Embankment Construction

A. General Information

Quality embankment construction is required to maintain smooth-riding pavements and to provide slope stability. Proper selection of soil, adequate moisture control, and uniform compaction are required for a quality embankment. Problems resulting from poor embankment construction have occasionally resulted in slope stability problems that encroach on private property and damage drainage structures. Also, pavement roughness can result from non-uniform support. The costs for remediation of such failures are high.

Soils available for embankment construction in Iowa generally range from A-4 soils (ML, OL), which are very fine sands and silts that are subject to frost heave, to A-6 and A-7 soils (CL, OH, MH, CG), which predominate across the state. The A-6 and A-7 groups include shrink/swell clayey soils. In general, these soils rate from poor to fair in suitability as subgrade soils. Because of their abundance, economics dictate that these soils must be used on the projects even though they exhibit shrink/swell properties. Because these are marginal soils, it is critical that the embankments be placed with proper compaction and moisture content, and in some cases, stabilization (see Section 6H-1 - Foundation Improvement and Stabilization).

Soils for embankment projects are identified during the exploration phase of the construction process. Borings are taken periodically along the proposed route and at potential borrow pits. The soils are tested to determine their engineering properties. Atterberg limits are determined and in-situ moisture and density are compared to standard Proctor values. However, it is impossible to completely and accurately characterize soil profiles because of the variability between boring locations. It is necessary for field staff and contractors to be able to recognize that soil changes have occurred and make the proper field adjustments.

Depending on roller configuration, soil moisture content, and soil type, soils may be under- or over-compacted. If soil lifts are too thick, the “Oreo cookie effect” may result, where only the upper part of the lift is being compacted. If the soils are too wet, over-compaction from hauling equipment can occur with resultant shearing of the soil and building in shear planes within the embankment, which can lead to slope failure.

Construction with soil is one of the most complicated procedures in engineering. In no other field of engineering are there so many variables as to the material used for construction. It is also widely recognized that certain soils are much more suitable for some construction activities than others.

A general understanding of soil and its different properties is essential for building a quality embankment. The engineering properties of a soil can vary greatly from gravel to clays. In order to build a quality embankment, the specific properties of the soil being used must be understood in order to make proper field judgments.

Ongoing debate exists among practitioners in geotechnical engineering about whether to compact soil wet-of-optimum-moisture content or dry-of-optimum moisture content. There is no decisive answer to this question. The only correct answer is that the ideal moisture content depends on material type and the desired characteristics (which often are competing) of the embankment. Strength, stability, density, low permeability, low shrink/swell behavior, and low collapsibility are all desired outcomes of a quality embankment.

Strength is obviously a desirable characteristic and is a function of many factors but can be directly related to moisture content. The U.S. Army Corps of Engineers (USACE) used the California Bearing Ratio (CBR) as an efficient measurement of strength in cohesive soils. The USACE reports, “the unsoaked CBR values are high on the dry side of optimum, but there is a dramatic loss in strength as molding moisture content is increased” (Ariema and Butler 1990; Atkins 1997). Hilf (1956) produced the same results from tests using penetration resistance as a measure of strength. When a soil is in a dry state, it exhibits high strength due to an appreciable inter-particle, attractive force created by high curvature of the menisci between soil particles. However, further wetting greatly reduces this friction strength by lubrication of the soil particles. Alternatively, in cohesionless soils, the strength is not as significantly affected by an increase in moisture, due to its high hydraulic conductivity.

Stability is a second desirable characteristic. However, stability cannot be defined as one characteristic. There is stability related to strength, which reacts to moisture contents described above; and there is also volumetric stability. When dealing with highly plastic clays, this is an extremely important factor since these clays exhibit shrink/swell behavior with a change in moisture content. Swelling of clays causes more damage in the United States than do the combined effects of all other natural disasters. It is general practice when dealing with fat clays to place the fill wet of optimum. This basically forces the clay to swell before compacting it in the embankment. Moisture content becomes important in cohesionless materials with respect to volumetric stability when the bulking phenomenon is considered. At the bulking moisture content, a cohesionless soil will undergo volumetric expansion, or “bulk” (see Section 6A-2 - Basic Soils Information). Additionally, the material will exhibit apparent cohesion, and compaction cannot be achieved. Therefore, in terms of volumetric stability, truly cohesionless materials should be compacted when dry or saturated.

