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Earthwork Construction

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This chapter is intended to acquaint field engineers and inspectors with good earthwork construction procedures and the reasons for developing them. It is not part of the contract documents and should not be used to supersede project plans, specifications, or special provisions. Field personnel must be thoroughly familiar with the project specifications. Questions and problems concerning earthwork construction should be referred to the project engineer and other staff specialists who are familiar with good embankment construction and can provide assistance when needed.

Good construction and materials will look good; and with reasonable care and effort, and thorough and competent inspection, an acceptable product will result.

PRELIMINARY WORK

Before the start of construction, the engineer and the contractor should review the topography of the project and the contractor's proposed erosion control plan for protecting the project from the elements. As the representative of the owner or agency, it is the engineer's responsibility to protect the property and facilities adjacent to the project from environmental pollution that originates from the project.

It is to the contractor's advantage to control surface runoff so that damage to completed work will be minimized and present and future operations will not be hindered. The benefits of erosion control are substantial. From the owner's or agency's viewpoint, the adjacent lands and waterways will not be polluted; from the contractor's viewpoint, surface water will be prevented from saturating the embankment foundation area, rainwater will run off rather than onto the embankment surface, and operations such as trench excavation and pipe installation will be protected.

Erosion control operations do not hinder the progress of the project significantly, and if they are performed, the contractor will not be hampered by a rainfall. At the most, some minor repair, such as removal of small quantities of mud, may be needed before full production can proceed. Items designated for temporary erosion control are usually in the contract to supplement the permanent features.

Good earthwork is most easily ensured by firm control of operations early in the contract when many seemingly more important operations also require attention. The amount of time spent closely inspecting the contractor's methods at this stage will be well spent because once the earthwork operation is correctly established, it generally runs smoothly. Therefore, an understanding of the contractor's proposed earthwork construction plan will permit realistic scheduling of the inspector's duties. This usually results in smoother and more efficient inspection that will require less field testing. Increased production for the contractor results in fewer delays and fewer problems.

CLEARING AND GRUBBING

Limits of clearing and grubbing are generally noted on the plans. Usually areas outside the work limits are to be left in their natural condition unless otherwise designated on the plans. In general, it is intended that the roadway fit into the landscape in a pleasing way. Natural features should be left undisturbed where possible.

Clearing is defined as the removal of all trees, brush, and so forth, and is required in all work areas. Grubbing is defined as the removal of stumps and roots. It is not always necessary to remove all stumps and root systems beneath embankments. Trees and brush should be cut off close to the original ground surface so that the initial layers of fill can be placed and compacted properly. Specifications should be read carefully to determine grubbing requirements.

SLOPE DITCHES

The specifications may require that top- or mid-slope ditches be completed before removal of materials from the cut. Some contractors prefer to ignore this detail as it is not a "production" item (such as excavation and fill placement), believing that they can complete the ditches whenever they have extra time. However, if the ditch work is not done in the beginning, problems may arise later that are detrimental to the work, and expensive corrective procedures may be required.

Two problems could occur if the ditches are not completed beforehand. First, the ditches are designed to collect surface runoff that otherwise would flow down the slope and into the excavation. This water can cause serious erosion as well as problems with cut-slope stability. Second, if the water is allowed to flow into the cut, the material to be excavated will become saturated, creating potential compaction problems when it is placed in the fill.

By delaying the ditch work, the contractor will create problems that not only are costly to correct, but also may delay other operations. Lack of accessibility to the work area, problems with disposal of the excavated materials, and improper placement of the ditch lining material, where required, result when ditch work is not performed before excavation is started. The engineer should insist that the contractor perform ditch work first. See Chapter 5 for additional information on drainage and erosion control.

EXCAVATION

Because the topsoil at the surface of earth cuts is usually unsuitable for use in compacted earth fills, it is normally stockpiled for later use in landscaping the project. The limits and depths of topsoil removal, where specified, are usually included in the plans.

As the excavation progresses it is good practice, depending on the topography and soil conditions, to keep the portion adjacent to the design slope at least 2 to 5 ft lower than the general level of the cut until the bottom is reached. In other words, providing a minimum of 2- to 5-ft-deep ditches along the sides of the excavation until the bottom "payment line" is reached helps to drain the section, resulting in a drier, more stable material for the contractor to excavate, transport, place, and compact. Because the cut is drained, the contractor will also have fewer equipment mobility problems.

Because of the highly variable properties of naturally occurring geologic deposits, specifications for roadway excavation often consider all soil and rock as unclassified excavation. This avoids the controversy, for example, of which bid price should apply to which material, or whether a deposit can be ripped or must be blasted.

ROCK EXCAVATION

If the material to be excavated is too tough or cemented to be ripped, then before drilling and blasting operations are begun, the engineer, contrac-

tor, and owner's or agency's geotechnical specialist experienced in blasting should hold a meeting at the project site to discuss all aspects of the blasting operations and set the ground rules for the contractor's operations and the basis for inspection of the work. The blasting specialist can help in determining the aspects of the work that need the most inspection, what to look for, and how it should look. A good reference on rock blasting is the FHWA manual (Konya and Walter 1985).

The owner's or agency's goal in the construction of rock slopes is that they require a minimum of maintenance and that they be hazard free. The contractor must thoroughly strip (overall removal of unsound material) or scale (removal of loose masses of rock) all rock slopes. If, after stripping or scaling operations, the engineer believes a hazardous rock slope situation still exists, a specialist should be requested to review the rock slope to determine if a hazardous condition exists and if so, propose solutions to correct it. For details on design and construction, the FHWA manual on rock slopes (Golder Associates 1989) should be consulted.

Some rock cuts will be designed with a broken rock trench to drain the section. The trench may be formed by extending the presplit or the production drill holes, or both, that fall within the typical section, or by drilling supplemental holes as necessary and fragmenting the rock. The limits and typical sections should be shown on the plans. Remember that this treatment must have a positive drainage outlet. Therefore, the plans and field conditions should be examined to confirm that positive drainage is provided.

