Title 210 – National Engineering Handbook

Part 645 – Construction Inspection

Subpart H – Earthfill and Rockfill

Amended March 2025

645.80 Introduction

A. NRCS uses earthfills and rockfills in work projects for berms, dikes, levees, embankments, and structural backfills. These projects' primary structural component is soil, rock, or a combination of the two.

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

C. The proper use of earth and rock as construction materials requires special attention to investigation, testing, and appropriate design procedures and assumptions. Use of onsite materials for 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.

D. Prior to earthfill and rockfill operations, the quality assurance (QA) inspector is responsible to:

1. Review and understand the drawings and specifications related to earthfill and rockfill.
2. Verify the diversion, dewatering, and drainage systems are in place.
3. Verify the construction of access and haul roads.
4. Verify the safety plans of earthfill and rockfill operations.
5. Verify the protection of buried utilities during required excavations.
6. Verify the acquisition of all required permits and the work's adherence to permit requirements.

645.81 Installation

A. Materials

1. Earthfill and Earth Backfill

a. Earthfill is composed of natural earth materials placed and compacted by construction equipment operated in a conventional manner. Earth backfill is 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.

b. Normally, builders construct earthfills from the most suitable materials available at or near the site after removal of rock particles that are larger than the maximum size specified. They must assess the materials' physical properties (permeability, strength, and compressibility), preferably from prior laboratory and field test results. They must interpret these laboratory and field test results to predict the suitability of the material for the type of structure planned.

c. Earthfill and earth backfill details in the construction drawings and specifications are based on the laboratory tests of samples taken from the foundation and borrow areas at the site. These details identify the types of materials used and their location in the installation according to their Unified Soil Classification System (USCS) designation. The USCS, developed by Casagrande in 1952 and adopted by most federal agencies as a standard for all engineering work, is the recognized classification standard for all engineering work in the NRCS. ASTM-International (ASTM) D2487 publishes the USCS standard. ASTM D2488 provides the field methods for classifying soils in accordance with the USCS.

d. All NRCS engineers and inspectors working on construction must be familiar with the USCS and the procedures outlined in both ASTM D2487 and D2488. NRCS provides soil mechanics training courses and modules for engineers and inspectors. Inspectors can take advantage of these and other available resources to improve their knowledge, skills, and abilities in understanding the engineering characteristics of various soil groups and their use in construction of conservation measures. See Title 210 National Engineering Handbook, Part 645 "Construction Inspection," Subpart G "Foundation Preparation, Removal of Water, and Excavation" for more information. Appendix B contains Worksheet (WS) 7.1 to help inspectors when performing a visual classification of the soil.

e. See figures 645H-1 to 645H-3 for examples of applying the USCS to using earthfill for engineering. The four properties used to evaluate earthfill are permeability, resistance to piping, compressibility, and workability. A numerical rating from 1 (most suitable) to 14 (least suitable) determines the relative suitability of soil materials in rolled earth embankments, channel sections, and foundations.

f. Earth backfill may be the same materials as earthfill, but the specified maximum particle size is usually smaller. Earth backfill may be composed

of plastic materials with low permeability for sealing off the movement of water. Common classifications of these types of earth backfill materials are CL, ML, SC, SM, CH, and MH.

g. Earth backfill may also be nonplastic materials such as clean sands and gravels, selected by builders 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.

h. 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 contain 5 to 12 percent fines. They are unsuitable for projects requiring free drainage. See 210 NEH Part 645 Subpart K "Drains and Filters" for more information.

i. 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.

j. Classifying soils according to the USCS alone does not always provide enough information to predict soil performance. NRCS classified gravelly and stony soils used in compacted embankments in three groups based on the durability of the coarse rock and soil materials. Refer to Technical Release 210-26, "The Use of Soils Containing More Than 5 Percent Rock Larger Than the No. 4 Sieve" for more information.

k. 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 have less permeable material placed as a cutoff or core zone and more permeable material placed at less strategic points such as the outside sections of the embankment. The QA inspector must be familiar with the quantity and quality of the borrow materials to verify their selection and placement in the embankment to produce the zones specified in the design. The design engineer must approve any changes to zone locations or limits.

l. Borrow areas commonly 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, places the materials in the designated zones where they are suitable for use. On some jobs, selecting borrow materials with a moisture content within the

specified range controls compaction moisture. Thus, material suitability is contingent on both texture and moisture content.

Figure 645H-1: Engineering of Earthfill - Important Properties of Soil Groups

Typical names of soil groups	Group symbols	Permeability when compacted	Shearing strength when compacted and saturated	Compressibility when compacted and saturated	Workability as a construction material
Well-graded gravels, gravel-sand mixtures, little or no fines	GW	Pervious	Excellent	Negligible	Excellent
Poorly graded gravels, gravel-sand mixtures, little or no fines	GP	Very pervious	Good	Negligible	Good
Silty gravels, poorly graded gravel-sand-silt mixtures	GM	Semipervious to impervious	Good	Negligible	Good
Clayey gravels, poorly graded clay-sand-silt mixtures	GC	Impervious	Good to fair	Very low	Good
Well-graded sands, gravelly sands, little or no fines	SW	Pervious	Excellent	Negligible	Excellent
Poorly graded sands, gravelly sands, little or no fines	SP	Pervious	Good	Very low	Fair
Silty sands, poorly graded sand-silt mixtures	SM	Semipervious to impervious	Good	Low	Fair
Clayey sands, poorly graded clay-silt mixtures	SC	Impervious	Good to fair	Low	Good
Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity	ML	Semipervious to impervious	Fair	Medium	Fair

Typical names of soil groups	Group symbols	Permeability when compacted	Shearing strength when compacted and saturated	Compressibility when compacted and saturated	Workability as a construction material
Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, lean clays	CL	Impervious	Fair	Medium	Good to fair
Organic silts and organic silt-clays of low plasticity	OL	Semipervious to impervious	Poor	Medium	Fair
Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	MH	Semipervious to impervious	Fair to poor	High	Poor
Inorganic clays of high plasticity fat clays	CH	Impervious	Poor	High	Poor
Organic clays of medium to high plasticity	OH	Impervious	Poor	High	Poor
Peat and other highly organic soils	P	N/A	N/A	N/A	N/A

Figure 645H-2: Engineering of Earthfill–Relative Desirability for Various Uses–Rolled Earth Dams and Canal Sections

Typical names of soil groups	Group symbols	Homogeneous Embankment – Rolled earth dams	Core – Rolled earth dams	Shell – Rolled earth dams	Erosion resistance – Canal sections	Compacted Earth Lining – Canal sections
Well-graded gravels, gravel-sand mixtures, little or no fines	GW	N/A	N/A	1	1	N/A
Poorly graded gravels, gravel-sand mixtures, little or no fines	GP	N/A	N/A	2	2	N/A
Silty gravels, poorly graded gravel-sand-silt mixtures	GM	2	4	N/A	4	4