Density is perhaps the characteristic most widely associated with embankment construction. The Proctor test is the most widely used laboratory test to determine maximum dry density and optimum moisture content of cohesive soils as a function of compaction energy. However, the standard Proctor test is not a valid test for all cohesionless soils. Cohesionless soils require the relative density test to determine a maximum and minimum dry density.

Once the desirable material properties have been identified, the next process in building a quality embankment is the correct placement of the soil. The importance of soil preparation before rolling is not adequately appreciated. Blending of the soil to achieve a homogeneous composition and moisture content is essential for quality embankment construction. Proper roller identification and use are also essential. Not all rollers are adequate for all soil types. Sheepsfoot rollers are ideal for cohesive soils, while vibratory rollers must be used on cohesionless materials. Inter-grade soils require inter-grade rollers, such as a vibratory sheepsfoot (Chatwin et al. 1994).

B. Site Preparation

1. **Clearing and Grubbing:** The site should be prepared by first clearing the area of vegetation, fencing rubbish, and other objectionable materials.

2. **Stripping, Salvaging, and Spreading Topsoil:** The site should be mowed and any sod shredded by shallow plowing or blading and thorough disking so the soil can be easily placed in a thin layer over areas to be covered.

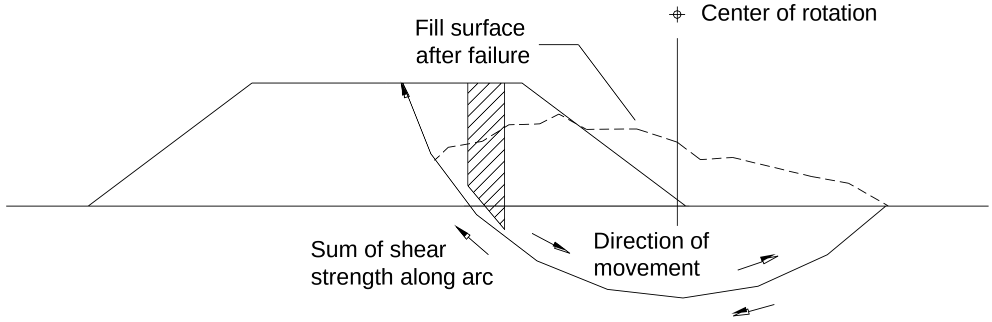
   An adequate amount of topsoil should be removed from the upper 12 inches of existing onsite topsoil to allow a finished grade of 8 inches of salvaged or amended topsoil. The topsoil may be moved directly to an area where it is to be used or may be stockpiled for future use. If existing topsoil lacks adequate organic content, off-site soil may be required, or existing topsoil may be blended with compost (see SUDAS Specifications Section 2010, 2.01 for proper blending ratios).

C. Design Considerations

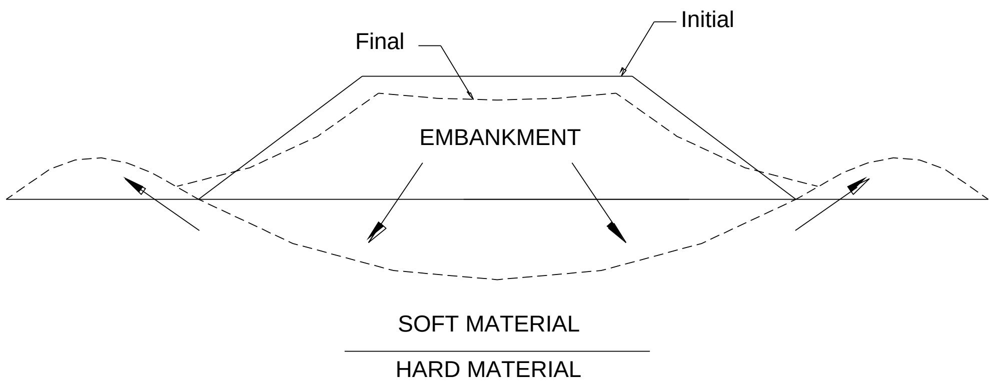
1. **Slope Stability Evaluation:** Foundation soils and embankments provide adequate support for roadways and other transportation infrastructure if the additional stress from traffic loads and geo-structures does not exceed the shear strength of the embankment soils or underlying strata (Ariema and Butler 1990). Overstressing the embankment or foundation soil may result in rotational, displacement, or translatory failure, as illustrated in Figure 6D-1.01.

