proctor, an engineer for the Bureau of Waterworks and Supply in Los Angeles, California, published four articles in the Engineering News Record describing how soil moisture is critical when compacting soils. Proctor said, “For a given energy, if a given soil is compacted at different water contents, the resulting dry density of the compacted soil will vary.” And he emphasized the importance of compaction moisture when he said “The effect of the moisture content of a soil upon the density to which it may be compacted is the most important principle of soil compaction.”

Proctor was a field engineer involved in the design and construction of earthen dams. He understood that geotechnical design of earthen structures relied on knowing the engineering properties of soil such as compressibility, shear strength, and permeability. But, since these engineering properties are contingent on compaction moisture and soil density, Proctor sought a way to relate laboratory compaction moisture and soil density to that of soil compacted in the field. His search lead him to determine that a standardized laboratory procedure was necessary for compacting soils at various compaction moisture contents, and his work lead to the development of what is commonly called the standard Proctor curve. Figure 8–2 illustrates Proctor’s principle and shows a typical standard Proctor curve.

The standard Proctor procedure is described in ASTM D698 and is commonly used worldwide. There is also a modified Proctor procedure (ASTM D1557) with a compactive effort approximately four times that of the standard Proctor effort, but it is rarely used for conservation engineering measures. Figure 8–3 shows the energy application (effort) for standard Proctor (ASTM D698) and modified Proctor (ASTM D1557). Subsequent information focuses on the standard Proctor method since it is the most commonly used.

As in Proctor’s time, geotechnical design of earthen structures requires engineering properties of soils be known for soils compacted:

- by a specific compaction effort
- at a specific moisture content
- to a specific density

Geotechnical design of earthen foundations and structures begins with soils sampled in the field being compacted in the laboratory by the procedure described in ASTM D698 or D1557. The soils’ optimum moisture and maximum density are determined from the resulting Proctor curve. The soils’ engineering properties can then be determined by testing the soil that has been compacted within a specific moisture range to some degree relative to maximum density. By specifying that the density of in-place soil be a value relative to maximum density, the earthen structure’s engineering properties should be similar to those considered by
the design engineer. This was Proctor’s goal when he sought a way to relate laboratory compaction moisture and soil density to that of soil compacted in the field.

In addition to density, compaction moisture must be specified and should be carefully controlled to gain efficient compaction and to meet the specification requirements. Compaction moisture not only affects the density to which it may be compacted, it also affects soil strength and permeability. Soil that is compacted at a moisture content that is below the optimum moisture content tends to be stronger but more permeable than if compacted at a moisture content above optimum. This is illustrated in figure 8–4 showing that soil particles tend to reorient themselves into a less permeable structure when compacted at a moisture content above optimum. The soil is also more flexible when compacted at a moisture content above optimum. For many conservation engineering measures, impermeability and flexibility are more desirable than high strengths. Thus, most NRCS specifications are written to specify compaction moisture above optimum. Conversely, for high fill structures or other structures and foundations requiring high soil strengths, compaction moisture below optimum is desirable.

Large increases in moisture content are best achieved by adding water in the borrow area. This is accomplished by irrigation and aided by the mixing that occurs when loading and transporting the material to the placement area.

![Figure 8–3](image-url) Standard and Modified Proctor efforts as specified in ASTM D698 (a) and ASTM D1557 (b)

(a) Standard Proctor effort as specified in ASTM D698
- 5.5-lb hammer
- dropped 12 in
- 3 lifts in 1/30 ft³ mold
- 25 blows per lift
Total energy is ≈12,400 ft-lb/ft³

(b) Modified Proctor effort as specified in ASTM D1557
- 10-lb hammer
- dropped 18 in
- 5 lifts in 1/30 ft³ mold, 25 blows per lift or
- 5 lifts in 1/13.33 ft³ mold, 56 blows per lift
Total energy is ≈56,000 ft-lb/ft³

![Figure 8–4](image-url) Compaction moisture's effect on soil strength and permeability

Water content (percent)
Reasonably small amounts of water can be added effectively on the fill and incorporated into the soil with the proper equipment and consistent processing. The size, weight, condition, and operating mode must be such that the equipment can efficiently and uniformly stir and mix the full lift depth of the soil that is being processed. One way to gauge the effectiveness of this equipment is by the ribbon test. Place a piece of survey ribbon on the ground where the soil is to be deposited; a piece approximately 10 feet long is sufficient. Place a small rock on each end to hold it in place. If the equipment for incorporating water is stirring and mixing the full depth of the lift, some of the survey ribbon will be brought to the surface. Otherwise, a change in equipment size, weight, condition, or mode or installing a thinner lift will be necessary.

Earthfill that is too wet must be dried out to the specified moisture content to assure success in attaining the desired density. Moisture can be removed on the fill area or in the borrow area and is best accomplished by diskng or plowing. Figure 8–5 can be used to estimate water needs for specified compaction.

With respect to moisture control, the inspector is responsible for verifying:

- foundation moisture is within the specified range
- compaction moisture is within the specified range throughout the full depth of the lift
- added water is properly incorporated into the earthfill to produce a uniform moisture content throughout the lift thickness

(2) Rockfill
Moisture content in rockfill is usually not critical. Minimal moisture content is sometimes specified.

Excessive moisture should be avoided as it may wet down adjacent earthfill and adversely affect the placement, processing, or compaction.

(e) Compaction

(1) Earthfill
When the proper preparation and processing has been completed, effective compaction can begin.

Compaction is the consolidation of the loosely placed and processed earthfill material. The objective is to reduce voids in the soil by removing air and water, thus making the mass denser. This process generally lowers the soil permeability and increases the strength properties. Compaction is achieved by mechanical means such as heavy equipment designed for compacting soil. Examples of equipment designed specifically for compaction are sheepfoot rollers, static or vibratory tamping foot rollers, static or vibratory smooth steel drum rollers, multitired pneumatic rollers, and grid rollers. Equipment such as bulldozers, loaded dump trucks, and loaded scrapers may be able to compact soils to the specified density but are generally not as efficient as specifically designed compaction equipment.

