

1 Embankments

This module documents the Department's standard of practice for the investigation, design, and construction of embankments. Highway embankments, bridge approaches, embankment widening, and storm damage issues are addressed. Primary references for this module are:

- Soil Slope and Embankment Design, FHWA-NHI-132033, September 2005.
- Washington State Dept. of Transportation Geotechnical Design Manual, M 46-03.09, December 2013, Chapter 9 Embankments.
- Standard Specifications, 2010, State of California, Department of Transportation

Additional references are listed in Section 7, References.

The geoprofessional's role is to provide geotechnical recommendations for the design, construction, and maintenance of embankments that are practical, cost-effective, constructible, and value driven.

Our clients are primarily district design units to which we provide both planning and design recommendations. District design units submit work requests to GS that should include the following information:

- Plan sheets with embankment area(s);
- Cross-sections (typically at 50-foot to 100-foot intervals, more or less depending upon topography, etc.);
- Profiles of the planned alignment.

For planning phase requests these items may not be very well defined, but the geoprofessional should receive some information that indicates planned embankment locations and heights. For design phase requests, these items should be more thoroughly developed and must be provided. Communicate with the client to assure a common understanding of work to be addressed and project constraints.

For the purposes of this module, embankments include the following:

- Rock embankments, defined as fills in which the material in all or any part of an embankment contains 25 percent or more, by volume, cobbles and/or boulders;
- Structure approach embankments, defined as fill extending from a bridge abutment for 150 feet;
- Embankments are fills that are not classified as rock or structure approach embankments, but that are constructed with soil;
- Lightweight fills contain lightweight fill or recycled materials as a significant portion of the embankment volume, and the embankment construction is usually controlled by special provision. Lightweight fills are most often used as a portion

of the structure approach embankment to mitigate settlement and/or stability issues, or in landslide repairs to reestablish roadways.

2 Embankment Investigations

The key geotechnical considerations for design and construction of embankments are stability and settlement of the foundation soils, the impact of the stability and settlement on the construction staging and time requirements, and impacts to nearby structures, such as buildings, bridge foundations, and utilities. The investigation should include a detailed site review outside the proposed embankment footprint in addition to within the embankment footprint. The investigation should extend at least two to three times the width of the embankment on either side and to the top or bottom of slopes adjacent to the embankment. Furthermore, areas below proposed embankments should be fully explored if landslide activity is suspected.

2.1 Planning the Field Exploration and Laboratory Testing

The geoprofessional should assess project requirements and anticipated subsurface conditions to determine the type and quantity of information to be obtained during the geotechnical investigation. In order to complete the assessment:

- Identify performance criteria (e.g. allowable settlement, time available for construction, seismic design requirements, etc.);
- Identify potential geologic hazards, areas of concern (e.g. soft soils), and potential variability of local geology;
- Identify engineering analyses to be performed (e.g. limit equilibrium slope stability analyses, settlement evaluations, liquefaction susceptibility, lateral spreading/slope stability deformations,);
- Identify engineering properties required for these analyses;
- Determine methods to obtain parameters and assess the validity of such methods for the material type;
- Estimate the number of tests/samples needed and appropriate locations for them.

The goal of the site characterization for embankment design and construction is to develop the subsurface profile and soil property information needed for stability and settlement analyses. Soil parameters generally required for embankment design include:

- Total stress and effective stress strength parameters (friction angle, cohesion);
- Unit weight;
- Compression indexes (primary, secondary and recompression);
- Coefficient of consolidation.

Table 1 provides a summary of site characterization needs, and field and laboratory testing considerations for embankment design.