   Factors of safety are used to indicate the adequacy of slope stability and play a vital role in the rational design of engineered slopes (e.g. embankments, cut slopes, landfills). Factors of safety used in design account for uncertainty and thus guard against ignorance about the reliability of the items that enter into the analysis, such as soil strength parameter values, pore water pressure distributions, and soil stratigraphy (Abramson et al. 2002). As with the design of other geostructures, higher factors of safety are used when limited site investigation generates uncertainty regarding the analysis input parameters. Investment in more thorough site investigation and construction monitoring, however, may be rewarded by acceptable reduction in the desired factor of safety. Typically minimum factors of safety for new embankment slope design range from 1.3 to 1.5. Factors of safety against slope instability are defined considering the likely slope failure mode and the strength of slope soils.

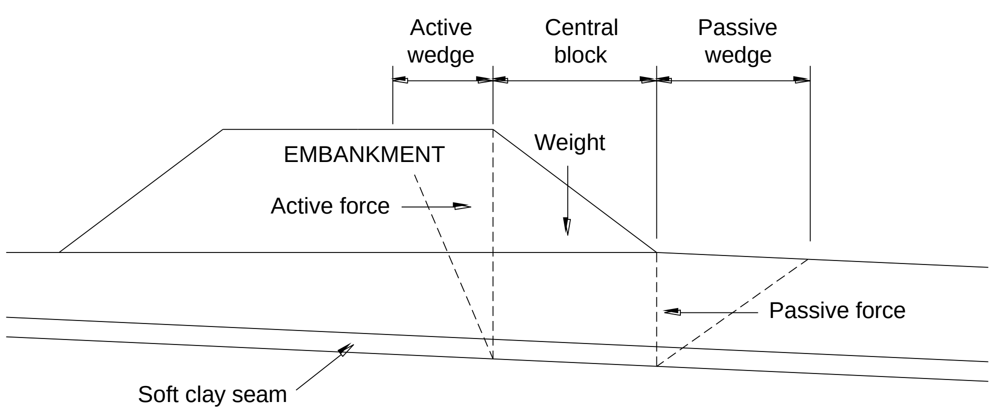
Figure 6D-1.01: Typical Embankment Failures



ROTATIONAL FAILURE



DISPLACEMENT FAILURE



TRANSLATORY FAILURE

Source: Ariema and Butler 1990

2. **Causes of Slope Instability:** Stable slopes are characterized by a balance between the gravitational forces tending to pull soils downslope and the resisting forces comprised of soil shear strength. The state of temporary equilibrium may be compromised when the slope is subject to de-stabilizing forces. The factors affecting slope stability may include those that increase the gravitational force (e.g. slope geometry, undercutting, surcharging) or those that reduce soil shear strength (e.g. weathering, pore water pressure, vegetation removal) (Chatwin et al. 1994).

3. **Slope Stability Problems in Iowa:** Slope instability poses problems for roadway systems in Iowa. Failures occur on both new embankments and cut slopes. The failures occur because identifying factors that affect stability at a particular location, such as soil shear strength parameter values, ground water surface elevations, and negative influences from construction activities, are often difficult to discern and measure. Hazard identification is a cornerstone of landslide hazard mitigation (Spiker and Gori 2003). Once a failure occurs or a potential failure is identified (i.e. low factor of safety), roadway agencies need information and knowledge of which methods of remediation will be most effective to stabilize the slope. Ideally, these stability problems can be discovered and addressed before a slope failure occurs.

   Approximately 50% of slope remediation projects involve changes in slope geometry (in effect, creating a stability berm). The design and construction of stability berms have historically been a simple and effective option of departments of transportation for preserving transportation infrastructure.

4. **Stabilization Methods:** A number of methods are available to stabilize slopes, including re-grading to flatten the slope; construction of stability berms; the use of lightweight fill, geofoam or shredded tires to reduce the load; and structural reinforcing methods such as geosynthetic reinforcements, stone columns, rammed aggregate piers, soil nailing, and piles. Additional information on such methods to address slope instability can be found in Section 6H-1 - Foundation Improvement and Stabilization.

D. Equipment

Table 6D-1.01 provides suggested compaction equipment and compacted lift thicknesses for coarse- and fine-grained soils, according to the USCS and AASHTO soil classification systems.