Typical names of soil groups	Group symbols	Homogeneous Embankment – Rolled earth dams	Core – Rolled earth dams	Shell – Rolled earth dams	Erosion resistance – Canal sections	Compacted Earth Lining – Canal sections
Clayey gravels, poorly graded clay-sand-silt mixtures	GC	1	1	N/A	3	1
Well-graded sands, gravelly sands, little or no fines	SW	N/A	N/A	3 if gravelly	6	N/A
Poorly graded sands, gravelly sands, little or no fines	SP	N/A	N/A	4 if gravelly	7 if gravelly	N/A
Silty sands, poorly graded sand-silt mixtures	SM	4	5	N/A	8 if gravelly	5 critical erosion
Clayey sands, poorly graded clay-silt mixtures	SC	3	2	N/A	5	2
Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity	ML	6	6	N/A	N/A	6 erosion critical
Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, lean clays	CL	5	3	N/A	9	3
Organic silts and organic silt-clays of low plasticity	OL	8	8	N/A	N/A	7 erosion critical
Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	MH	9	9	N/A	N/A	N/A
Inorganic clays of high plasticity fat clays	CH	7	7	N/A	10	8 volume change control

Typical names of soil groups	Group symbols	Homogeneous Embankment – Rolled earth dams	Core – Rolled earth dams	Shell – Rolled earth dams	Erosion resistance – Canal sections	Compacted Earth Lining – Canal sections
Organic clays of medium to high plasticity	OH	10	10	N/A	N/A	N/A
Peat and other highly organic soils	P	N/A	N/A	N/A	N/A	N/A

Figure 645H-3: Engineering of Earthfill–Relative Desirability for Various Uses–Foundations

Typical names of soil groups	Group symbols	Seepage important - Foundations	Seepage non-important - Foundations
Well-graded gravels, gravel-sand mixtures, little or no fines	GW	N/A	1
Poorly graded gravels, gravel-sand mixtures, little or no fines	GP	N/A	3
Silty gravels, poorly graded gravel-sand-silt mixtures	GM	1	4
Clayey gravels, poorly graded clay-sand-silt mixtures	GC	2	6
Well-graded sands, gravelly sands, little or no fines	SW	N/A	2
Poorly graded sands, gravelly sands, little or no fines	SP	N/A	5
Silty sands, poorly graded sand-silt mixtures	SM	3	7
Clayey sands, poorly graded clay-silt mixtures	SC	4	8
Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity	ML	6	9
Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, lean clays	CL	5	10
Organic silts and organic silt-clays of low plasticity	OL	7	11
Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	MH	8	12
Inorganic clays of high plasticity fat clays	CH	9	13
Organic clays of medium to high plasticity	OH	10	14
Peat and other highly organic soils	P	N/A	N/A

m. With respect to earthfill and earth backfill materials, the QA inspector is responsible for verifying:
   (1) Adequate knowledge and competency in the field use of the USCS.
   (2) Materials used are properly identified and do not differ significantly from those materials specified in design.
   (3) Materials are routed to specified locations in the earthfill.
   (4) Frozen materials are not used in any earthfill, or earth backfill.

(5) Moisture content of borrow materials is within the specified range or will be adjusted to comply with specification requirements before compaction.
(6) Significant changes in materials are promptly reported to the responsible engineer.

2. Rockfill

a. Rockfill are 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, some specifications may allow various amounts of sand and fine-grained materials. 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 a weathered but economical choice for zoned fill. These types of materials will break down during processing and compaction, so they require close attention to the specified methods and field test results.
b. The drawings and specification must clearly identify borrow sources (onsite or offsite), gradation, quality of rockfill materials, processing, and compaction needs.
c. The QA inspector must verify the contractor only approves and installs rockfill materials that meet the job specifications.

B. Foundation Preparation

1. 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 provide the necessary details for preparing the foundation.

2. Prior to placing earthfill or rockfill, the foundations must be prepared as specified by removing vegetation and other unsuitable material, excavation, and dewatering to facilitate placement, processing, and compaction.

3. Rockfill foundations must be cleaned in a similar fashion to earthfill. Bonding at the contact area is not a concern if the contact is clean and moist. Overhangs and vertical surfaces may require some contouring.

4. 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. Dams and other structures designed to restrain water movement require specially treating rock outcrops. Otherwise, occasional rock outcrops do not require special treatment.

5. Dams, and other structures designed to impound water, require their 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 must be compacted to the specified density with the soil at the specified moisture content. Rock foundations, in the same situation, must be clean, moist, and contoured to eliminate overhangs, vertical surfaces, and excessively steep surfaces.

6. Some foundation soils, when left exposed to the sun and wind for any length of time, will shrink and crack. These soils require careful inspection to ensure their removal is needed to assure that these soils are removed, and the surface reworked to restore a competent foundation.
7. Frozen material must not be placed on a foundation surface and no materials may be placed on a frozen foundation surface. The fill operations may begin only after all foundation surfaces are approved as meeting the specifications.
8. Abutment and sloping surfaces for both kinds of fill must be cleared of all loose material by hand or other effective means and must be free of standing water when fill is placed upon them. Foundation and abutment surface steepness must be as specified for the job. Fill material may not be placed until the specified foundation preparation has been approved.
9. See 210 NEH Part 645 G for more information about foundation preparation.
10. For foundation preparation, the QA inspector's responsibilities include verifying:
    a. The foundation is prepared as specified prior to material placement.
    b. The surface and subsurface drainage features are in place to control water during earth or rockfill operations.
    c. The clearing and foundation preparation work adheres to safety standards.

C. Placement and Processing

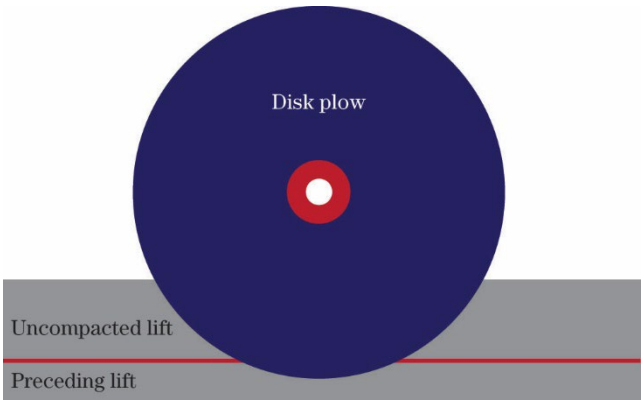
1. Earthfill
    a. During the placement of earthfill, the inspection of borrow materials coming to the work area is most important. Earthfill compaction, which follows the placement process, is dependent on clean materials that allow a consistent compaction effort to produce a uniformly dense material. Any material that interferes with this compaction process is detrimental to the operation. Debris, sticks, stones, roots, other organic material, soil too wet to compact, and frozen soil all interfere with this process.
    b. 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 must understand this process and be alert to contractors taking shortcuts in any aspect of this sequence of operations.
    c. It is vital to ensure that 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 pre-compaction lift thickness is an important first step.