EMBANKMENT FOUNDATIONS

The embankment foundation provides the base upon which the fill is constructed. After clearing and grubbing, the contractor should prepare the foundation in accordance with the plans, specifications, standards, and any special provisions. Preparation of the foundation may require stripping topsoil (particularly for fills less than 10 ft high), removing organic deposits and underwater backfill, compacting the ground surface, or placing a construction lift (a stable platform for later construction activities). In general, for problems identified during design, specific treatments will be shown on the plans or described in the contract documents. However, site conditions may be different, and some revisions to the design and construction plans may be required.

Embankment foundations are discussed in detail in Chapter 6. Construction procedures will depend on how firm or how soft the foundation is and whether the foundation soils require special treatment.

Firm Ground

No special foundation work is necessary in situations in which the height of embankment above firm ground is greater than the expected maximum depth of frost penetration. The topsoil may be left in place, especially under the outer edges of embankments. All embankment layers should conform to compaction specification requirements.

Depending on its natural in situ density, the surface on which the embankment or subbase, or both, is to be placed may need to be compacted to provide a stable platform upon which to place the subsequent embankment or subbase materials, or both. Proper compaction of each lift depends to a large degree on the density and stiffness of the surface upon which it is placed. If the foundation soil is in a loose state, the contractor may have difficulty compacting the initial embankment layers, unless the foundation is properly prepared and compacted first.

Clearing, grubbing, removal of the topsoil, and other special treatments will be noted on the plans when the embankment height is less than maximum depth of the expected frost penetration.

Soft Ground

Embankments that cross low, wet areas may require an initial stabilization layer, which is a thick lift of granular material, in order to provide adequate support for construction equipment. Usually specifications allow the engineer to permit a working platform up to 3 ft thick to be placed in one lift to bridge the soft areas. Experience has shown that sand, gravel, or well-graded blasted or crushed rock is excellent for this initial lift, especially when used with a stabilization geotextile (Christopher and Holtz 1985).

In some cases, low wet areas are anticipated during design, and a construction or stabilization lift with select materials is specified. Compaction of these initial lifts in soft areas should proceed with caution. In general, the use of vibratory rollers should be discouraged, as the vibration may cause the underlying soil to be pumped up into the granular fill. Separation geotextiles may be used to significantly reduce the thickness of this granular stabilization layer (Christopher and Holtz 1985).

Embankments placed on soft foundation soils may be designed so that the soft soils can be left in place. Methods of foundation treatment include the use of preload surcharges, sand, or prefabricated drains to accelerate the consolidation, stone columns, side berms, and so forth. [See Chapter 6 for a description of foundation stabilization techniques and additional references; for example, see NCHRP Synthesis of Highway Practice 147

(Holtz 1989).] These treatments are often critical and, when required, will be shown on the plans. They must be constructed strictly according to the specifications, and designers of these treatments should communicate their special concerns to the responsible construction personnel.

Unsuitable Materials

Unsuitable materials, such as peats and organic soils, mine and municipal wastes, swelling and collapsible soils, and so forth, are not generally appropriate for embankment foundations and must either be removed (undercutting) and replaced or specially treated. Limits and depths of removal or treatment of unsuitable materials will be shown on the plans; construction procedures will be detailed in the contract documents. Foundation treatment methods are discussed in Chapter 6 and by Holtz (1989).

Undercutting is the process of excavating below the usual subgrade cut limits to remove unsuitable soils. If these soils are anticipated during design, the undercut will be shown on the plans, backfill materials will be specified, and payment quantities provided. Unanticipated subgrade conditions encountered during construction that need corrective action should not be overlooked or ignored. The engineer should always be consulted in these cases.

The materials used to backfill undercuts and their placement requirements depend on the reason for the undercut and the site conditions encountered when the work is performed. Each case is different, and materials that are good for one case may not be satisfactory for another.

The two primary conditions for which undercut and backfill work are necessary are to (a) minimize damage caused by differential frost action, and (b) provide a stable platform to support the pavement (and construction operations).

In areas of cold winter weather, frost action, particularly differential frost heave, is probably the most dangerous situation encountered. As noted in the section on Frost Action in Embankment Design and Construction, Chapter 8, the conditions necessary for frost action are (a) presence of water, (b) freezing temperatures, and (c) frost-susceptible soils. Water may be controlled to some degree by side ditches and underdrains, but most frost problems occur because of capillary action, which is not helped by drainage. Frost-susceptible subgrade soils can be removed and replaced with clean, free-draining granular materials that are less susceptible to frost action. In this case, undercutting is designed to specifically reduce or eliminate frost susceptibility.

Sometimes problem soils are treated with lime to reduce the effects of frost heave. Areas that are selected to be undercut or lime modified should not be changed in the field without proper approval. Cold weather

construction is discussed in Chapter 4; environmental aspects of frost action are described in Chapter 8.

Instability of natural subgrade soils is the other reason for corrective undercutting and backfilling work. In cuts, the pavement subbase is generally placed directly on the natural soil or rock exposed by the excavation unless the natural soils have insufficient strength or are highly compressible. In such cases, the undercut and backfill is designed to provide a stable platform to support the pavement structure.

Wet, silty soils are responsible for most subgrade stability problems. Groundwater emerging on the floor of the excavation can saturate these soils and reduce their strength. Construction equipment can cause excess pore pressures and weaving or pumping (see section on Weaving and Pumping) of the subgrade, or rutting (see section on Rutting), and machinery vibrations tend to draw water to the surface that further reduces soil strength. Sometimes conditions get so bad that the wet soils have to be excavated with a drag line.

The requirements for the placement and compaction of backfill material in undercut areas depend on the condition of the soils at the bottom of the excavation. When the bottom is firm, backfill can be placed and properly compacted according to the specifications. For soft foundations, stabilization layers or geotextiles, or both, probably will be required, as described earlier in the section on Soft Ground. In any event, for undercut situations, lift thickness and compaction equipment do not necessarily have to conform to normal compaction specifications. For example, vibratory rollers should be avoided because the vibrations may cause the silt to pump up into the backfill.