Compaction equipment must be capable of compacting the entire lift of earthfill to the minimum required density. The compaction equipment must be suited to the type of material being placed. The inspector should be familiar with the different kinds of compactors and the types of materials for which each is best suited. Table 8–2 and figure 8–6 provide guidance for judging compaction equipment suitability for various soils identified by the USCS.

If the compaction equipment is not able to compact the entire lift of soil to the specified density, it may be necessary to get heavier equipment, decrease the lift thickness, increase the number of passes of the equipment, verify that the correct compaction curve is being referenced, consider a different type of equipment, or check to make sure the moisture content is appropriate.

When earthfill or earth backfill is being compacted, it is important that the equipment establish a consistent pattern of travel to get complete coverage of the area being compacted. Additionally, implementing a consistent compaction process maximizes the probability that in-place testing of the earthfill will be representative of the entire area being compacted.

As with most specifications, there are two ways to specify compaction. One is to specify the compacted soil density meet or exceed a minimum density or fall within a specified range of values. Specifications written in this manner are called performance-based specifications, or performance specs. The other way compaction can be specified is by method specification, or method specs. In a method spec, the contractor must
Figure 8–5  Water requirements for compaction

This graph can be used to arrive at the gallons of water per cubic yard required to raise the moisture content of embankment materials to optimum moisture.

The density used in arriving at the water requirement should represent the density of the material at the time the water is added (in-bank density, loose density, or compacted density).

Example: Material has a moisture content of 14 percent. Optimum moisture content is 20 percent. Water is to be added to material on fill. Estimated density at time water is added is 100 lb/ft³. How much water will be required to raise moisture content to optimum?

From graph: 3.24 gal/yd³/1% increase in moisture content where density=100 lb/ft³

Water required: 3.24 \times (20-14) = 19.4\text{ gal/yd}^3
### Table 8–2 Compaction characteristics of soils

#### (a) Compaction characteristics of coarse-grained soils

<table>
<thead>
<tr>
<th>Unified class</th>
<th>Relative ease of compaction</th>
<th>Compacted lift thickness (in)</th>
<th>Importance of water content</th>
<th>Preferred type of equipment</th>
<th>Number of passes</th>
<th>Typical dry unit weights (PCF)</th>
<th>Typical water content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW</td>
<td>Very easy</td>
<td>10–12</td>
<td>Either dry or saturated</td>
<td>Crawler tractor vibratory roller</td>
<td>3–4</td>
<td>125–135</td>
<td>9–12</td>
</tr>
<tr>
<td>GP</td>
<td>Good to excellent</td>
<td>10–12</td>
<td>Either dry or saturated</td>
<td>Crawler tractor vibratory roller</td>
<td>3–4</td>
<td>115–125</td>
<td>12–16</td>
</tr>
<tr>
<td>GM</td>
<td>Good with close control</td>
<td>6–8</td>
<td>Fairly important</td>
<td>Rubber-tired or tramping roller</td>
<td>3–5</td>
<td>120–135</td>
<td>6–13</td>
</tr>
<tr>
<td>GC</td>
<td>Good</td>
<td>6</td>
<td>Very important</td>
<td>Rubber-tired or tramping roller</td>
<td>6–8</td>
<td>115–130</td>
<td>9–14</td>
</tr>
<tr>
<td>SW</td>
<td>Excellent</td>
<td>10–12</td>
<td>Either dry or saturated</td>
<td>Crawler tractor vibratory roller</td>
<td>3–4</td>
<td>110–130</td>
<td>10–16</td>
</tr>
<tr>
<td>SP</td>
<td>Fair</td>
<td>10–12</td>
<td>Either dry or saturated</td>
<td>Crawler tractor vibratory roller</td>
<td>3–4</td>
<td>100–120</td>
<td>13–22</td>
</tr>
<tr>
<td>SM</td>
<td>Fair</td>
<td>6–6</td>
<td>Important</td>
<td>Rubber-tired or tramping roller</td>
<td>6–8</td>
<td>110–125</td>
<td>10–16</td>
</tr>
<tr>
<td>SC</td>
<td>Good</td>
<td>6</td>
<td>Very important</td>
<td>Rubber-tired or tramping roller</td>
<td>4–6</td>
<td>105–125</td>
<td>10–18</td>
</tr>
</tbody>
</table>

#### (b) Fine-grained and highly organic soils

<table>
<thead>
<tr>
<th>Unified class</th>
<th>Relative ease of compaction</th>
<th>Compacted lift thickness (in)</th>
<th>Importance of water content</th>
<th>Preferred type of equipment</th>
<th>Number of passes</th>
<th>Typical dry unit weights (PCF)</th>
<th>Typical water content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML</td>
<td>Fair</td>
<td>6</td>
<td>Important</td>
<td>Tamping Roller</td>
<td>4–6</td>
<td>95–120</td>
<td>12–22</td>
</tr>
<tr>
<td>CL</td>
<td>Good to fair</td>
<td>6</td>
<td>Very Important</td>
<td>Tamping Roller</td>
<td>4–6</td>
<td>95–120</td>
<td>12–22</td>
</tr>
<tr>
<td>MH</td>
<td>Poor</td>
<td>6</td>
<td>Very important</td>
<td>Tamping Roller</td>
<td>4–6</td>
<td>70–95</td>
<td>22–40</td>
</tr>
<tr>
<td>CH</td>
<td>Very Poor</td>
<td>6</td>
<td>Critical</td>
<td>Tamping Roller</td>
<td>4–6</td>
<td>75–105</td>
<td>20–40</td>
</tr>
<tr>
<td>OL</td>
<td>Fair</td>
<td>6</td>
<td>Important</td>
<td>Tamping Roller</td>
<td>4–6</td>
<td>80–100</td>
<td>20–32</td>
</tr>
<tr>
<td>OH</td>
<td>Very Poor</td>
<td>6</td>
<td>Important</td>
<td>Tamping Roller</td>
<td>4–6</td>
<td>65–100</td>
<td>20–32</td>
</tr>
<tr>
<td>Pt</td>
<td>Not Suitable</td>
<td></td>
<td>Not suitable for most fills - usually placed with draglines and little compaction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) Compaction characteristics of coarse-grained soils