**Table 1: Summary of Information Needs and Testing Considerations for Embankments
(Adapted From Sabatini, Et. Al., 2002)**

Engineering Evaluations	Required Information for Analyses	Field Testing and Sampling	Laboratory Testing
<ul style="list-style-type: none"> • settlement (magnitude & rate) • bearing capacity • slope stability • lateral pressure • internal stability • borrow source evaluation (available quantity and quality of borrow soil) • geosynthetic reinforcement • liquefaction • delineation of soft soil deposits • potential for subsidence (karst, mining, etc.) • constructability 	<ul style="list-style-type: none"> • subsurface profile (soil, ground water, rock) • compressibility parameters • shear strength parameters • unit weights • time-rate consolidation parameters • horizontal earth pressure coefficients • interface friction parameters • pullout resistance • geologic mapping including orientation and characteristics of rock discontinuities • shrink/swell/ degradation of soil and rock fill 	<ul style="list-style-type: none"> • CPT (w/ pore pressure measurement) • SPT • piezometers (GWT and pore pressures during construction) • vane shear • geophysical testing • rock coring (RQD) • plate load test • test fill • settlement plates • slope inclinometers • Undisturbed Sampling 	<ul style="list-style-type: none"> • Consolidation Testing (1-D Oedometer) • triaxial tests • unconfined compression • direct shear tests • grain size distribution • Atterberg Limits • specific gravity • organic content • moisture-density relationship • hydraulic conductivity • geosynthetic/soil testing • shrink/swell • slake durability • unit weight • relative density

The size, complexity and extent of the sampling program will depend primarily on the type, height, and size of the embankment(s) as well as the anticipated soil conditions.

Generally, embankments 10 feet or less in height, constructed over average to good soil conditions (e.g., medium dense to very dense sand, silt or gravel, stiff or overconsolidated clays with low expansion potential, with no signs of previous instability, non-liquefiable) will require only a basic level of site investigation. A geologic site reconnaissance, combined with a few shallow borings, hand holes or possibly a few test pits to verify field observations and the anticipated site geology should be sufficient, especially if the geology of the area is well known, or if there is some prior experience in the area.

For larger embankments, or for any embankment to be placed over soft or potentially unstable ground, geotechnical explorations should be spaced no more than 500 feet apart

for uniform conditions. In non-uniform soil conditions, spacing should be decreased to intervals to achieve at least one boring in each major landform or geologic unit or a sufficient number of borings to adequately define subsurface conditions. A key to the establishment of exploration frequency for embankments is the potential for the subsurface conditions to impact the construction of the embankment and the long-term performance of the finished project.

Embankments over 10 feet in height, embankments over soft soils, or those embankments that could impact adjacent structures (i.e., bridge abutments, buildings etc.); must have geotechnical borings (existing borings that provide the needed information will suffice) for their design. The more critical areas for stability of a large embankment are between the hinge point and toe of the slope. This is where base stability is of most concern and where a majority of the borings should be located, particularly if the near-surface soils are expected to consist of soft fine-grained deposits. At critical locations, (e.g., maximum embankment heights, maximum depths and/or thicknesses of soft strata), a minimum of two borings in the transverse direction to define the subsurface conditions for stability analyses should be obtained. Additional borings to define the stratigraphy, including the conditions within and below existing fill, may be necessary for very large fills or erratic site conditions.

Embankment widening projects may need borings near the toe of the existing fill to evaluate the present condition of the underlying soils, particularly if the soils are fine-grained.

In addition, borings through the existing fill into the underlying consolidated soft soil, or, if over-excavation of the soft soil had been done during the initial fill construction, borings to define the extent of removal, should be obtained to define conditions below the existing fill.

In some cases, the stability and/or durability of the existing embankment fill may be questionable because the fill materials are suspect or because slope instability in the form of raveling, down-slope lobes, or slope failures are present. In these cases consider additional borings through the core of the embankment to sample and test the condition of the fill. If the distress is surficial, consider obtaining hand borings or grab samples for determining compaction and strength characteristics. The depth of borings, test pits, and hand holes will generally be determined by the expected soil conditions and the depth of influence of the new embankment. Explorations must penetrate through problem soils such as loose sand, soft silt and clay and organic materials, and at least 10 feet into competent soil. As a rule of thumb, geotechnical borings should be drilled to a minimum depth of twice the planned embankment height. However in some cases the width of the embankment may have a greater influence on the stress distribution and/or magnitude of settlement than the height and therefore will require that borings be drilled to depths greater than twice the embankment height. In mountainous areas this minimum depth recommendation may not necessarily apply because bedrock and or competent soils may

exist at depths shallower than twice the planned embankment height or less than what the width of what the proposed embankment would be. In order to ensure that the soils located under the proposed embankment are adequately studied, the geoprofessional should consider the following:

- local and/or site specific geologic conditions,
- the height and width of the new embankment to be built,
- the pressure influence or stress distribution that the new embankment will impart on the supporting soils.