Subgrade stability problems often depend on local water conditions at the time that the cut is made. Because stability problems are difficult to determine during design, the limits for undercut and backfill work are generally left to the engineer to determine in the field. Stability problems may be reduced in some cases if the cut is allowed to drain after it has been completed to the original pay lines. A waiting period may allow the groundwater table to stabilize and the material beneath the subgrade to dry out somewhat. This may allow the extent and depth of the undercut to be reduced, which would result in a significant cost saving. These treatments are critical and they must be constructed strictly according to the design. When required, they will be shown on the plans.

Disposal of Excessive or Unsuitable Materials

All excess or unsuitable materials should be disposed of in the areas designated on the plans, preferably within the right-of-way. Disposal outside the project limits may be necessary in some cases. Whenever

additional disposal areas are needed, special attention should be given to their location, method of construction, and final appearance. All disposal areas, inside or outside the right-of-way, should be under the direct control of the engineer.

EMBANKMENTS

Usually, materials that are to be used to construct the embankment are selected by the contractor and approved by the engineer. Many agencies have general requirements in their standard specifications for the soil types that are acceptable for embankment construction. These requirements or any special provision for the project should be strictly adhered to so that no unsuitable materials are used.

Suitable materials, if properly placed and compacted, will make satisfactory embankments. Water content in the natural state has no bearing on suitability. However, materials with excessive moisture will require drying before placement and compaction, or they must be replaced with materials having a proper water content. The location of the project will dictate which approach is appropriate, or perhaps the contractor will make the decision. During excavation if materials are uncovered that have an excessive water content, construction personnel should refer to the contract specifications. If there is still a question about whether to use the wet soils, the engineer should be consulted.

Some man-made materials may be suitable for constructing embankments (see Chapter 9, section on Waste Materials). Excavated pavement materials are inert and can be used. On the other hand, incinerator ash and other wastes may contain hazardous substances (see Chapter 8, section on Hazardous and Objectionable Materials) that could leach into the groundwater if placed in an embankment or cause a dust problem during construction. The use of waste materials and any related environmental regulations should be explained in the project soils report, which should be read carefully and made available to project personnel.

Swelling soils (see Chapter 9, section on Compaction Problems with Swelling Clays) are common in some parts of the country and can cause serious problems, particularly on pavements. Methods of treatment, use, or disposal of swelling soils will be detailed in the plans or specifications. Disturbance by excavation and placement in fills may change the stable environment in which the soils existed before construction to an unstable environment that allows the absorption of moisture. When these soils absorb moisture, they can swell tremendously or exert large, undesirable swelling pressure if movement is restrained. Methods of treating and

handling swelling soils are usually recommended by specialists in these materials.

Frozen soils (see Chapter 8, section on Frost Action in Embankment Design and Construction) are unacceptable for embankment fills because they are difficult to compact. Construction operations should be stopped whenever frozen materials are brought onto the fill. Cold-weather construction problems are discussed later in this chapter.

When rock is used in embankments, care must be taken to achieve dense fills. Otherwise, large voids or cavities may exist within a fill, and finer materials from above can settle into the voids. Eventually the subbase material supporting the pavement is lost and the pavement fails.

In constructing a rock fill, the proper sequence of operations is to dump the rock onto the lift under construction. The material is then pushed by a bulldozer over the leading edge of the lift, thoroughly wetted, and compacted with heavy equipment. Materials with sizes up to 2 ft may be placed in lifts up to 3 ft in maximum thickness. The larger sizes should be placed near the outer slopes, and very large (> 1 yd^3) boulders should be embedded in the slopes, broken down to smaller sizes, or wasted. Finer materials must be applied to the top of the layer being compacted to fill any voids.

Shales and other materials that break down during compaction present special problems; the use of shales in embankments is discussed in Chapter 9, section on Construction of Embankments of Shale.

COMPACTION

General

Compaction of a soil layer is probably the most important aspect of proper embankment construction. A uniform, densely compacted embankment will provide a satisfactory platform upon which to place the base courses and pavement. The word "uniform" is important in that uniform conditions during construction of the embankment will result in uniform behavior of the pavement, assuming that foundation conditions do not enter the picture. The benefits of good compaction are substantial and the consequences of poor compaction are severe. As noted in Chapter 3, compaction increases bearing capacity, slope stability, and resistance to frost action. It also decreases settlement and permeability. Inadequate compaction may result in general and differential subsidence, which causes depressions and perhaps premature failure of the pavement.

The contractor should be encouraged to route his hauling equipment as evenly as possible over the entire surface of the embankment during fill

placement. The purpose of this is to reduce the total amount of compactive effort required as well as to minimize localized rutting and damage that might be caused by heavy, repetitive, concentrated tracking by equipment. Loaded self-propelled scrapers may weigh in excess of 100 tons and may overload even a densely compacted embankment. Equipment operators have a natural tendency to follow the established track (path of least resistance), and some effort will be required to have them cover the entire surface. A good contractor will have a motor grader or dozer on the embankment to keep the surface smooth and to allow increased speeds over the entire surface. The performance of the embankment under the tires of scrapers will also give a good indication of the uniformity and quality of compaction.

Moisture Control

As discussed in Chapter 3, moisture acts as a lubricant and helps the soil particles to move relative to each other into a denser condition when compactive effort is applied. Thus dry soils must have water added and mixed thoroughly throughout the layer being compacted. Adding water in the cut rather than on the fill improves mixing and increases uniformity. However, adding water to the loosely deposited fill on the excavation is the usual method employed. The choice is ordinarily left to the contractor.