Not Suitable

Not suitable for most fills - usually placed with draglines and little compaction
use equipment that meets some specified criteria and must traverse the area with this equipment a specified minimum number of passes. When performance specs are used, the inspector must verify that the required density and water content results are achieved by the compaction process. When compaction is performed by a method spec, the inspector must document that the equipment and number of passes complies with the spec and the moisture content at the time of compaction is within the specified range. Regardless of how the work is specified (performance or method spec), careful attention needs to be paid to verifying complete coverage over the entire area requiring compaction. Areas that are confined or otherwise difficult for the equipment to cover must be given special attention. Abutment interfaces or ties into existing earthfill slopes are examples of areas to be given special attention. Different, more maneuverable equipment may be called for, or in some cases, thinner lifts and hand compaction methods employed.

After a temporary or seasonal shutdown of an earthfill operation, the water content and density of the surface of the unfinished earthfill must be checked for compliance with the job specifications. It may be necessary to recondition or remove and replace this material before resuming operations.

There are three classes of earthfill defined in NEH 642 Construction Specification 23: Class A—compaction to a specified density for each borrow material used, Class B—a given mass density for all the material (generally only used on rocky materials that vary considerably in the amount of rock in the soil matrix), and Class C—compaction by a prescribed method. Class B compaction is rarely used. Class A compaction

---

**Figure 8–6** Selection of compactor type

<table>
<thead>
<tr>
<th>Compactor zones of application</th>
<th>Compactive method</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% Clay Sheepsfoot</td>
<td>Static weight, kneading</td>
</tr>
<tr>
<td>100% Silt Grid</td>
<td>Static weight, kneading</td>
</tr>
<tr>
<td>100% Sand Smooth steel drums</td>
<td>Static weight, vibration</td>
</tr>
<tr>
<td></td>
<td>Static weight</td>
</tr>
<tr>
<td>Multitired pneumatic</td>
<td>Static weight, kneading</td>
</tr>
<tr>
<td>Heavy pneumatic</td>
<td>Static weight, kneading</td>
</tr>
<tr>
<td>Vibratory tamping foot</td>
<td>Static weight, kneading</td>
</tr>
<tr>
<td>Towed tamping foot</td>
<td>Static weight, kneading</td>
</tr>
<tr>
<td>High speed tamping foot</td>
<td>Static weight, kneading, impact, vibration</td>
</tr>
<tr>
<td>Tamping foot</td>
<td>Static weight, kneading, impact, vibration</td>
</tr>
<tr>
<td>Tamping foot</td>
<td>Static weight, kneading, impact, vibration</td>
</tr>
</tbody>
</table>
is used extensively where a quality earthfill is required and testing for field control will be carried out. Class C compaction is used where compaction may not be critical, materials are difficult to define, and/or testing capabilities for field control are not available. Table 8–3 provides a summary of these compaction classes.

The inspector’s responsibilities related to compaction of earthfill, include verifying:

- appropriate compaction equipment is being used properly to compact earthfill and earth backfill
- compaction equipment is being controlled to provide a systematic and complete coverage of entire area requiring compaction
- for classes A and B compaction, the specified density is attained throughout the full depth of each lift of earthfill
- for class C compaction, the prescribed equipment and method are being consistently applied
- for zoned embankments, all zones are located and configured as specified or as shown on the drawings

Table 8–3  Summary of compaction classes defined in NEH 642, Construction Specification 23

<table>
<thead>
<tr>
<th>Compaction class</th>
<th>Type specification</th>
<th>Items specified</th>
<th>Advantage/disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Performance</td>
<td>Density test method and required percent of maximum density</td>
<td>Provides a way to verify the earthfill density meets or exceeds the minimum specified density which has been deemed necessary for the earthfill to function as designed. Requires inspector to employ testing equipment and match the soil to a Proctor curve developed by the inspector or by a lab. Works best for soil containing no rocks or gravel or for soil containing uniformly distributed gravel.</td>
</tr>
<tr>
<td>B</td>
<td>Performance</td>
<td>Required minimum mass density</td>
<td>Like Class A, provides a way to verify the earthfill density meets or exceeds the minimum specified density. Unlike Class A, works for soil containing rocks and gravel including nonuniform amounts of rock or gravel. Requires large equipment and several man-hours to conduct one test. Rarely specified.</td>
</tr>
<tr>
<td>C</td>
<td>Method</td>
<td>Type of equipment including weight and contact pressure, minimum vibrating force and frequency for vibrating equipment, and minimum number of passes</td>
<td>Requires no density testing, but requires constant surveillance by the inspector to verify the specified method is employed over the entire area. Used where compaction may not be critical, materials are difficult to define, and/or testing capabilities for field control are not available.</td>
</tr>
</tbody>
</table>

(2) Earth backfill
Earth backfill is earthfill placed in confined spaces such as trenches, around concrete structures, and around pipelines. Earth backfill adjacent to structures or in confined spaces, is compacted by manually directed equipment. Manually directed power tampers employ a foot of various shapes and sizes that jump up and down to impact the soil and work best on finer grained materials that have plasticity. Manually directed plate vibrators sit on the surface and compact by static weight and vibration; they are most effective on coarse-grained nonplastic materials.

Two markedly different types of materials and corresponding installation operations are associated with earth backfill. One type of backfill materials can be categorized as plastic soils; the other type is sands and gravels. Since the compaction characteristics of plastic soils differ from those of sands and gravels, each type is described separately.

Plastic backfill material is normally compacted by tamping rollers when space is available or by hand-controlled power tampers in confined areas. Tamping rollers must proceed with caution when operating near pipes and concrete structures to avoid damage.
to these structures. It is common to specify plastic backfill materials be compacted to a density that is equal to or greater than the surrounding earthfill. Or, specifications may require the earth backfill be compacted to a minimum density that is some percentage of standard Proctor maximum density. For example, the specification may read “compact to 95 percent of standard Proctor maximum density as determined by ASTM D698.” Earth backfill compaction moisture is typically specified as minus 1 percent to plus 2 percent of optimum moisture. Compacted cohesive backfill is generally placed in 6-inch layers prior to compaction. Backfill composed of plastic materials must be protected from drying and cracking until covered by permanent cover.