d. After initial placement and spreading, all roots, vegetative growth, oversize rocks, and any debris 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 handpicking.

e. Large, hard lumps or masses of soil must be pulverized by disking, harrowing, or other means. Any water added at the time of placement must be thoroughly and uniformly mixed into the entire lift. The disk or plow used to mix and incorporate water into the soil must penetrate completely through the current lift and into the preceding (previously placed) lift as depicted in figure 645H-4. This promotes good bonding to the lower lift. When the specifications require disking, the disk must meet the size and type specified and be capable of penetrating and mixing the full depth of the lift. When the disk or plow cannot completely penetrate completely the current lift, the alternatives are to get a bigger, heavier disk or reduce the lift thickness until the equipment can meet the requirements.

Figure 645H-4: Disk Penetrating into Preceding Lift



f. During embankment construction, the top surface must be maintained approximately level with just enough slope for drainage. Unless otherwise specified, this slope must drain upstream toward the sediment pool area. This drainage minimizes erosion on the back slope and transportation of the resulting sedimentation downstream.

2. Earth Backfill

a. 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 QA inspector must understand the specification requirements for this operation. The height of the earth backfill adjacent to a structure must be maintained at 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 210 NEH Part 642, Construction Specification (CS)-23 “Earthfill.”

b. For earthfill and earth backfill placement and processing, the QA inspector is responsible for verifying that:
   (1) Earthfill zones are properly staked out.
   (2) Earthfill is installed at locations designated on the drawings and specifications.
   (3) Foundation and embankment surfaces are conditioned for bonding and comply with the specified grades and density.
   (4) Oversize stones, roots, and debris are removed before compaction.
   (5) The type of earthfill materials comply with specification requirements.
   (6) Earthfill placed in an embankment has a top surface that is maintained close to horizontal and properly sloped for drainage.
   (7) The earthfill was placed, processed, and had its moisture adjusted according to the job drawings and specifications.
   (8) No frozen materials were placed on site and no materials were placed on a frozen foundation or fill surface.

3. Rockfill

   a. Rockfill must be staked out and placed in the designated zones or areas.
   b. The preferred method to place rockfill is to dump it on the surface of the layer being placed and then spread it to the desired thickness with a crawler tractor by pushing the material over the advancing faces of the layer. This process separates larger rocks into the bottom of the lift and smaller rocks, spalls, and finer materials into the upper part. The main advantage of this technique is the relatively smooth upper surface resulting from pushing the dumped rock a short distance on top of each layer being placed so that depressions and voids between larger rocks are filled with the smaller materials. This approach also maintains the desired lift thickness because the dozer operator is always advancing the lift ahead on the smooth surface at its proper elevation. The smooth layer also reduces tire wear, allows higher truck speeds, and provides a better surface for compaction equipment operation.
   c. The rockfill material's maximum size controls the lift thickness.
   d. The QA inspector must ensure the rock materials are of the size range anticipated in the design. When this is not the case, the QA inspector must notify the responsible engineer and see that changes are made in the lift thickness to fit the size range of the rockfill.
   e. With respect to rockfill placement, the QA inspector must verify that:
      (1) The rockfill zones or areas are properly staked out.
      (2) The rockfill is installed at locations designated on the drawings and specifications.
      (3) The prescribed placement methods are followed to produce a competent rockfill.
      (4) The lift thicknesses are appropriate for the material being placed.

D. Moisture Control

1. Earthfill and Earth Backfill

a. Compaction moisture is the water content of soil at the time of compaction and is very important. 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."
b. 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 led him to determine that a standardized laboratory procedure was necessary for compacting soils at various compaction moisture contents. His work developed what is called the standard Proctor curve. Figure 645H-5 illustrates Proctors' principle and shows a typical standard Proctor curve.
c. ASTM D698 describes the standard Proctor test method used worldwide. ASTM D1557 describes a modified Proctor test method with a compactive effort approximately four times that of the standard Proctor method. Conservation engineering measures rarely use the modified procedure. Figure 645H-6 shows the energy application (effort) for the standard Proctor method and 645H-7 shows the energy application for the modified Proctor method. The rest of this subpart focuses on the more commonly used standard Proctor method.
d. The Proctor method and resultant Proctor curve (figure 645H-5) yield two important values. The first value, termed maximum dry density, is the maximum dry density of the soil that can be obtained when compacted by the Proctor method. The second value is the optimum moisture content. Optimum moisture is the soil moisture at which the maximum dry density can be attained.
e. As in Proctor's time, geotechnical design of earthen structures requires engineering properties of soils be known for soils compacted:
   (1) By a specific compaction effort.
   (2) At a specific moisture content.
   (3) To a specific density.
f. Geotechnical design of earthen foundations and structures begins by compacting the field-sampled soils in the laboratory with the standard or modified Proctor method. 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 must match 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.

g. In addition to density, compaction moisture must be specified and must 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.