If a soil is too wet, the compactive effort only increases the pore water pressure and this tends to keep the particles apart. Using a heavier compactor results in a decrease in strength at the same water content (see section on Weaving or Pumping). Thus, wet soils must be dried; natural drying is the most widely used method. To hasten drying, the soil may be spread and mixed by the use of disks, harrows, or rotary tillers. Lime has also been used to dry soil, but it is expensive; however, it also stabilizes the soil (TRB 1987).

Each project should receive from the laboratory a set of laboratory compaction control charts or a family of curves (AASHTO T 272) developed from standard (AASHTO T 99) or modified (AASHTO T 180) Proctor values representing the soils being used in the embankment. These curves are plots of density (or dry unit weight) versus water content and provide a standard of acceptability for the field tests.

When field compaction control tests (Chapter 3) are performed, the results are compared with the laboratory compaction control chart values or the family of curves to determine the applicable percent of maximum density, called the relative compaction or sometimes the percent compaction (Equation 3-3). The specifications will give the percent compaction

required. If this value is not obtained, additional compactive effort or a change in water content will be required to reach the minimum specified value.

The specifications or laboratory compaction control charts will usually indicate a water content range associated with the maximum required density or percent compaction. To achieve the proper compaction, the moisture content can be varied depending on the embankment soils and compaction equipment. However, to do this requires specialized testing and analyses, and field personnel should not attempt such an analysis without proper training.

Moisture control becomes more critical as the particle size of the material being compacted decreases. Clays are greatly affected by changes in moisture content whereas sands are not. Small amounts of fines in granular soils will also affect moisture requirements. Well-graded materials will usually exhibit steep, sharp compaction control curves showing well-defined optimum moisture content (OMC) (Figure 4-2). Uniform materials, particularly sands, will exhibit flat curves with no well-defined OMC. These latter materials may be successfully compacted at a relatively large range of moisture contents, although they may experience bulking problems at some water contents.

Weaving or Pumping

Weaving or pumping is an elastic-type deformation of the soil. When loaded, the material deforms and as the load is removed, the material springs back to its original position (almost like a waterbed). The construction equipment looks as if it is riding on a wave as it travels over the fill. The soil will deflect and a wave will be created ahead of the wheel, but once the equipment moves on, the area looks the same, although there may be some cracking of the surface. Weaving occurs when there is excess moisture in the soil that does not have time to drain as the load is applied. The load is then borne partly by the soil structure and partly by the pore water pressure. This gives a temporary elasticity to the soil, thus creating the weaving or pumping effect. Note that in this condition the strength of the soil is substantially reduced.

Initially, weaving is not necessarily damaging to the embankment. The easiest solution is to simply stay off the area and allow the excess pore water pressures to dissipate naturally. The soil will then tend to regain its strength. If the fill is weaving under the action of compaction equipment, a lighter compactor will produce lower pore water pressures and thus reduce weaving and pumping. However, repeated loadings will continue to create cumulative pore pressures and may ultimately result in shear

failure or rutting. If a weaving condition exists, the engineer should be called for advice. The engineer should then explain to the contractor that continued compaction operations can only worsen the situation.

Rutting

Rutting is a surface shear or bearing failure. As the equipment moves across the embankment, the loads imposed exceed the shear strength of the soil, the wheels sink, and deep ruts occur. Rutting destroys the previous compaction and makes it impossible to place the next lift to a uniform thickness. The integrity of the work suffers and the contractor's operations are hindered. Corrective measures such as changing the method of operation, materials, or loading are usually the contractor's responsibility.

COLD WEATHER CONSTRUCTION

It is extremely difficult, uneconomical, and under some circumstances, virtually impossible to compact moist or wet soil while freezing temperatures exist and to obtain the densities necessary for proper performance of an embankment.

Experience has shown that, if adequate densities are not obtained during construction, significant differential settlement and sideslope instability will occur as the frozen portions of the embankment thaw. Depending on the dimensions of the embankment and the location(s) of the frozen portions, the thawing process may take several years. The resulting poor performance of the embankment may require substantial maintenance expenditures to correct.

Consequently, most agencies located in freezing climates and engaged in earthwork construction do not permit embankment construction during the winter months. The only exception is construction using blasted rock. The specifications of one northeastern state read: "Earthwork construction operations requiring compaction shall not be performed from November 1 through April 1, except with written permission of, and under such special conditions and restrictions as may be imposed by the Regional Director."

Temperature has a noticeable effect on soil compaction when the temperature of the soil is above freezing. Raising soil temperature increases the maximum dry density obtained from a given compactive effort. In contrast, lowering soil temperature causes the water in the soil to become more viscous, reducing the workability of the soil, and conse-

quently, lowering the maximum dry density for a given compactive effort (Johnson and Sallberg 1962).

Soil temperature becomes critical to the compaction process at approximately 32°F. As the soil temperature falls below 32°F, there is an immense decrease in the maximum dry density obtained from the application of any given compactive effort. When the water coating the soil grains freezes, the three-phase system of soil grains, water, and air that existed above 32°F becomes a two-phase system of soil grains, each coated with ice and air. This latter system does not occur at exactly 32°F but at somewhat lower temperatures, probably as a result of the heat energy imparted to the soil by the action of the compaction equipment or perhaps as a result of the pore water chemistry.

Compaction of soils at temperatures below freezing was investigated on a section of Interstate 47 in Albany, New York, by the Bureau of Soil Mechanics of the New York State Department of Public Works during the winter of 1957–1958. The roadway was on an embankment for the entire length of the project. Construction began in the spring of 1957, and excellent progress was made during the summer and fall months. In late fall the contractor requested permission to continue embankment construction operations during the winter.

Until this time, it was believed by many, but not all, of the department's construction engineers that noncohesive semigranular and clean granular materials could be properly compacted at temperatures below freezing with no significant problems. Because the only two types of soils to be compacted were a fine sand with a trace of silt (used for embankment construction) and a sand with some gravel and a trace of silt (used for trench, bridge, and culvert backfill purposes), permission was granted, provided that the contractor achieve at all temperatures and at all locations the dry densities stipulated by the specifications (AASHTO T 99, standard method). Because the project was located only a short distance from the Bureau of Soil Mechanics laboratory, it offered researchers an excellent opportunity to study in detail compaction of these soils at temperatures below freezing and resolve the controversy concerning compacting granular soils in freezing temperatures.