Consolidation of granular materials is accomplished by pneumatic rollers, tractors, and surface vibrators or internal vibrators. Manually directed vibratory rollers or plate vibrators are generally used for backfill. Moisture control is not needed for gravels. Sands are generally compacted dry or thoroughly wetted because they are difficult to compact if the moisture content is within a range which causes bulking. This moisture range varies depending on the soil, but for clean sands the bulking moisture range is generally between 2 and 8 percent. One method of compacting clean sand is to flood and drain it. The flooding breaks the sand particle bonds that occur from bulking moisture and the movement of water through the sand matrix causes the particles to settle into a denser configuration. Additional movement caused by mechanical vibration can make the particles settle even more.

When cohesionless, free-draining materials are placed as compacted backfill, the density requirement is specified as a percentage of sand relative density or as a percentage of the one-point Standard Proctor maximum density. As an alternative, a method specification may be employed. Regardless of how compaction is specified, sand is best compacted by flooding and applying some vibratory compaction as the material is draining. The uncompacted lift thickness is generally specified to be a maximum of 12 inches and limited to 8 inches when only manually directed compaction effort is applied. Gravels can be placed in thicker layers, require no moisture control, and may require little compactive effort beyond that incidental to placement. For more on the installation of free-draining materials, see Chapter 11, Drains and Filters, of this handbook.

When placing backfill against a pipe and some small structures, the level of backfill on each side of the pipe or structure should be about the same so as not to displace or damage the pipe. It may also be important to guard against overcompaction near pipes or other structures to avoid similar displacement and damage.

The inspector’s responsibilities related to compaction of earth backfill include, verifying:

- the material and particle size for backfill meet the specification requirements
- the appropriate compaction requirements are met for the material involved
- the finished backfill is appropriately protected from drying and cracking until permanent cover is placed
- backfill is not overcompacted

(3) Rockfill

Rockfill, once placed in the required lift thickness, is best compacted by heavy vibratory compaction equipment. Heavy vibratory steel-wheeled rollers can be very effective. Heavy bulldozers working to spread rockfill may provide adequate compaction on some smaller sized materials.

Weathered rock that is inclined to break down and produce smaller material, including soil, may best be compacted with a tamping roller. A grid roller is also useful on this type material.

Rockfill compaction is specified by method of compaction, rather than a performance specification. Inspectors must know what method is specified and plan how best to verify specification compliance. There are three classes of compaction listed in CS 25—Rockfill: classes I, II, and III. These classes of compaction range from the most dynamic method to the least dynamic method. They produce the densest result to the least dense result respectively.

When a bedding layer is used under the rockfill or a transition zone is called for adjacent to the rockfill, the proper compaction of these materials is important. Bedding will obviously be placed and compacted prior to rockfill. Transition zones may be placed and compacted before or after depending on whether the transition zone is below or above the rockfill. The
inspector must verify that the zones are located and configured as specified or as shown on the drawings.

The inspector's responsibilities related to compaction of rockfill include verifying:

- the specified equipment is used and specified method of compaction is strictly followed
- compaction equipment is in good condition and being operated properly
- the proper sequence of placing and compaction of transition zones is implemented
- all zones are located and configured as specified or as shown on the drawings

### 645.0802 Sampling and testing

When specified, in-place testing for moisture and density of compacted earthfill must be carried out to verify compliance with contract specification requirements. This testing is a significant part of contractor quality control and NRCS quality assurance inspection. In-place testing involves the following steps:

**Step 1:** Determine the frequency of testing.
**Step 2:** Determine the test location.
**Step 3:** Obtain the sample.
**Step 4:** Perform the specified test.
**Step 5:** Evaluate the test results.
**Step 6:** Record the test results.
**Step 7:** Assess the need for additional testing.

There may also be action required to correct noncompliant work identified from negative results.

**(a) Determining frequency of testing**

The Quality Assurance Plan (QAP) for any earthwork job should specify a minimum frequency of compliance testing to be performed by the Quality Assurance Inspector (QA). Frequency of inspection required of Contractor Quality Control (CQC) is specified in CS 94, Contractor Quality Control. The actual field testing frequency necessary to provide verification of specification compliance, can only be determined on the job during the performance of the work.

In general, more field compliance testing is needed early in an earthwork construction job rather than later. Later in the job, the contractor has usually developed a process that consistently gets the specified results. CS 94 may require the CQC to make in-place tests for density/moisture on the order of one test for every 1,000 cubic yards of compacted earthfill. It may take the contractor several days to get the process going, and to get production up to 1,000 cubic yards per day. In this situation, the CQC should take at least one test each day, and the QA should verify the CQC testing at least once per day. This same scenario could happen when new borrow material is beginning to be
placed or a new zone of fill is established. The frequency of QC testing should be whatever is necessary for the contractor to verify that the earthfill process is achieving the specified density/moisture results.

When the contractor is satisfied, the QA should verify the CQC results. Once a reliable earthfill process has been established and consistent density/moisture results are being obtained, the frequency of testing and verification of these results can be reduced. Thus, the higher frequency of testing is needed to establish a reliable process, and a lower frequency needed for verifying and documenting compliance thereafter. Where CQC testing is not specified the entire above scenario falls on the QA.

More frequent in-place testing is required in areas where a consistent earthfill process cannot be established (i.e., areas susceptible of poor compaction effort). This occurs where earthfill or earth backfill is to be placed in confined or limited access areas where equipment and traffic patterns are limited. Such areas include those adjacent to structures or against steep foundations like the abutment of a dam. The inspector must be aware of areas that are susceptible to poor compaction effort. Since placing, processing, and compaction of earthfill in these areas are generally accomplished in a variety of ways, it is not possible to rely on an established method to achieve specified results. In these cases, more frequent testing is the only way to check compliance to specification requirements.