Figure 645H-5: Proctor Curve

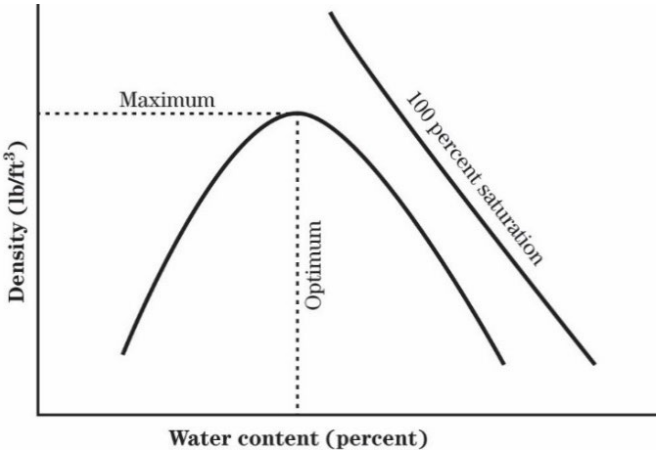


Figure 645H-6: Standard Proctor test method as specified in ASTM D698

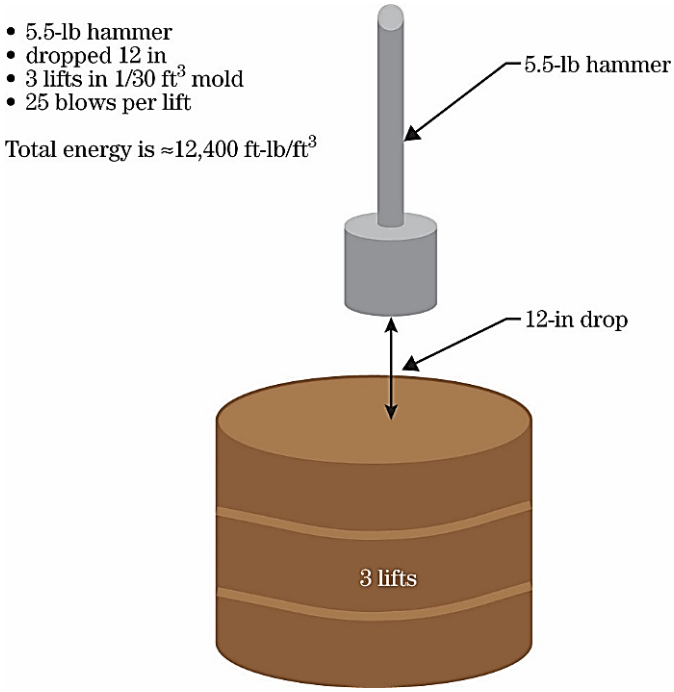
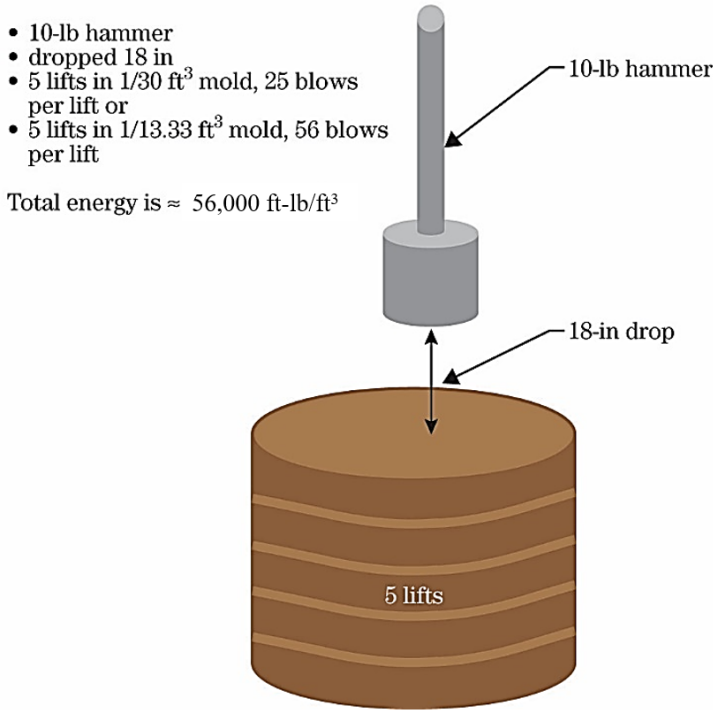


Figure 645H-7: Modified Proctor test method as specified in ASTM D1557

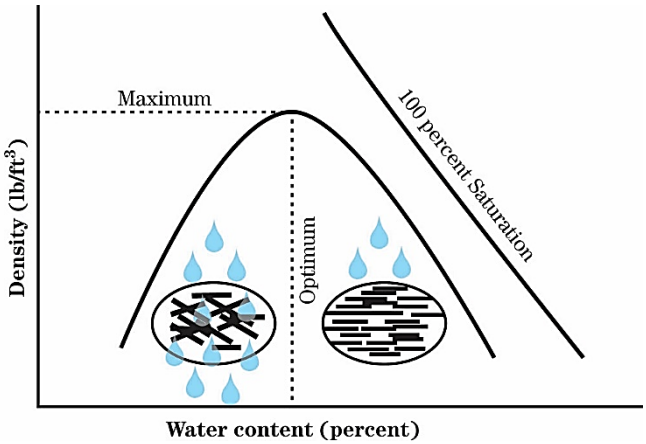


h. Soil compacted at a moisture content below optimum tends to be stronger but more permeable than if compacted at a moisture content above optimum. Figure 645H-8 illustrates this concept, showing that soil particles tend to reorient themselves into a less permeable structure when compacted at a moisture 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.

i. Adding water in the borrow area is the best way to achieve large increases in moisture content. This is accomplished by irrigation and aided by the mixing that occurs when loading and transporting the material to the placement area.

j. 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.

Figure 645H-8: Compaction Moisture's Effect on Soil Strength and Permeability



k. One way to gauge the effectiveness of the equipment used is by the ribbon test. Place a piece of survey ribbon on the ground where the soil will 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, it will bring some of the survey ribbon to the surface. Otherwise, a change in equipment size, weight, condition, or mode or installing a thinner lift is necessary.

l. 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 in the fill area or in the borrow area and is best accomplished by disking or plowing. Use the graph in figure 645H-9 to estimate water needs for specified compaction.

m. With respect to moisture control, the QA inspector must verify that:
   (1) The foundation moisture is within the specified range.
   (2) The compaction moisture is within the specified range throughout the full depth of the lift.
   (3) Any added water is properly incorporated into the earthfill to produce a uniform moisture content throughout the lift thickness.

2. Rockfill

   a. Moisture content in rockfill is usually not critical but may be specified.
   b. Avoid excessive moisture as it may wet down adjacent earthfill and adversely affect the placement, processing, or compaction.

E. Compaction

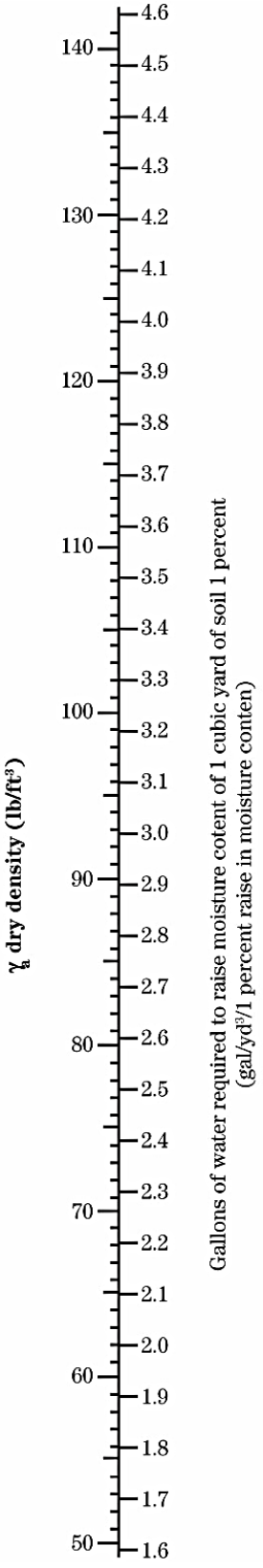
1. Earthfill

   a. When the proper preparation and processing is complete, effective compaction can begin.
   b. 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 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 sheepsfoot rollers, static or vibratory tamping foot rollers, static or vibratory smooth steel drum rollers, multi-tired 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 not as efficient as specifically designed compaction equipment.