Construction continued into the winter of 1957–1958. The first discovery the bureau made was that it was essential that the frozen soil excavated from the test hole be thawed before it was compacted into the Proctor mold. As embankment construction proceeded into December, the contractor found it increasingly difficult to achieve the specified densities and finally ceased grading operations until spring.

Using the bureau's frost study facilities, the moisture-density relationships for each of the two soil types at 74°F, 30°F, 20°F, and 10°F under both AASHTO T 99 (standard method) and AASHTO T 180 (modified

method) compaction test procedures were established. The results are shown in Figure 4-1 for the brown fine sand with a trace of silt and Figure 4-2 for brown sand, some gravel, and trace of silt. The curves indicate that an immense increase in compactive effort is required to compact a soil at temperatures below freezing. This is particularly true of the finer-grained soils. Note that for the brown fine sand with a trace of silt (Figure 4-1), application of the standard compactive effort at 74°F achieved a higher density than application of the modified compactive effort, which has 4.5 times the energy of the standard, at 30°F.

The curves also show that at a temperature in the vicinity of 10°F to 20°F, depending on the soil type, the shape of the moisture-density curve changes completely, indicating that it may be practically impossible to properly compact a soil at or below those temperatures with presently available methods and equipment.

COMPACTION EQUIPMENT

The compaction equipment that the contractor selects should be determined by the type of soils encountered. Certain types of compactors work better with some types of soils than others. In many cases, however, the contractor will use whatever equipment he already owns or has leased. Whatever equipment the contractor uses must comply with the specification requirements and must be approved by the engineer. Minimum wheel loads and tire pressures for pneumatic rollers and minimum weight for steel wheel rollers are specified, whereas for vibratory drum compactors, a specific frequency range and a minimum dynamic force are usually specified. Length of feet, minimum weight per square inch of cross-sectional area of the tamping feet, and operating speed are specified for sheepsfoot rollers.

A maximum lift thickness should be specified, depending on the equipment being used or the project soils, or both. In this way, the inspector will know in advance the maximum thickness that the contractor will be allowed to place and compact. The contractor can place thinner lifts if he chooses.

Pneumatic-tired compactors achieve compaction by the interaction of (a) wheel load, (b) tire size, (c) tire ply, (d) inflation pressure, and (e) the kneading action of the rubber tires as they pass over the lift. Pneumatic-tired rollers should be ballasted to meet at least the minimum wheel load.