Table 6D-1.01: Recommended Field Compaction Equipment

Soil	First Choice	Second Choice	Comment
Rock fill	Vibratory	Pneumatic	--
Plastic soils, CH, MH	Sheepsfoot or pad foot	Pneumatic	Thin lifts usually needed
Low-plasticity soils, CL, ML	Sheepsfoot or pad foot	Pneumatic, vibratory	Moisture control often critical for silty soils
Plastic sands and gravels, GC, SC	Vibratory, pneumatic	Pad foot	--
Silty sands and gravels, SM, GM	Vibratory	Pneumatic, pad foot	Moisture control often critical
Clean sands, SW, SP	Vibratory	Impact, pneumatic	--
Clean gravels, GW, GP	Vibratory	Pneumatic, impact, grid	Grid useful for over-size particles

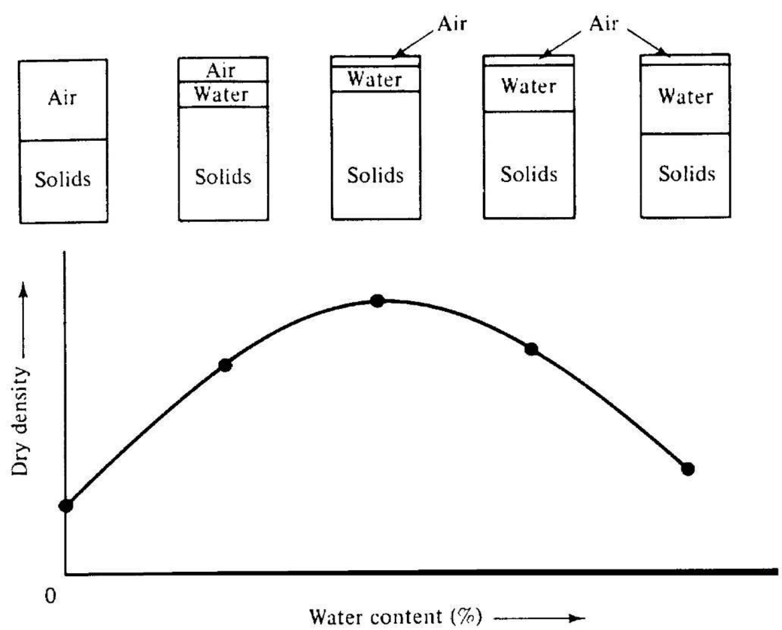
Source: Rollings and Rollings 1996

E. Density

Maximum Dry Density: Compaction requirements are measured in terms of the dry density of the soil. The expected value for dry density varies with the type of soil being compacted. For example, a clay soil may be rolled many times and not reach 125 pcf, whereas a granular soil may have a dry density above this value without any compactive effort. Therefore, a value for the maximum possible dry density must be established for each soil (Atkins 1997).

For any compactive effort, the dry density of a soil will vary with its water content. A soil compacted dry will reach a certain dry density. If compacted again with the same compactive effort, but this time with water in the soil, the dry density will be higher, since the water lubricates the grains and allows them to slide into a denser structure. Air is forced out of the soil, leaving more space for the soil solids, as well as the added water. With even higher water content, a still greater dry density may be reached since more air is expelled. However, when most of the air in the mixture has been removed, adding more water to the mixture before compaction results in a lower dry density, as the extra water merely takes the place of some of the soil solids. This principle is illustrated in Figure 6D-1.02.

Figure 6D-1.02: Variation of Dry Density with Water Content



The first step in compaction control is to determine the maximum dry density that can be expected for a soil under a certain compactive effort, and the water content at which this density is reached. These are obtained from a compaction curve, as discussed in Section 6A-2 - Basic Soils Information. The compaction curve is also called a moisture-density curve or a Proctor curve (named after the originator of the test). The curve is plotted from the results of the compaction test. Dry density is plotted against water content, and a curve is drawn through the test points. The top of the curve represents the maximum dry density for the soil with the test compactive effort and the corresponding water content, which is called the optimum water content (W_o).

F. Compaction

In-situ soils used as subgrades for the construction of roadway pavements or other structures and transported soils used in embankments or as leveling material for various types of construction projects are usually compacted to improve their density and other properties. Increasing the soil's density improves its strength, lowers its permeability, and reduces future settlement.