### (b) Testing location

Selecting the location of a test is based on two areas of concern. The first is a random test of the recently placed and compacted material. This test needs to be representative of all the material in that section or area. The second is testing specific areas of concern. This may be a soft area, an overly compacted area, or areas susceptible of poor compaction effort. Both kinds of testing are needed to adequately document the quality of the in-place fill.

Additionally, it is important to verify that the moisture and density at the test location is representative of the earthfill in the specific lift being tested. Close observation is needed to verify the consistency of processing and compaction of the lift. If there is an observed difference in the processing and compaction effort, the testing should be located in the weaker section identified. The elevation of the compacted lift surface and the actual elevation of the test location must be recorded if the test is documented. The horizontal location is usually referenced as an offset distance from a centerline or by rectangular coordinates.

### (c) Sampling

Sampling and maintaining the integrity of the sample are critical steps in the testing process. All of the in-place density methods, with the exception of the nuclear method, take a soil sample from the test area. The purpose of this removed soil sample is to provide a weight and volume determination needed to compute a density value and provide a portion of the sampled soil for the determination of water content. Until these determinations can be made, the sampled soil needs to be protected from moisture loss by being placed in a plastic storage bag or an air-tight container. Sampling requirements are typically specified in all ASTM test standards. Sampling according to the specification is required for the test to be valid. When sampling is required to conduct a test (generally required except for when the nuclear gauge is employed), consider sampling the most critical part of the test method.

### (d) Testing

The required test methods will be spelled out in performance specifications where the specifications call for end result testing of in-place earthfill. Construction Specification 23, Earthfill (NEH 642), contains two classes of compaction that fit this category, classes A and B.

The inspector needs to have an operational knowledge of each standard test method. For soil in-place density, the following test methods apply: sand-cone method, ASTM D1556; rubber balloon method, ASTM D2167; drive cylinder method, ASTM D2937; and nuclear method, ASTM D6938. There are other methods, but these are the most commonly used in NRCS field work.

For water content testing the following tests apply: oven dry method, ASTM D2216; microwave oven method, ASTM D4643; direct heating method, ASTM
D4959; calcium carbide gas pressure (Speedy Moisture Tester) method, ASTM D4944; and nuclear method, ASTM D6938. These are the primary methods used for NRCS field work. Moisture content testing yields a value used to convert wet density to dry density. Moisture content testing is also needed to verify that compaction moisture is within the specified range. Other important uses are to assess the water content of borrow materials and monitor drying efforts for fill materials that are too wet for compaction.

The ASTM methods are well written and generally easy to follow once the format becomes familiar. There are some significant precautions that should be emphasized for most methods. They are briefly summarized below.

(1) Density testing

- **Sand cone method, ASTM D1556**—While a long-time proven method, this method requires excellent technique. The procedure for this test involves determining the volume of excavated soil from a hole in the compacted earthfill. The excavation is carried out through a base plate that is secured to the prepared soil surface prior to any digging.

  Free-flowing sand of known unit weight is then poured into the hole from a jug and a calibrated cone (fig. 8–7). The volume of the hole is determined from this operation. Knowing the volume, the density of the soil in-place can then be determined by the weight of the soil removed and saved from the excavation. This saved soil is then used to determine the in-place water content of the test material. Care must be taken to place all of the soil being excavated from the hole in a suitable container to protect it from losing moisture prior to performing the density and water content determinations.

  The sand calibration required to determine the unit weight of the sand must be accurate and performed frequently. Temperature and relative humidity variations affect these calibrated values. Proper storage and protection of calibrated sand will greatly reduce this vulnerability. ASTM D1556 has a specific sand gradation requirement, but NRCS experience has shown a need for even tighter control on the sand. The NRCS recommends using Ottawa Sand as described in ASTM C778. ASTM D1556 covers this calibration procedure and all calculations in detail.

  This test is appropriate for all fine-grained soils from the USCS (CL, ML, CH, MH), sands with fines (SM, SC), and gravels with fines (GM, GC) with particles less than 1.5-inch diameter.

  The test is generally not suitable for noncohesive soils or soft saturated soils because it is difficult to maintain a stable hole in these soils while performing the test.

  A primary advantage of this test method is the opportunity to visually observe the in-place soil material as it is excavated out of the hole. This observation should be helpful in identifying borrow materials and evaluating the processing of the fill materials. Identifying borrow materials is important for determining the standard reference curve to be used for evaluating the density test results.

  As mentioned earlier, excellent technique is critical for obtaining good test results. There are some cautions that deserve mention as they are common causes of errors. The operator is...
cautioned to ensure the hole from which the soil sample is obtained does not deform when running the sand cone test. Placing a knee near the hole may deform the hole thereby reducing the volume of the hole and causing the reported density values to be erroneously high. Also, vibrations might occur from heavy equipment operating near the test site causing an increase in sand density, which would cause reported density values to be erroneously low.

Appendix B contains worksheet WS 8.8 to aid in the performance of the sand cone moisture-density determination.

- **Rubber balloon method, ASTM D2167**—Not a widely used method, but it will return good results when the equipment is in good shape and used properly. The purpose of this test is to determine the volume of an excavated hole in the compacted earthfill. The hole is excavated through a plate attached to the leveled ground surface. The excavated soil is saved and weighed for the density calculation and later used for the water content determination. The volume is determined by measuring the volume of the water that is needed to fill up a rubber balloon as the balloon expands through the plate and into the hole to the boundaries of the hole. A graduated glass cylinder measures the water required to fill the balloon in the hole (fig. 8–8). ASTM D2167 contains the details on this procedure and the calculations required.

This test is appropriate for cohesive fine-grained soils (CL, ML, CH, MH) and dirty sands and gravels (SM, SC, GM, GC) with less than 5 percent oversize (i.e., no more than three-fourths inch). It is not practical to use this test method on soils having particles larger than three-fourths inch, due to irregularities in the excavated hole the balloon cannot accurately measure. This test is generally not suitable for noncohesive soils or soft saturated soils as it is difficult to maintain a stable hole in these soils while performing the required test.