Vibratory drum compactors develop their compactive effort by vibrations. Four machine features must be known in order to rate vibratory rollers: (a) unsprung drum weight, (b) rated dynamic force, (c) frequency
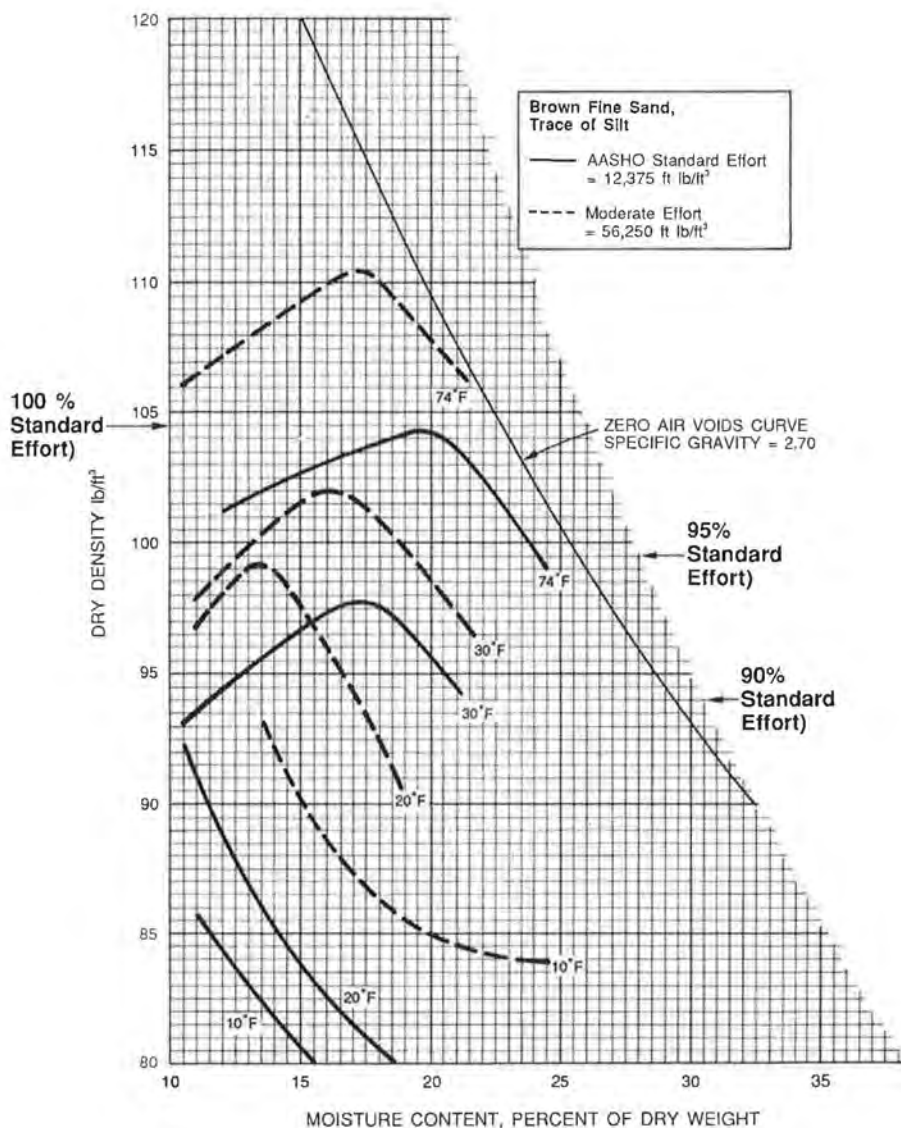
FIGURE 4-1 Compaction control curves (standard and modified AASHTO) for a brown fine sand with a trace of silt at different temperatures (*courtesy W. P. Hofmann*).
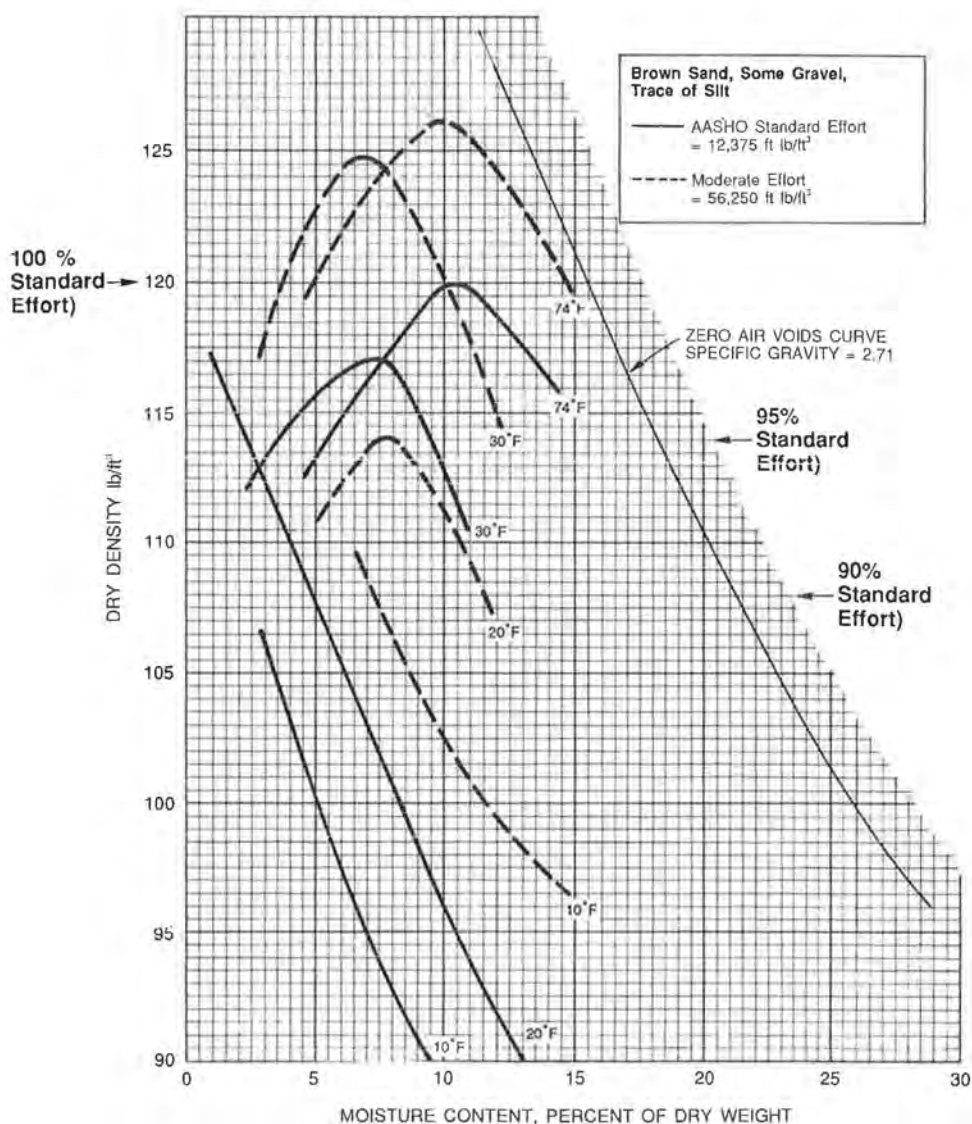
FIGURE 4-2 Compaction control curves (standard and modified AASHTO) for a brown sand with some gravel and a trace of silt (*courtesy W. P. Hofmann*).

at which the rated dynamic force is developed, and (d) drum width. The contractor or equipment supplier should have these data. Vibratory rollers should operate between 1,100 and 1,500 vpm, and the dynamic force at the operating frequency should be at least 2.5 times the unsprung drum weight (see the manufacturer's literature for the roller). Therefore, by using the machine data and the specification requirements, a range of acceptable frequencies can be determined.

The contractor should be required to provide at least one vibrating reed tachometer when vibratory rollers are used. This device is used to measure the frequency at which the machine is vibrating. The dynamic force is proportional to the square of the frequency. A reduction in the frequency will significantly reduce the compactive force. Therefore, the inspector should monitor the frequency often.

Compaction of granular soils is mostly due to the dynamic force created by a rotating eccentric weight. Vibratory compactors dramatically lose their effectiveness when the vibration is shut off because the compaction is due solely to the static weight of the machine. Satisfactory compaction of thick lifts cannot be accomplished in this case.

When sheepsfoot rollers are used, the criteria for job control can be determined by a test in the field. The feet must penetrate into the loose lift. If they ride on top, the machine is too light and the ballast must be increased. With succeeding passes, the feet should "walk out" of the layer. The number of passes required for the feet to walk out of the layer will then be used to control subsequent layers. If the feet do not walk out, the machine is too heavy and is shearing the soils, or the soil is too wet. The roller should be lightened and a new test should be performed for job control or the soil should be dried by the methods previously mentioned.

To be effective, smooth steel wheel rollers should weigh at least 10 tons and exert a minimum force of 300 lb per linear inch of width on the compression roll faces. These data can usually be obtained by referring to the manufacturer's specifications for the roller. At least eight passes over the lift at a maximum speed of 6 ft/sec is usually adequate. These rollers may be used on lifts of 8 in. or less of compacted thickness.