The evaluation of the density reached as a result of compactive efforts with rollers and other types of compaction equipment is the most common quality-control measurement made on soils at construction sites. The density of the soil as compacted is measured and compared to a density goal for that soil, as previously determined in laboratory tests. The moisture-density relationships for fine-grained (cohesive) soils and coarse-grained (cohesionless) soils are discussed in Section 6A-2 - Basic Soils Information.

1. **Compaction of Fine-grained Soils:** The compaction method for a fine-grained soil is entirely different than that for a coarse-grained soil. The reason is that fine-grained soils possess cohesion. It should be remembered that the finer fraction of the fine-grained soils exists in a colloidal state, and all colloids possess cohesion. The mineral grains of a cohesive soil are not in physical contact, as they are in a coarse-grained soil. Every grain is surrounded by a blanket of water, whose molecules are electrically bonded to the grains. This blanket of water isolates the grains and prevents them from being in physical contact with adjacent grains (Duncan 1992).

   The degree to which a fine-grained soil can be compacted is almost wholly dependent on the in-situ moisture content of the soil. The moisture content that corresponds to the maximum degree of compaction (under a given compaction energy) is called the optimum moisture content. The approximate optimum moisture content of several soil groups is given in Table 6D-1.02.

Table 6D-1.02: Maximum Dry Density and Optimum Moisture Content
(Typical for Standard Compaction Energy)

AASHTO Classification	Maximum Dry Density (pcf)	Moisture Content (%)
A-1	115-135	7-15
A-2	110-135	9-18
A-3	110-115	10-18
A-4	95-130	10-20
A-5	85-100	15-30
A-6	95-120	10-25
A-7	85-115	15-30

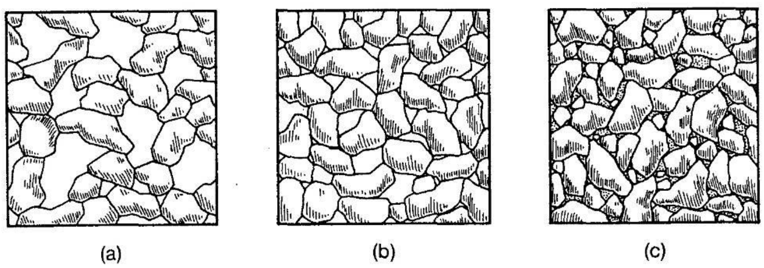
2. **Compaction of Coarse-grained Soils:** The method behind why compaction works for a coarse-grained soil is entirely different than that for a fine-grained soil. Coarse-grained soils exist by their very nature in inter-granular contact, much like a bucket of marbles. The way these grains are arranged within the mass and the distribution of particle size throughout the mass, will ultimately determine the density, stability, and load-bearing capacity of that particular soil (Duncan 1992).

   The honeycombed structure shown in Figure 6D-1.03a is representative of very poor inter-granular seating. Such a structure is inherently unstable and can collapse suddenly when subjected to shock or vibration. The stability and load-bearing capacity of this type of soil will be improved by compaction because of the resulting rearrangement in inter-granular seating. With sufficient compaction, this structure will take on the characteristics of the arrangement shown in Figure 6D-1.03c.

The arrangement of particles shown in Figure 6D-1.03b provides maximum inter-granular contact, but there are insufficient fines to lock the larger particles in place. Compaction of this type of arrangement is ineffective, since neither additional particle contact nor additional stability can be achieved. This soil is inherently stable, however, when it is laterally restrained, and demonstrates good load-bearing characteristics. When insufficiently restrained, however, this soil will be free to move laterally, in which case there is a pronounced loss in stability and load-bearing characteristics.

The arrangement of particles shown in Figure 6D-1.03c not only provides maximum inter-granular contact, but also inherent stability. This very important property of stability is due to the inclusion of fines in the spaces between the larger particles. One cautionary note must be made concerning fines: too many fines are detrimental to the mix because they may separate the larger grains, thereby destroying the inter-granular contact between them. In this instance, the larger grains are more or less floating in a sea of fines.