Be sure to have extra balloons, and be careful with the glass cylinder. As with most tests, it is important to protect the material excavated from the hole from loss of moisture by putting it in...
an airtight container until the density and water content determinations are made.

Similar to the sand cone method, excavating the hole in the in-place soil can be helpful for making judgments about borrow materials. The hole will be smaller than that excavated for the sand cone, so problems may be less obvious. If a larger hole is needed to make these judgments, the inspector may need to dig a larger hole after the test is conducted.

Appendix B contains worksheet WS 8.9 to aid in the performance of the rubber balloon moisture-density determination.

- **Drive cylinder method, ASTM D2937**—A simple and accurate method, this test is accomplished by driving a thin-walled metal cylinder of known volume into the prepared surface of the compacted soil using a drop hammer. Figure 8–9 shows the cylinder and drop hammer. The cylinder is then extracted from the soil by digging it out, and the sample is trimmed to determine the volume of soil in the cylinder. The weight of the soil in the cylinder then allows the determination of the density of the test sample. Soil removed from the cylinder is used to determine the water content of the test sample. While the density is determined with the soil still in the cylinder, the soil must be removed and protected prior to determining the water content. All test details and required calculations are covered in ASTM D2937.

  This method is appropriate for all fine-grained cohesive soils, but will not work for cohesionless soils. It also has limited use in gravelly soils due to the likelihood of deformations and voids along the sides of the cylinder caused by the coarse material as the cylinder is being driven in the ground.

  This method also provides a visual observation of the in-place material that can be used to evaluate borrow materials and mixing consistency. The cylinder must be driven into the soil deep enough to get a complete sample. The ensuing excavation of the cylinder must extend below the bottom of the cylinder to allow removal without damaging the captured soil sample in the cylinder. The test method may be both laborious and tricky in some soils.
Appendix B contains worksheet WS 8.10 to aid in the performance of the drive-cylinder moisture-density determination.

- **Nuclear method, ASTM D6938**—Although this method is the fastest and easiest to use, it requires certification training for safe use, safe transportation, and operation of the nuclear device. Also, regulations require periodic inspections and calibration of the equipment, and equipment storage is strictly regulated. States that have nuclear gauges have an annual license expense and expenditures related to employees’ training and licensure; however, if a State does a lot of moisture and density testing of earthfill, these items associated with owning and operating the equipment have proven to be well worth the required time and cost.

The nuclear gauge can be used to determine the in-place density and water content of most soil/aggregate mixtures used in earthfills and structural backfill. The wet density is determined by gamma rays either in a backscatter mode from the surface or by a direct transmission mode from the tip of a probe inserted into the material being tested. The direct transmission mode measures an average density from the depth at which the source rod is positioned back to the detectors located in the base of the gauge. The direct transmission mode is generally more accurate and reliable than the backscatter mode and preferred by most users.

The water content is determined by a second source that emits neutrons in a backscatter mode and provides a measurement that is biased toward the surface. If the soil moisture content is uniform throughout the soil profile, this measurement will not present a problem. If the moisture in the soil profile is variable, the value determined may not accurately represent the moisture content over the full depth of the density measurement.

Water content values obtained by the nuclear gauge may be misleading in some soils. The gauge actually reports hydrogen ions in the soil. If the only hydrogen ions present are in the soil moisture, the measurement will be quite accurate. When other sources of hydrogen are in the soil, the moisture reading will be erroneously high making it necessary to calibrate the gauge to provide a true moisture value. Although rare, there are some soils that absorb neutrons and cause the reading to be low. Either way, a calibration is usually required.

Since the nuclear gauge measures only wet density and moisture, it must compute the dry density. If the moisture measurement is erroneously high, the computed dry density will be low. Some QC inspectors claim that by not calibrating the gauge, the resulting dry density value will be lower than the specified minimum and, thus, be conservative. However, there may be concerns with overcompaction that would not be addressed if the true value of density is not known and; therefore, verifying that compaction moisture is within the specified range is important. Thus it is essential to have water content calibration corrections, especially for most fine-grained soils, as these generally contain no moisture related hydrogen or contain elements that can absorb neutrons.

The procedures and precautions for this test method are covered in detail in ASTM D6938.

Appendix B contains worksheet WS 8.11 to aid in the performance of the nuclear gauge moisture-density determination.

(2) **Water content testing**
In all methods used for water content testing, it is extremely important to protect the soil materials during sampling and transporting so that they do not dry out prior to determining the water content.

- **Oven dry method, ASTM D2216**—This test method is the standard to which all other tests are calibrated and compared. The main drawback is the test takes 24 hours to get a result.

- **Microwave oven method, ASTM D4643**—Still not quite “the oven” method, but reliable. A less expensive and readily available piece of equipment makes this method more adaptable to field work.

- **Direct heating method, ASTM D4959**—Simple equipment and field oriented. Watch out for burning off organic material, which will yield an incorrect higher water content value.

- **Speedy moisture tester, ASTM D4944**—Handy and portable for field work. Needs cali-
ibration and has a sample size limitation. Less accurate with the more plastic fine-grained soils of higher water content.

• **Nuclear method, ASTM D6938**—It is essential with this method to have good water content calibration for each soil type involved in field testing. Water content generally reads high, especially for fine-grained soils, and only rarely low with this test method. The other limitation, previously addressed, is that the water content is always determined in a backscatter mode and is biased to the surface and, thus, may not be truly representative throughout the density sample range.

It is important for the inspector to have ready access to the applicable current ASTM Standard specified for a given job. Onsite test results are only meaningful and valid when they are performed in accordance with the appropriate ASTM Standard.

(3) **Correction for oversize particles**
When performing in-place moisture or density tests on soils containing gravel, a correction for oversize particles may be necessary. Oversize particles are particles that are larger than the maximum size particle in the soil that was used to develop the Proctor curve. For example, if the Proctor curve was made according to ASTM D698 Method A, the curve represents a soil with a maximum particle size no greater than the No. 4 sieve size (3/16 inch). Thus, if the field compacted soil contains a significant amount of oversize particles (an amount greater than five (5) percent of the mass of the soil is generally considered significant), a correction for oversize particles must be made so that the measured field density and moisture values can be compared to the Proctor curve values for moisture and density.