c. 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 QA inspector must understand the different kinds of compactors and the types of materials for which each is best suited. Figures 645H-10 and 645H-11 provide guidance for judging compaction equipment suitability for various soils identified by the USCS.
d. 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.
e. 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.
f. 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 known as performance-based specifications, or performance specs. The other way to specify compaction is by method specification, or method specs. In a method spec, the contractor must use equipment that meets some specified criteria and must traverse the area with this equipment a specified minimum number of passes. Performance specs require the QA inspector to verify the compaction process achieves the required density and water content results. Method specs require the QA inspector to document that the equipment and number of passes complies with the spec and that the moisture content at the time of compaction is within the specified range.
g. Regardless of specification (performance or method), the QA inspector must pay careful attention to verifying complete coverage over the entire area requiring compaction, especially confined areas, or areas difficult for the equipment to cover. Abutment interfaces or ties into existing earthfill slopes are examples of areas that require special attention. The work may require different, more maneuverable equipment, thinner lifts, or hand compaction methods to achieve the desired results.

Figure 645H-9: 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/ft^3. How much water will be required to raise moisture content to optimum?

From graph: 3.24 gal/yd^3/1% increase in moisture content where density=100 lb/ft^3

Water required: 3.24 (20–14)=19.4 gal/yd^3

Figure 645H-10: Compaction Characteristics of Coarse-grained Soils

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

Figure 645H-11: Compaction Characteristics of Fine-grained and Highly Organic Soils

Unified class	Relative ease of compaction	Compacted lift thickness (in)	Importance of water content	Preferred type of equipment	Number of passes	Typical dry unit weights (PCF)	Typical water content (%)
ML	Fair	6	Important	Tamping roller	4-6	95-120	12-22
CL	Good to fair	6	Very important	Tamping roller	4-6	95-120	12-22
MH	Poor	6	Very important	Tamping roller	4-6	70-95	22-40
CH	Very poor	6	Very important	Tamping roller	4-6	70-105	20-40
OL	Fair	6	Critical	Tamping roller	4-6	80-100	20-32
OH	Very poor	6	Important	Tamping roller	4-6	65-100	20-32
Pt	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable

h. After an earthfill operation's temporary or seasonal shutdown, the water content and density of the surface of the unfinished earthfill must be checked for compliance with the job specifications. This material might need to be reconditioned, removed, or replaced before resuming work.

i. CS-23 defines three classes of earthfill. See figure 645H-13 for more.
   (1) Class A is compaction to a specified density for each borrow material used. It is used extensively where a quality earthfill is required and testing for field control will be carried out.
   (2) Class B is a given mass density for all the material (only for rocky material with varying rock amount in the soil matrix) and is rarely used.
   (3) Class C is compaction by a prescribed method. It is used where compaction may not be critical, materials are difficult to define or testing capabilities for field control are not available.

j. The QA inspector's responsibilities for earthfill compaction include verifying:
   (1) The appropriate compaction equipment is properly used to compact earthfill and earth backfill.
   (2) The compaction equipment is properly controlled to provide a systematic and complete coverage of entire area requiring compaction.
   (3) For classes A and B compaction, the specified density is attained throughout the full depth of each lift of earthfill.
   (4) For class C compaction, the prescribed equipment and method are consistently applied.
   (5) For zoned embankments, all zones are located and configured as specified or as shown on the drawings.

Figure 645H-12: Selection of Compactor Type

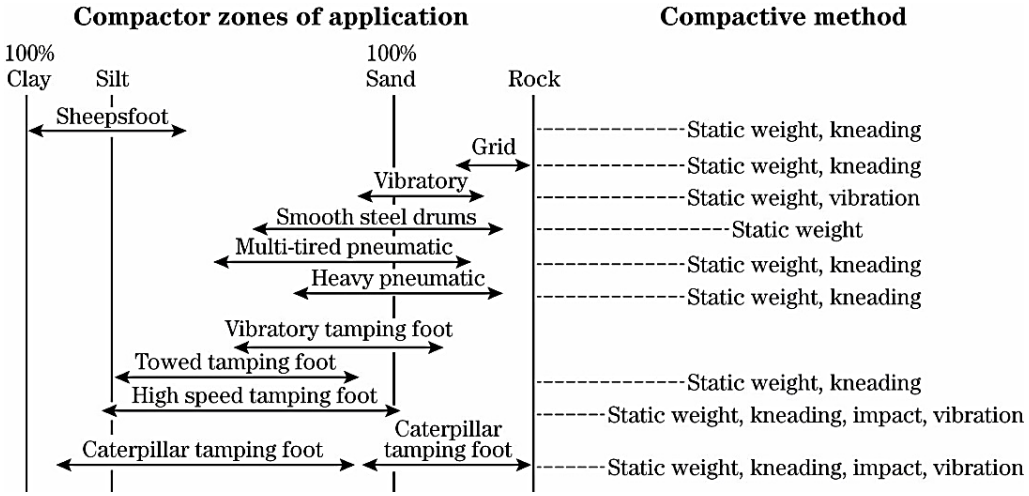


Figure 645H-13: Summary of Compaction Classes Defined in CS-23

Compaction Class	Type specification	Items specified	Advantage or disadvantage
A	Performance	Density test method and required percent of maximum density.	Provides a way to verify the earthfill density meets or exceeds the minimum specified density required for the earthfill to function as designed. Requires the QA inspector to use testing equipment and match the soil to a Proctor curve developed by the QA inspector or by a lab. Works best for soil containing no rocks or gravel or for soil containing uniformly distributed gravel.
B	Performance	Required minimum mass density.	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 hours to conduct one test. Rarely specified.
C	Method	Type of equipment including weight and contact pressure, minimum vibrating force and frequency for vibrating equipment, and minimum number of passes.	Requires no density testing, but constant surveillance by the QA inspector to verify the specified methos is employed over the entire area. Used where compaction may not be critical, materials are difficult to define, and testing capabilities for field control are not available.