Figure 6D-1.03: Inter-granular Seating and Gradation of Coarse-grained Particles



(a) Poorly graded, poorly seated particles
(b) Poorly graded, but well-seated
(c) Well-graded and well-seated particles

The inter-granular seating of a coarse-grained soil can be improved by the process of compaction. Particle distribution can be improved by the physical addition and mixing of fines into the soil. Both of these separate actions increase the density of the soil. Density is a function of the amount of voids contained within a given volume of soil. The potential for a soil to be further densified depends upon how much of a reduction can be made in the void ratio. This reduction is not without limit. Every mixture of granular material inherently has a minimum void ratio (maximum density), and for a given mixture, this ratio cannot be changed. Once a soil has been compacted to its maximum density, continued efforts at compaction will only result in the crushing of the individual grains as described in Section 6A-2 - Basic Soils Information.

Compaction of coarse-grained soils is usually considered to be adequate when the relative density of the soil in place is no less than some specified percentage of its maximum possible density. Relative density is a term used to numerically compare the density of an in-place natural or compacted soil, with the densities represented by the same soil in the extreme states of looseness and denseness, as described in Section 6A-2 - Basic Soils Information.

3. **Compaction of Mixed-grained Soils:** Natural deposits of soil frequently contain gravel, sand, silt, and clay in various proportions. Such soils are referred to as mixed-grained. Soils that are mixed-grained will, in all likelihood, exhibit some of the characteristics of both coarse-grained and fine-grained soils. The deciding factor as to whether a particular soil should be compacted according to coarse-grained or fine-grained requirements is that of cohesion (true or apparent) (Duncan 1992).

a. **Soils that do not Exhibit any Measurable Cohesion:** Treat as coarse grained soil; base compaction on the relative density.

b. **Soils that do Exhibit Measurable Cohesion:** Treat as fine-grained soil; base compaction on the Proctor Density Test.

c. **Inter-grade Soils:** Conduct both Relative Density and Proctor Density Tests; base compaction on the test method yielding the highest maximum density.

G. Embankment Soils

SUDAS classifies Iowa cohesive soils into select subgrade materials, suitable soils, or unsuitable soils, depending on soil index properties and Proctor test results. See Section 6E-1 - Subgrade Design and Construction for more information.

1. **Select Subgrade Soils:** Select materials (see Section 6E-1 - Subgrade Design and Construction) or subgrade treatments (see Section 6H-1 - Foundation Improvement and Stabilization) may be used in the prepared subgrade (the top 12 inches immediately below the pavement or subbase, if present) to provide adequate volumetric stability, low frost potential, and good bearing capacity as it relates to the California Bearing Ratio (CBR ≥ 10).

2. **Suitable Soils:** Suitable soils are used throughout the fill and under the prepared subgrade. Suitable soils may be used in the prepared subgrade if they meet the requirements of select subgrade soils or are stabilized to meet those requirements (i.e., CBR ≥ 10). Suitable soils must meet all of the following conditions:

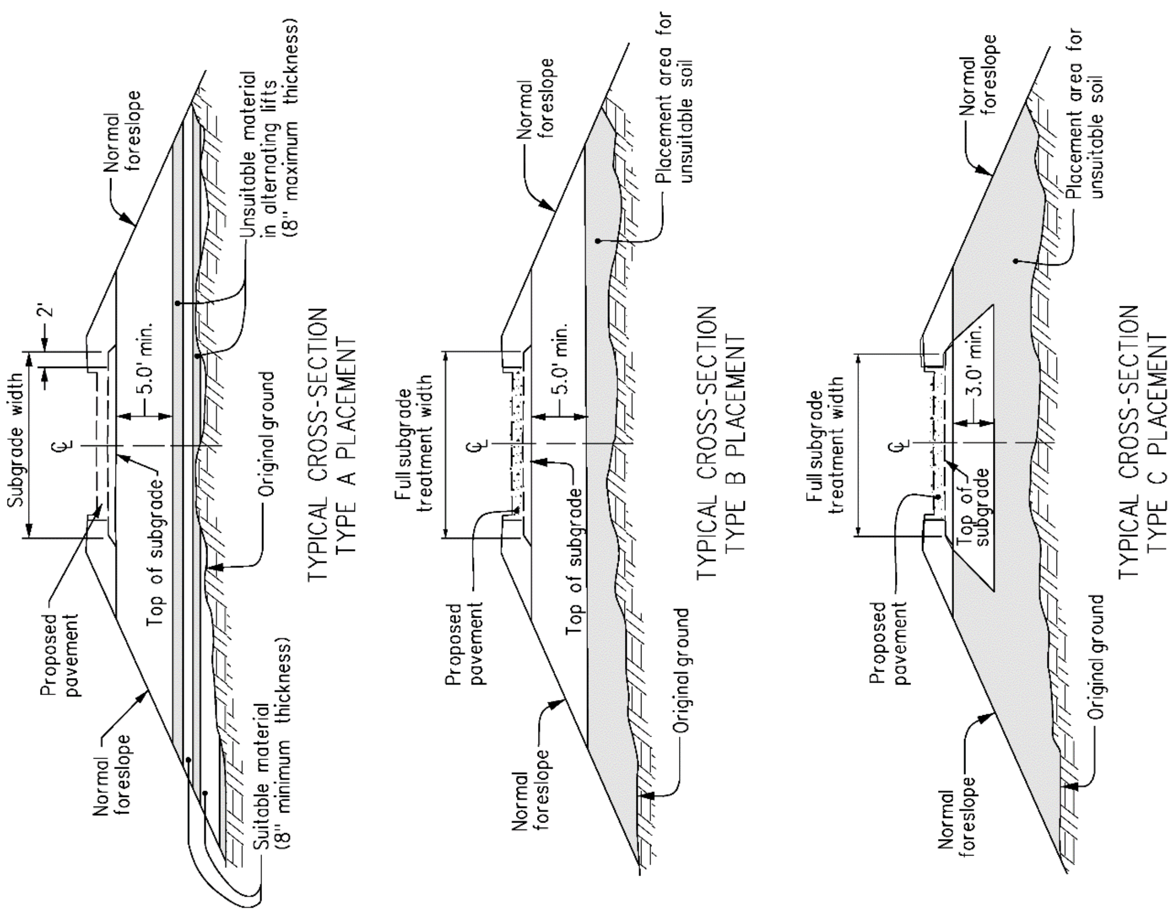
   a. Standard Proctor Density ≥ 95 pcf

   b. Group index < 30 (AASHTO M 145)

3. **Unsuitable Soils:** The SUDAS Specifications do not allow use of unsuitable soils in the right-of-way. However, there may be situations where the Engineer might consider the placement of unsuitable soils in the right-of-way. The Iowa DOT allows this placement. Figure 6D-1.04, modified from Iowa DOT Standard Road Plan EW-102, illustrates Iowa DOT's guidance for the use of unsuitable soils in an urban embankment section.

Figure 6D-1.04: Placement of Unsuitable Soils

Placed 4 feet below subgrade in fills outside curbline	1. Broken PCC in 6 inch sizes or smaller (pulverized HMA may be used as subgrade replacement)
Type A Placement Place in layers (8 inch max. thickness) 5 feet below subgrade and 2 feet outside curbline in fills. Provide alternate layers of suitable soils or soils other than A-7 or A-5 containing 3% or more carbon)	1. Shale 2. A-7-5 or A-5 soils having a density greater than 86 pcf but less than 95 pcf (ASTM D 698 Standard Proctor Density).
Type B Placement Placed 5 feet below subgrade and outside curbline in fills	1. A-7-6 (Plasticity index of 30 or greater) 2. Residual clays (overlying bedrock) regardless of classification.
Type C Placement Placed 3 feet below subgrade in fills (may be placed 2 feet outside of curbline).	1. All soils other than A-7-5 or A-5 having a density of 95 pcf or less (ASTM D 698 Standard Proctor Density). 2. All soils other than A-7 or A-5 containing 3% or more carbon.
Slope dressing only	1. Peat or muck 2. Soils with a plasticity index of 35 or greater 3. A-7 or A-5 (AASHTO) having a density less than 85 pcf (ASTM D 698 Standard Proctor Density)



Source: Modified version of Iowa DOT's Standard Road Plan EW-102.

H. Testing

Inherent to the quality construction of roadway embankments is the ability to measure soil properties to enforce quality control measures. In the past, density and moisture content have been the most widely measured soil parameters in conjunction with acceptance criteria.