Note that the sand cone, rubber balloon, and nuclear gauge methods may be used for testing soils with oversize particles, but the drive cylinder is not used for soils containing gravels.

The procedure described in ASTM D4718 Standard Practice for Correction of Unit Weight and Water Content for Soils Containing Oversize Particles should be employed whenever there are significant amounts of oversize particles in soil that is being tested for moisture or density. Worksheet WS 8.13 in appendix B can be used in conjunction with D4718 to make the correction.

The inspector’s responsibilities related to test location, sampling, and testing include verifying:

• selected in-place testing locations are truly representative of the section or area being evaluated
• areas that have suspect compaction effort or may be too dry or too wet are tested
• soil materials from the testing and sampling process are properly protected to retain their integrity until the required determinations are completed
• any test selected from those specified is performed in strict accordance with the specified test standard and is appropriate for the soils being tested
• a moisture and density correction is made according to ASTM D4718 whenever the soil being tested contains significant amounts of oversize particles
• test location and results are promptly recorded

(e) **Evaluating test results**

The evaluation of compaction and moisture test results includes selecting the Proctor curve that best fits the tested soil and making sure the test results are reasonable. Begin by choosing a Proctor curve.

**Choosing a Proctor curve**—A field density and water content determination is compared to the chosen Proctor curve that has been developed for the soil being compacted. Historically, Proctor curves for NRCS projects were developed in a laboratory from soils that were sampled during the geologic investigation that preceded the design. The curves were available to CQC and QA who would be tasked with determining which curves fit the various soils being used for the earthfill. CQC and QA developed additional Proctor curves during the course of the job if those supplied by the lab did not represent all of the soils or *composite soils* being used for earthfill or earth backfill. The greatest source for error in evaluating field test results for compaction was likely in determining which curves fit the various soils being used to construct the earthfill.
To determine which Proctor curve fits the soil being tested, the inspector must be able to field classify the soils by the method described in ASTM D2488 for field classifying soils according to the USCS. Many soils can be reliably matched with their corresponding Proctor curve by field classification and visual appearance. Three methods have generally been used for verifying which Proctor curve should be used to evaluate the field compaction test values. These methods—the jar, one-point, and the family of curves/one-point—are described.

(1) Jar method
The jar method is a simple visual method and is most applicable when only a few different soils having distinct visual appearances are involved. Samples of soils used to develop the Proctor curves are obtained from the laboratory and placed in jars that are labeled with the corresponding Proctor curve designation. Soil being tested for in-place density and water content can then be compared to the jar samples to select the Proctor curve that best matches the soil being tested.

(2) One-point method
The one-point method is used to verify that a Proctor curve matches the soil being tested. The soil being tested is compacted according to ASTM D698 or D1557, as applicable, at a moisture content judged to be about 2 percent dry of optimum. The results are then plotted on the same sheet as the Proctor curve, and the plotted point will fall on the Proctor curve if the curve and soil match. The best match becomes the Proctor curve that will be used for comparison to the field test results if the results do indeed plot on or very near the Proctor curve.

(3) Family of curves/one-point method
The jar and one-point methods work well if the soils that are being placed and compacted correspond to the available Proctor curves. However, most earthfills are constructed from a mixture of soils that have different compaction characteristics than the individual soils making up the mixture. These soil mixtures vary in field classification and visual appearance, and these variations make it difficult to identify which Proctor curve best matches the soil. The family of curves/one-point method can be utilized to fill in some of the gaps between existing compaction curves. This method is used by many of the State highway departments across the country, and there is an American Association of State Highway Transportation Officials standard, AASHTO T 272, “Standard Method of Test for Family of Curves-One Point Method,” that covers this method.

A family of curves can be developed specifically for each job by plotting all of the Proctor curves available for the job on the same sheet. A smooth curved line is then drawn to best-fit the apex of each curve. The Proctor curves are then moved to the left or right to align with this best-fit curved line. Any curve that has to be moved so much that its moisture content values change more than 2 percent should not be included in the family of curves. If large gaps exist between the remaining plotted curves, additional curves may be needed to make use of the family of curves. See the family of curves in figure 8–10.

After the family of curves is developed, the results of a one-point test made from any site-specific soil can be plotted on the family of curves sheet. If the point falls on one of the curves, that curve is selected to represent the soil being compacted and tested in the field. If the point falls between two curves and these curves are fairly close together, a new Proctor curve can be free-hand drawn to pass through the plotted point and the best-fit curved line. The shape of the free-hand curve should follow that of the nearest existing curves. This free-hand curve becomes the Proctor curve that will be used for comparison to the field test results of the soil being compacted and tested in the field. The dotted line in figure 8–10 is intended to depict a free-hand curve.

Departments of Transportation (DOT) in several States have developed a family of curves from Proctor curves in their States. These curves have been successfully used in other areas outside the State where they were developed. If one of these DOT family of curves is to be used on any job, especially on a job located outside of the state where it was developed, its applicability to the soils on the jobsite should be verified. This can be done by plotting a few site-specific Proctor curves on the same sheet as the DOT family of curves to see if they align with the family of curves. Alignment would verify that the DOT family of curves applies to these site-specific soils and very likely would apply to other soils on the site.

Make sure test results are reasonable—Both the ASTM D698 and D1557 standards require a zero air voids (ZAV) curve be plotted on the same sheet as the Proctor curve. The ZAV curve will always plot on
the wet side or to the right of the Proctor curve. Since the absolute maximum density of any soil at a specific moisture content is attained when all of the air voids are filled with water, the ZAV curve represents the maximum density of the soil at various water contents.

Figure 8–11 shows a ZAV curve (100% saturation line) plotted with the Proctor curve. If the corresponding test results of field density and water content were plotted on this same sheet, the point will plot to the left of the ZAV curve. If it plots to the right of the ZAV curve, something is wrong, since water content cannot increase once the soil is saturated.