2. Earth Backfill

    a. 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 with plasticity. Manually directed plate vibrators sit on the surface and compact by static weight and vibration. They work best on coarse-grained nonplastic materials.
    b. Earth backfill has two markedly different types of materials with corresponding installation operations and compaction characteristics. The first type is plastic soils and the second is sands and gravels.
    c. Plastic backfill material is compacted with tamping rollers, when space is available, or by hand-controlled power tampers in confined areas. Tamping rollers must be operated with caution near pipes and concrete structures to avoid damaging them. Plastic backfill materials are often specified to be compacted to a density that is equal to or greater than the surrounding earthfill. Some 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. Plastic backfill material must be protected from drying and cracking until covered by permanent cover.
    d. Sands and gravels are consolidated with pneumatic rollers, tractors, and surface or internal vibrators. Backfill generally uses manually directed vibratory rollers or plate vibrators. Clean gravels do not require moisture control. Sands are 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 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.
    e. 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. See 210 NEH Part 645 Subpart K "Drains and Filters" for more information.

f. When placing backfill against a pipe and some small structures, the level on each side of the pipe or structure must be the same to avoid damaging or displacing the pipe. It is important to guard against over-compaction near pipes or other structures to avoid similar damage and displacement.

g. The QA inspector's duties for compacting earth backfill include verifying:
   (1) The material and particle size for backfill meet the specification requirements.
   (2) The compaction requirements are met for the material involved.
   (3) The finished backfill is protected from drying and cracking until permanent cover is placed.
   (4) Backfill is not over compacted.

3. Rockfill

   a. 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.

   b. Weathered rock is inclined to break down and produce smaller material, including soil, is best compacted with a tamping roller or grid roller.

   c. Rockfill compaction is specified by method specs rather than performance specs. Inspectors must know what method is specified and plan how best to verify specification compliance. CS-25 "Rockfill" lists three classes of compaction: classes I, II, and III. These classes of compaction range from the most dynamic method to the least dynamic method and produce results from most to least dense, respectively.

   d. When using a bedding layer under the rockfill or a transition zone adjacent to the rockfill, these materials must be properly compacted. Bedding must 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 QA inspector must verify the zones are located and configured as specified or as shown on the drawings.

   e. The QA inspector's duties related to compaction of rockfill include verifying:
      (1) The specified equipment is used and specified method of compaction is strictly followed.
      (2) All compaction equipment is in good condition and operated properly.
      (3) That placing and compacting transition zones is in the right sequence.
      (4) All zones are located and configured as specified or as shown on the drawings.

645.82 Sampling and Testing

A. When specified, in-place testing for moisture and density of compacted earthfill must be conducted 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:

1. **Determine the frequency of testing**.

   a. The Quality Assurance Plan for any earthwork job must specify the minimum frequency of compliance testing the QA inspector must perform. CS-94 "Contractor Quality Control" specifies the frequency of inspection required from the Contractor Quality Control (CQC). The actual field-testing frequency for verifying the specification compliance can only be determined on the job during the work performance.

   b. In general, earthwork construction requires more field compliance testing earlier rather than later in the job. Later, 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 and moisture of about 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 must test once daily, and the QA inspector must verify the daily CQC testing. This same scenario could happen when the contractor brings in new borrow material or establishes a new zone of fill. The QC testing frequency must be whatever the contractor needs to verify the earthfill process achieves the specified density and moisture results.

   c. When the contractor is satisfied, the QA must verify the CQC results. Once a reliable earthfill process has been established and consistent density and 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.

   d. 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 QA 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.

2. **Determine the test location.**

    a. Selecting the test location 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 to poor compaction effort. Both tests are required to adequately document the quality of the in-place fill.
    b. It is also 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 must be 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.

3. **Obtain the sample.**

    a. Sampling and maintaining the integrity of the sample are critical steps to the testing process. All the in-place density methods, except for the nuclear method, take a soil sample from the test area. This removed soil sample provides 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 fill. Proper sampling may also involve scrapping off the surface lift to be tested to ensure all loose material is removed and not affect the results of the test.

4. **Perform the specified test.**

    a. The required test methods are identified in the performance specifications where they call for end-result testing of in-place earthfill. CS-23 contains two classes of compaction that fit this category, classes A and B. The QA inspector must have an operational knowledge of each standard test method.
    b. For soil in-place density, the following test methods apply: sand-cone method, ASTM D1556; drive cylinder method, ASTM D2937; and a nuclear method, ASTM D6938 Nuclear Moisture/Density Method or ASTM D8167 Low-Activity Nuclear Density Method. NRCS does not currently have conventional nuclear density gauges used for ASTM D6938, but contractor's quality control personnel may be using them.

NRCS does have several of the D8167 gauges for use in QA activities. There are other methods, but these are the most used in NRCS field work.

c. 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.

d. The ASTM methods are well written and easy to follow once the format becomes familiar. However, several significant precautions for these methods are outlined below.

e. Density Testing

(1) Sand Cone Method, ASTM D1556

(a) A proven method that 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.

(b) Free-flowing sand of known unit weight is then poured into the hole from a jug and a calibrated cone (figure 645H-14). 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 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.

(c) 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.

(d) 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.

(e) 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.

(f) 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 helps to identify borrow materials and evaluate fill material processing. Identifying borrow materials is important for determining the standard reference curve to be used for evaluating the density test results.

(g) 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.

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

Figure 645H-14: Sand Cone Apparatus (NRCS-TX)

(2) Drive Cylinder Method, ASTM D2937

(a) 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. 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.

(b) Figures 645H-15 through 645H-17 show the cylinder and drop hammer method.

(c) 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 it is being driven in the ground.

(d) 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 excavation must extend below the bottom of the cylinder to allow removal without damaging the captured soil sample inside. The test method may be both laborious and tricky in some soils.

(e) Appendix B contains worksheet WS 8.10 to aid in the performance of the drive-cylinder moisture-density determination.

Figure 645H-15: Drive Cylinder Apparatus – Driving head placed on the cylinder (NRCS-TX).

Figure 645H-16: Drive Cylinder Apparatus – Extracting Cylinder after being driven into the ground (NRCS-TX).

Figure 645H-17: Drive Cylinder Apparatus – Trimming soil from cylinder after excavation (NRCS-TX).

(3) Nuclear Method ASTM D6938 and Low-Acidity Nuclear Method ASTM D8167

(a) There are two nuclear methods used for density testing. The first is the conventional moisture density gauge covered by ASTM D6938. Although this method is the fastest and easiest to use, it requires certification training for safe use, transportation, and operation of the nuclear device. Also, regulations require periodic inspections and calibration of the equipment, and equipment storage is strictly regulated.

(b) The nuclear gauge can be used to determine the in-place density and water content of most soil or 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.

(c) 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.

(d) Water content values obtained by the nuclear gauge may be misleading in some soils. The gauge 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.

(e) 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 QA 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.

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

(g) ASTM D8167 covers the use of a low-activity nuclear gauge for soil density. This equipment was developed recently and has the advantage of not having the license requirements of the conventional nuclear gauge. The testing process is very similar except this gauge only measures soil moist density. The moisture content of the soil must be determined with another test and the dry density computed. The gauge may come furnished with a moisture probe, or the water content can be determined by one of the methods shown below.