1. **In-place Soil Density Requirements:** The Engineer must first establish the standard to which the field work must conform. This standard differs depending upon whether the soil is classified as coarse-grained, fine-grained, or inter-grade (Duncan 1992).

   a. **In-place Soil Density:** The SUDAS Specifications require 95% Standard Proctor Density for cohesive soils and 70% Relative Density for cohesionless soils. If different density requirements are warranted for a project, the Engineer must specify those modifications. As the default, SUDAS Specifications require moisture and density control for embankment construction. In lieu of moisture and density control, the Engineer may specify Type A compaction, which is roller walkout and does not require moisture and density testing.

   b. **Tests to Verify In-place Soil Density:** For these classifications of soil, the dry density of the in-place, compacted soil must be determined. There are three procedures whereby the wet density of the in-place soil can be readily determined in the field. Once the in-place wet density and the moisture content are known, the dry density can be easily computed. These procedures are described in the following ASTM Standards:
      1) **Density of Soil in Place by the Sand-cone Method (ASTM D 1556):** This method is generally limited to soil in an unsaturated condition. It is not recommended for soil that is soft or easily crumbled or for deposits where water will seep into the test hole.
      2) **Density and Unit Weight of Soil in Place by the Rubber Balloon Method (ASTM D 2167):** This method is not suitable for use with organic, saturated, or highly plastic soils. The use of this method will require special care with unbonded granular soils, soils containing appreciable amounts of coarse aggregate larger than 1½ inches, granular soils having a high void ratio, and fill materials having particles with sharp edges.
      3) **Density of Soil and Soil Aggregate in Place by Nuclear Methods (ASTM D 2922):** This method provides a rapid, non-destructive technique for the determination of in-place wet soil density. Test results may be affected by chemical composition, heterogeneity, and surface texture of the material being tested. The techniques also exhibit a spatial bias in that the apparatus is more sensitive to certain regions of the material being tested. Nuclear methods, of course, pose special hazards and require special care. The work must be done in strict conformance with all safety requirements and must be performed only by trained personnel.

2. **Field Control of Moisture Content:** SUDAS Specifications Section 2010 requires a moisture content of optimum moisture to 4% over optimum moisture. As discussed earlier, the moisture content may need to be modified, depending on the material type and desired characteristics. There are four general procedures whereby moisture content can be determined:

   a. Accurate results can be achieved by the laboratory analysis of samples using a drying oven according to AASHTO T 265. This method, however, may be too time consuming.

   b. Fast results can be obtained in the field with a portable moisture tester. This particular tester, which conforms to AASHTO T 217, provides for almost continuous monitoring of the moisture content because the test can usually be performed in three minutes or less.

   c. A microwave may be used for fine-grained soils, according to ASTM D 600.

d. A nuclear density unit may be used to provide an estimate of the moisture content, according to AASHTO T 239.

It is important that the moisture content of the soil be maintained as close to the target moisture content as can reasonably be expected during all stages of the compaction process. When the soil is too dry, the moisture content can be increased by sprinkling water over the surface, after which it must be thoroughly mixed into the soil to produce uniform moisture content throughout the mass. When the soil is too wet, the moisture content can be reduced by spreading the soil out, disking it, and letting it dry in the sun.

3. **Strength and Stability of Compacted Soil:** Two methods are used to determine the strength and stability of compacted soil.

   a. **California Bearing Ratio (CBR):** This method is probably the most widely used. A subgrade generally requiring a CBR of 10 or greater is considered good and can support heavy loading without excessive deformation (see Section 6E-1 - Subgrade Design and Construction, for additional information). For reference, some typical values of CBR soils are shown in Table 6D-1.03.

   b. **Dynamic Cone Penetrometer (DCP) Index:** This index, expressed in millimeters per blow, has been correlated to CBR for use in pavement design and evaluation, and is presented in ASTM Section B, Test Method No. 8. The correlation is advantageous because most flexible pavement design procedures are based on CBR. Several other DCP versus CBR relationships have been developed as well.

Table 6D-1.03: Typical CBR Values for Various Soils

Material Description	CBR
SC: clayey sand	10-20
CL: lean clays, sandy clays, gravelly clays	5-15
ML: silts, sandy silts	5-15
OL: organic silts, lean organic clays	4-8
CH: fat clays	3-5
MH: plastic silts	4-8
OH: fat organic clays	3-5

Source: Rollings and Rollings, 1996

Table 6D-1.04: Simple CBR Indicators of Wet Clay Soil

Material Description	CBR
Thumb penetration into the wet clay soil	
Easy	< 1
Possible	1
Difficult	2
Impossible	3+
A trace of a footprint left by a walking man	1

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