Furthermore, compacting soil to 100 percent saturation, although not impossible, is very unlikely to occur with conventional compaction equipment. Generally, soils are compacted to a density that falls within the 70 to 90 percent saturation range. It is good practice to plot a 70 percent ZAV curve and a 90 percent ZAV curve along with the Proctor curve and ZAV curve. Field test results can then be plotted on the same sheet to quickly determine if they fall within the reasonable range of 70 to 90 percent saturation. Any field test results that fall outside of this range are suspect and should be evaluated further. If results plot outside of the 70 to 90 percent saturation range, there is a high probability that either the Proctor curve does not correspond to the tested soil or there was an error made when performing the test or recording test results.

ASTM D698 and D1557 include the formula for computing the ZAV curve. The specific gravity of the soil must be known to compute the ZAV curve. The formula is:

$$w_{(\text{max})} = \left[\frac{62.4}{\gamma_{\text{dry}}} - \frac{1}{G_s}\right] \times 100$$

where:
- $w_{(\text{max})}$ = the maximum water content at a given dry density in percent
- $\gamma_{\text{dry}}$ = dry density in lb/ft³
- $G_s$ = the specific gravity of the soil
Figure 8–11 Proctor and ZAV curves

The 70 percent and 90 percent ZAV curves are computed by the following formulas, which are the same formula multiplied by 0.7 and 0.9.

\[ w_{(70\%)} = \left( \frac{62.4}{\gamma_{dry}} - \frac{1}{G_s} \right) \times 70 \]

\[ w_{(90\%)} = \left( \frac{62.4}{\gamma_{dry}} - \frac{1}{G_s} \right) \times 90 \]

where:

- \( w_{(70\%)} \) = 70 percent of maximum water content at a given dry density
- \( w_{(90\%)} \) = 90 percent of maximum water content at a given dry density

These curves and the ZAV curve for a specific soil are shown in figure 8–12. Note that there are several points plotted along with the curves. These points were plotted from actual test results obtained by testing the compacted soil in the field. If the specific

Figure 8–12 70% ZAV curve, 90% ZAV curve, and ZAV curve
The designer specifies the tests for determining the in-place water content and density of earthfill materials. The water content is specified as a range above and/or below optimum water content. The density is specified as a percentage of the maximum dry density. An example of an earthfill specification might look like this: “the earthfill is to be compacted to 95 percent of maximum dry density as defined in ASTM D698. The water content at the time of compaction shall range from –1 to +2 percent of the optimum water content as defined in ATSM D698.” The inspector is responsible for verifying and documenting that the in-place processed and compacted soil complies with specifications such as these, but this is only a part of the inspector’s responsibilities. The other part is to verify that the results represent the soil throughout the lift that is being compacted and that enough test results are evaluated to verify that the entire lift is compacted to the density and at the moisture content specified.

If test results fail, action must be taken. The first action is to verify the test was conducted properly and the correct Proctor curve was indeed used in evaluating the test results. This generally requires retesting near the same failed test location. If the second test is conducted properly and also fails, more tests may be needed to determine the extent, both depth and lateral limits, of the noncompliant earthfill or earth backfill. These actions are the responsibility of the CQC. The CQC should work with the contractor to fix any noncompliant earthfill or backfill. This may require more processing and compaction and may even require removal of some in-place material. When failures occur, every effort should be made to determine the cause of the failure and make necessary adjustments to the earthfill process in an effort to limit reoccurring failure. The QA inspector should allow this process to play out before getting too involved. When CQC is satisfied that noncompliant work has been fixed and the process has been adequately adjusted to limit reoccurring failure, the QA should then verify specification compliance and document the scenario including any consultation with CQC and contractor.

The inspector’s responsibilities related to evaluating test results include verifying:

- the selected Proctor curve represents the soil or composite soils being tested
- test results are reasonable
- soils are retested if initial test results are unreasonable
- actions are taken to correct noncompliant work when reasonable test results fail
- any reworked areas are again tested to verify and document compliance with specifications
645.0803 Records and reports

Accurate records of testing and test results are needed to document:

- the method used to select the Proctor curve
- the horizontal and vertical location of the field density and moisture test and the section or area represented by the test
- the standard test method applied and the test results
- any other actions or testing done for verification of test results
- any actions taken to correct noncompliant work identified by negative test results

The job diary should reference or further explain all of the information listed.

These records and reports are related to earthfill and rockfill:

- Daily diary—used to record the day-to-day activities of earthfill and rockfill construction.
- WS 8.1—Test Fill Report
- WS 8.2—Weekly Summary of Density Determinations
- WS 8.3—Determination of Volume of Compaction Mold ASTM D698 and D1557
- WS 8.4—Worksheet for Reference Density Compaction Data ASTM D698 and D1557
- WS 8.5—Moisture Correction Determination
- WS 8.6—Earthfill Construction Report
- WS 8.7—Bulk Sand Density Determination and Calibration of Cone and Base Plate for ASTM D1556
- WS 8.8—In-Place Moisture-Density Determination: Sand Cone Method: ASTM D1556
- WS 8.9—In-Place Moisture-Density Determination: Rubber Balloon Method: ASTM D2167
- WS 8.10—In-Place Moisture-Density Determination: Calibrated Cylinder Method: ASTM D2937
- WS 8.11—Nuclear Compaction Test Data for ASTM D6938
- WS 8.12—In-Place Moisture-Density Determination: Template & Plastic Liner Method: ASTM D5030
- WS 8.13—Correction of Unit Weight and Water Content for Soils Containing Oversized Particles

These worksheets, guidance on filling out the worksheets and examples are included in this handbook in appendix B along with example entries to illustrate the proper use of the worksheets. The job diary entries should reference the applicable worksheets that are used. Some test results may be included in the regular diary entries when they are pertinent to the daily activity and needed for clarification. Relevant sample job diary entries are included in appendix C of this handbook.
645.0804 References


U.S. Department of Agriculture, Soil Conservation Service. 1964. The Use of Soils Containing More than 5 Percent Rock Larger than the No. 4 Sieve. Technical Note 26. Washington, DC.