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

f. Water Content Testing

(1) Oven Dry Method, ASTM D2216

(a) This test method is the standard to which all other water content tests are calibrated and compared. The main drawback is the test takes 24 hours to get a result.

(2) Microwave Oven Method, ASTM D4643

(a) Les reliable and less expensive than the oven dry method, the readily available nature of equipment makes this method more adaptable to field work.

(3) Direct Heating Method, ASTM D4959

(a) Simple equipment and field oriented. Be cautious not to burn off organic material, thereby yielding an incorrect higher water content value.

(4) Speedy Moisture Tester Method, ASTM D4944

(a) Handy and portable for field work. Needs calibration and has a sample size limitation. Less accurate with the more plastic fine-grained soils of higher water content.

(5) Nuclear Method, ASTM D6938

(a) This method requires 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.

(6) 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.

(7) The QA inspector must 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.

g. Correction for Oversized Particles
   (1) 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 number 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.
   (2) The sand method may be used for testing soils with oversized particles, but the drive cylinder is not used for soils containing gravels.
   (3) The procedure described in ASTM D4718 Standard Practice for Correction of Unit Weight and Water Content for Soils Containing Oversize Particles must 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.

h. The QA inspector's responsibilities related to test location, sampling, and testing include verifying that:
   (1) Selected in-place testing locations are truly representative of the section or area being evaluated.
   (2) Areas that have suspect compaction effort or may be too dry or too wet are tested.
   (3) Soil materials from the testing and sampling process are properly protected to retain their integrity until the required determinations are completed.
   (4) Any test selected from those specified is performed in strict accordance with the specified test standard and is appropriate for the soils being tested.
   (5) A moisture and density correction is made according to ASTM D4718 whenever the soil being tested contains significant amounts of oversize particles.
   (6) Test location and results are promptly recorded.

5. Evaluate the test results.

a. 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.
b. 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 preceding 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 job if those supplied by the lab did not represent all 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.

c. To determine which Proctor curve fits the soil being tested, the QA 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 are used to verify which Proctor curve is appropriate to evaluate the field compaction test values. These methods—the jar, one-point, and the family of curves or one-point—are described below.

(1) Jar Method

(a) 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 be compared to the jar samples to select the Proctor curve that matches the test soil best.

(2) One-Point Method

(a) 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 or One-point Method

(a) 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 or 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.

(b) A family of curves can be developed specifically for each job by plotting all 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. Do not include any curve that must be moved so much that its moisture content values change more than 2 percent 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 645H-18.

(c) 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 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 645H-18 depicts a freehand curve.

(d) 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 must 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.

d. Make sure test results are reasonable.

(1) 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 the air voids are filled with water, the ZAV curve represents the maximum density of the soil at various water contents.

(2) Figure 645H-19 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.

(3) Furthermore, compacting soil to 100 percent saturation, although not impossible, is very unlikely to occur with conventional compaction equipment. Soils are usually 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 must 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.

(4) 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:

$$w_{sat} = \frac{(\gamma_w)(G_s)-\gamma_d}{(\gamma_d)(G_s)}\ x\ 100$$ where:

w_{sat} = the maximum water content at a given dry density in percent

γ_d = dry density in lb/ft^3

γ_w = unit weight of water (62.32 lbf/ft3)

G_s = the specific gravity of the soil

Figure 645H-18: Typical Family of Curves

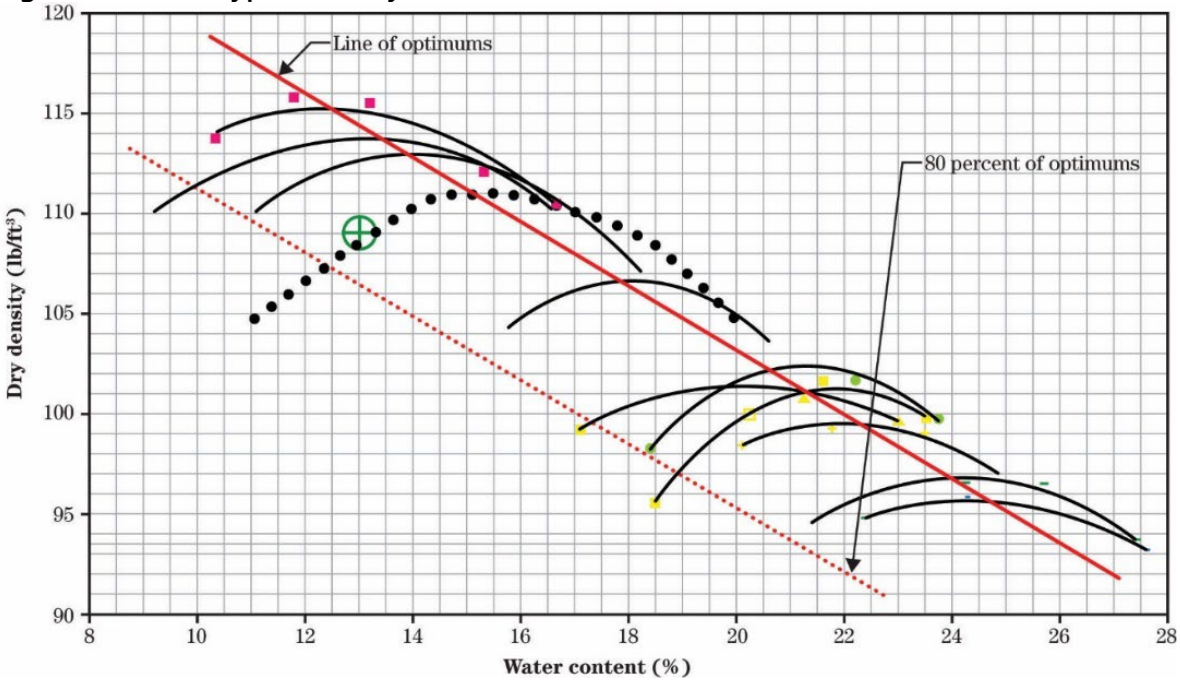
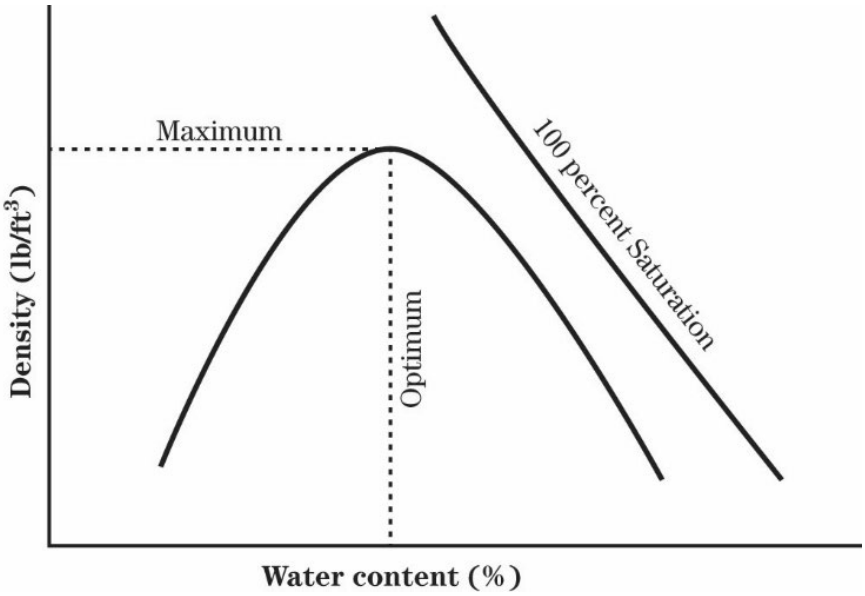