If the contractor wants to use equipment that cannot be placed into one of the preceding categories, a job site test should be performed to evaluate the effectiveness of the equipment and determine job control requirements. If such a situation exists, the engineer should be contacted for assistance.

COMPACTION IN CONFINED AREAS

There are two types of compaction: in large areas accessible to full-sized compactors and in confined areas accessible only to smaller, highly ma-

neuverable or hand-operated mechanical compactors. There is no precise definition of confined areas; each case should be considered on its own merits. For example, projects for which the pavement is being widened 2 ft on either side may be considered to be in a confined area, even though the job is 10 mi long, because the subbase material will be placed in a trench much narrower than the width of conventional embankment compaction equipment.

Compacting material behind a bridge abutment may require high maneuverability, which the usual fill compactors do not have. Pipe and conduit backfill and backfill behind retaining walls and minor structures are common cases that require confined-area compaction.

Any compaction equipment except hand tampers (unless mechanized) may be used in confined areas. Equipment that may not be acceptable in some situations may be acceptable in confined areas. For example, vibratory rollers with small diameter drums and operating at a high frequency should not be used to compact large areas, but they may be quite satisfactory in confined areas. The basic question for a confined-area compactor is, "Will it do the job?"

Material placed within confined areas should be limited to lifts not exceeding 6 to 8 in. before compaction. Some equipment may require even thinner lifts. The material should then be compacted with a number of passes sufficient to meet the specification density requirements.

INSPECTION

The field inspector has a number of aspects to check during compaction operations. There may be different density requirements in different areas of the fill. Certain types of compaction equipment may work better with one soil type than another. However, the contractor must have control over his own operations. If there are two ways to perform an operation, the contractor decides which method to employ. Continuous inspection can ensure that the work is performed in accordance with the specifications.

When specifications require certain equipment and methods of operation, the inspector will be required to verify that the equipment used complies with the specification requirements. If a job site test is required, the specifics of the test will be determined by the engineer. The inspector will probably be required to observe and measure the results, but it will be the engineer's responsibility to interpret them and determine whether the contractor has complied with the specifications.

It is extremely important that the layer or lift thickness not exceed the maximum allowable thickness. As the lift thickness increases, the effec-

tiveness of a compactor is reduced significantly because the compactive stresses at the bottom of the layer are too low to ensure proper compaction.

From tests using a pneumatic-tired roller, it is known that stresses are reduced by one-half at a depth of 12 or 14 in. The layer thicknesses given in the specifications should be established so that a desirable minimum stress level is exerted at the base of a layer, and together with the minimum number of passes, will result in proper compaction.

The inspector must also verify the compactive effort applied to the lift. This involves checking to ensure that the compactor applies at least the minimum number of passes at or below the maximum specified speed. The initial passes increase the density of the soil considerably. If the specified minimum number of passes is not applied, then the material at the bottom of the lift will not be compacted to the desired degree, and future settlement of the layer can be expected.

Verification of the number of passes becomes more significant because of limitations in the amount of density testing and the tendency toward thicker embankment lifts. The inspector is not going to test everything, but should base decisions to test on visual observations. In an end-result type of specification (see Chapter 3, section on Specifications), the type of equipment and number of passes probably will not be specified. To ensure that compactive effort is being obtained, much more density testing is usually necessary. Therefore, the inspector must use good judgment in such cases.

The stability of the lift under the action of the compactor will usually dictate the course of action to be taken. Corrective action should be taken when the lift shows significant weaving, pumping, or rutting under the action of the compactor (see sections on Weaving and Pumping and Rutting). This again is a judgment decision on the part of the engineer, but if a machine is merely leaving a tire print, this is not considered to be significant rutting. However, if the equipment displaces the soil laterally out of the wheelpath and leaves a visible rut, then something is wrong and corrective action must be taken before additional fill layers are placed. In this case, it does not matter what the present density is.

The main purpose of inspection of the compaction operations is to verify that the embankment is uniform and dense. A properly placed embankment will ensure acceptable performance throughout its useful life. As a general rule, a proper visual inspection of the compaction operations can ensure that this result is attained. Once the inspector knows how the compaction and hauling equipment affects a properly compacted layer, the contractor can be allowed to proceed with additional fill when the minimum specification requirements have been met.

In order to become familiar with soil conditions, it will probably be necessary to conduct more density tests at the beginning of the project and at the time that a new soil type is encountered. In this way, the compaction characteristics can be determined for the entire embankment lift rather than just at the test location. With the widespread use of the moisture/density nuclear gauges (see Chapter 3, section on Density and Water Content by Nuclear Methods), many more tests can be conducted in a shorter time and, therefore, specification compliance is more easily ensured today than in the past.

As described in Chapter 3, section on Specifications and Compaction Control, there are a number of methods for performing field density tests, such as the sand cone method (AASHTO T 191), balloon method (AASHTO T 205), and the nuclear gauge (AASHTO T 238). All of these tests provide acceptable results. Nuclear testing equipment requires a special license and may only be used by a licensed operator.

At the close of each day's work, the working surface of the fill should be crowned, shaped, and rolled with smooth steel wheel or pneumatic-tired rollers to ensure proper drainage, should it rain overnight. Thus, rainwater will be directed to the edges of the fill, and unless the rain is intense and of long duration, damage to the surface will be limited to the top few inches. The next day this wet material may be scraped off to the side to dry or be allowed to dry in place. Normal construction activities may then proceed. If, however, a significant rainfall occurs, the water may infiltrate the fill and require extensive corrective action. There will be instances in which this is unavoidable, but they will be minimized if the preceding preventive measures are taken.

STRUCTURE BACKFILL

The backfill of structures, pipes, and culverts must be performed correctly and compacted to specification requirements. Improper placement of backfill material or poor compaction can result in undesirable settlements and subsidence of the pavement.