Figure 645H-19: Proctor and ZAV Curves



(5) 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.

$$w_{70\%} = \frac{(\gamma_w)(G_s) - \gamma_d}{(\gamma_d)(G_s)} \; x\, 70$$

$$w_{90\%} = \frac{(\gamma_w)(G_s) - \gamma_d}{(\gamma_d)(G_s)} \; x\, 90$$

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

(6) See figure 645H-20 for these curves and the ZAV curve for a specific soil. Several points are plotted along with the curves. The points were plotted from real results obtained by testing compacted soil in the field. If the specific gravity value used to develop the ZAV curves is that of the tested soil, the following are true:

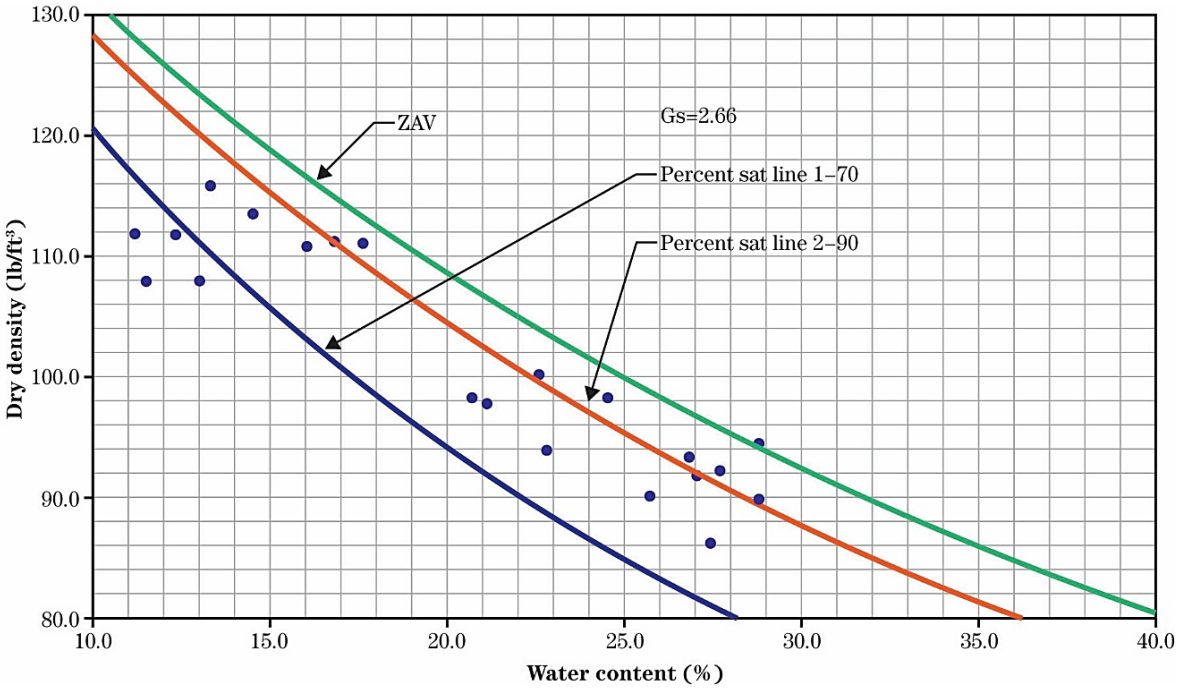
(a) The moisture and dry density values that fall within the 70 and 90 percent ZAV lines are reasonable values.

(b) Moisture and dry density values used for plotting points that fall outside of these lines are suspect.

(c) The moisture or dry density value used to plot any point that lands to the right of the ZAV curve is wrong.

(d) The selected Proctor curve represents the soil or composite soils being tested.

Figure 645H-20: 70% ZAV Curve, 90% ZAV Curve, and ZAV Curve



6. Record the test results.

a. 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 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 QA 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 QA 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.

7. **Assess the need for additional testing.** There may also be action required to correct noncompliant work identified from negative results.
    a. If test results fail, action must be taken. The first step is to verify the test was properly conducted and the correct Proctor curve was used to evaluate the test results. This requires retesting near the same failed test location. If the second test is properly conducted and fails, more tests may be needed to determine the extent, both depth and lateral limits, of the noncompliant earthfill or earth backfill. This is the CQC's responsibility. They must work with the contractor to fix any noncompliant earthfill or backfill. This may require more processing, compaction, and even removal of some in-place material. When failures occur, every effort must be made to determine the cause of the failure and make necessary adjustments to the earthfill process to limit reoccurring failure. The QA inspector must allow this process to play out before getting too involved. When the CQC is satisfied the noncompliant work is fixed and the process is adequately adjusted to limit reoccurring failure, the QA inspector must verify specification compliance and document the scenario including any consultation with the CQC and contractor.
8. The QA inspector's responsibilities related to evaluating test results include verifying that:
    a. Test results are reasonable.
    b. Soils are retested if initial test results are unreasonable.
    c. Action is taken to correct noncompliant work when reasonable test results fail.
    d. Any reworked areas are retested to verify and document compliance with specifications.

645.83 Records and Reports

A. Accurate records of testing and test results are needed to document:
    1. The method used to select the Proctor curve.
    2. The horizontal and vertical location of the field density and moisture test and the section or area represented by the test.
    3. The standard test method applied and the test results.
    4. Any other actions or testing done for verification of test results.

5. Any actions taken to correct noncompliant work identified by negative tests.

B. The job diary must reference or further explain all the information listed.

1. These records and reports are related to earthfill and rockfill:

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

2. Appendix B includes the worksheets, guidance to complete them, examples worksheets, and example entries. The QA inspector must reference the applicable worksheet in their job diary entries and may include some test results when they relate to the daily activity and need clarification. See appendix C for sample job diary entries.

645.84 References

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