Usually, a loose lift thickness of 6 in. and at least the same relative compaction as specified for the embankment are required. These specifications, together with the backfill gradation requirements, thorough inspection, and frequent density testing will generally ensure satisfactory results. Because the required degree of compaction is high and the areas are confined, the contractor must use small, highly maneuverable compaction equipment that does not exert high loads on the soil (see section on Compaction in Confined Areas). It is almost impossible to visually judge the adequacy of the compaction operations in these areas, and

much more frequent density tests are necessary. See Chapter 7 for additional information on structure backfills.

PROOF ROLLING

The specifications may require proof rolling of embankment fills in order to find areas of poor compaction, and in cuts, areas of the subgrade that are so soft that they will not satisfactorily support the proof roller. Proof rolling is done before placement of the subbase. If the compaction of the upper embankment layers is not uniform, or if the excavated soil conditions are not uniform and dense, these nonuniformities will be reflected in poor performance and high maintenance of the pavement.

In most jobs, the contractor has had complete control over the construction of the embankment, and proof rolling will provide a check on quality control. Because most proof rollers are ballasted with soil, a correlation can be determined between height of ballast in the roller box and different gross loads. An average density of 115 pcf for the ballast will generally give satisfactory results.

The proof roller should be operated briefly, and the response of the embankment under the action of the roller should be watched closely. If there is consistent lateral displacement of soil out of the wheelpaths, the proof roller may be loaded too heavily. Lateral displacement means rutting and shearing of the soil. Proof rolling is not designed or intended to cause the embankment to fail, but rather to point out areas of inadequate as well as nonuniform compaction. If the roller weight is reduced and consistent rutting still occurs, the proof roller should be further unballasted. This procedure may be followed until the roller does not consistently displace the soil.

Once a final acceptable weight has been determined, the roller should make two complete coverages on the subgrade surface within the outside edges of shoulders (roadway limits). Depressions should be filled with material similar to the subgrade soil so that uniformity will be maintained.

Major deficiencies must be corrected; the corrected areas are then recompacted in the normal manner and proof rolled again. All corrected deficiencies are at the contractor's expense until the subgrade surface shows a satisfactory uniform response to proof rolling. It is the earthwork contractor's responsibility to provide a suitable foundation for the pavement structure. Until this suitable foundation is provided, the earthwork construction is not complete, with two exceptions: proof rolling embankments may be eliminated in areas of limited access or maneuvering space

when it might damage adjacent construction or when the proof roller may come within 5 ft of a culvert, pipe, or other conduit.

Because correction of subgrade deficiencies in cuts is the owner's responsibility (see section on Soft Ground), once an area is undercut and backfilled by design, proof rolling should not be necessary. For example, an area ordered by the engineer to be undercut and backfilled because of conditions discovered during construction should not require proof rolling.

The proof roller used in cuts is normally loaded to 30 tons gross load and has tires inflated to 40 psi. Note that these conditions may be different from the ones normally used in embankment sections. It is not in the owner's interest to overload the roller because this may falsely show more areas requiring corrective undercut and backfill work.

Two complete passes are generally satisfactory. The engineer may require additional undercut and backfill work based on the action of the proof roller on the subgrade. As in embankment sections, proof rolling in cuts is not intended to destroy the subgrade, but to point out areas of inadequate subgrade support.

TRANSITIONS

As the name implies, transitions—both longitudinal and transverse—attempt to provide a gradual change from one subgrade support condition to another. Significant differences, if they are abrupt, will be adversely reflected in the finished pavement.

There are two main subgrade conditions in which transitions are necessary: (a) cut to embankment fill, and (b) rock cut to soil cut. Transitions are generally constructed with materials, as specified, that contain no particles that have a maximum dimension greater than 6 in. The intent is uniformity rather than a material with special properties. Therefore, specifying a high quality fill material should only be necessary when conditions warrant. For example, if the soil cut is unstable in a soil cut-rock cut transition, the high quality fill material should be continued into the rock cut.

Water in the subgrade may run along the surface of the rock and, unless it drains, may saturate the soil cut, causing an unstable condition. The rock may be naturally fractured or porous enough to remove any excess water. At times, blasting operations near this rock-soil interface will fracture the rock below the required subgrade level and provide an outlet for the water.

The necessity for longitudinal transitions depends on conditions at the site when the cut is completed; it cannot be determined during design. Therefore, each longitudinal transition from rock cut to soil cut must be

inspected and evaluated by the engineer, who will decide whether a longitudinal transition should be installed.

BENCHING

When embankments are to be constructed on slopes or where a new fill is to be placed against an existing embankment, the slopes of the original hillside or existing embankment normally are benched in order to key the new fill into the existing slope. Benching is usually specified for all embankments intersecting an existing earth slope that is one vertical on three horizontal or steeper, either transversely or longitudinally. Without benching, the sloping original ground surface creates a natural plane of weakness when the embankment fill is built against it. Benching breaks up the potential failure plane, thus increasing the stability of the entire system. The widths of the benches are variable, depending on the slope angle, with the height typically held to approximately 4 ft.

SLOPE PROTECTION

Often excavations for earthwork construction intercept the existing groundwater table, thus interrupting the natural flow of groundwater. This does not affect the highway until the groundwater flow emerges on the cut slope. If the flow is small, there may be no adverse effects. However, when the flow is significant and the conditions at the site are favorable, flowing water can cause seepage forces that will in turn cause the slope to slough or fail.

To stabilize slopes under these conditions, a heavy material is placed on the face of the slope. This material is heavy enough to hold down the existing soil even though seepage forces are acting in an outward direction. At the same time, it is open enough to carry all the water emerging from the existing soil. A coarse-graded stone, slag, or gravel blanket on top of a recommended geotextile has proven to be effective in these cases. The drainage blanket should be designed before construction, but weather conditions during construction will substantially influence the actual need for such treatment. Chapter 5 contains additional information on erosion control and drainage.

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ABBREVIATIONS

    AASHTO   American Association of State Highway and Transportation Officials
    FHWA   Federal Highway Administration

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