Cone penetration test (CPT) probes should, if practicable, be used to supplement conventional borings. Besides being significantly less expensive, CPT probes allow the nearly continuous evaluation of soil properties with depth. They can detect thin layers of soil, such as a sand lens in clay that would greatly reduce consolidation time that would otherwise be missed in a conventional boring. In order to utilize the sand lenses, they must be continuous and extend beyond the loaded area to provide drainage. In addition, CPT probes can measure pore pressure dissipation responses to evaluate relative soil permeability and consolidation rates. Because there are no samples obtained, CPT probes should be used in conjunction with a standard boring program.

Consider geophysical testing for void detection, water infiltration and seepage, and evaluation of subsurface variability. Geophysical testing can also provide nearly continuous coverage along the length of an embankment and may be used both to plan the drilling investigation and to extrapolate information beyond test boring and piezometer locations. Geophysical investigations should be considered where supplementation of the drilling investigation is needed.

2.2 Groundwater

At least one piezometer should be installed in borings drilled in each major fill zone where stability analysis will be required and groundwater is anticipated. Water levels measured during drilling are often not adequate for performing stability analysis. This is particularly true where drilling is in fine-grained soils that can take many days or more for the water level to equalize after drilling. Even in more permeable coarse grained soils, the drilling fluid can obscure detection of the groundwater level. When encountered, groundwater must be measured after each boring is drilled. Information regarding the time and date of the reading and any fluctuations (such as loss of drilling fluid) that might be seen during drilling should be included on the field logs.

For embankment widening projects, piezometers are generally more useful in borings located at or near the toe of an existing embankment, rather than in the fill itself. Exceptions are when the existing fill is along a hillside or if seepage is present on the face of the embankment slope.

The groundwater levels should be monitored periodically to provide useful information regarding variation in levels over time. This can be important when evaluating base stability, consolidation settlement or liquefaction. As a minimum, the monitoring should be accomplished several times during the wet season (October through April) to assess the likely highest groundwater levels that could affect engineering analyses. If practical, a series of year-round readings taken at 1 to 2 month intervals should be accomplished in all piezometers.

The location of the groundwater table is particularly important during stability and settlement analyses. High groundwater tables result in lower effective stress in the soil affecting both the shear strength characteristics of the soil and its consolidation behavior under loading. The geoprofessional should identify the location of the groundwater table and determine the range in seasonal fluctuation.

If there is a potential for a significant groundwater gradient beneath an embankment or surface water levels are significantly higher on one side of the embankment than the other, the effect of reduced soil strength caused by water seepage should be evaluated. In this case, more than one piezometer should be installed to estimate the gradient. Geophysical methods may be employed to evaluate locations and the extent of seepage within an embankment. Also, seepage effects must be considered when an embankment is placed on or near the top of a slope that has known or potential for seepage through it. A flow net or a computer model may be used to estimate seepage velocity and forces in the soil. This information may then be used in the stability analysis to model pore pressures.

3 Embankment Design

3.1 Typical Embankment Materials and Compaction

General instructions for embankment construction are discussed in the specific construction specifications provided in Section 6, Control of Materials, and Section 19, Earthwork, of the Standard Specifications. Compaction requirements for approach embankments are defined by Highway Design Manual (HDM), topic 208.11 and Figure 208.11A. Compaction requirements for embankments outside of approach embankments are defined by Standard Specifications Sections 19-5, Compaction, 19-6 Embankment Construction, and 19-7 Borrow Material. The geoprofessional should determine if any of the material from planned earthwork will be suitable for embankment. Consideration should be given to whether the material is moisture sensitive and difficult to compact during wet weather.

Landscape Architecture may request reduced compaction requirements from 90-95% relative compaction to 85-88% relative compaction so as to promote the growth of vegetation on embankment slopes. Careful consideration of this type of request should be made as well as discussion with all project stakeholders should be held to determine what will be acceptable slope performance.

3.1.1 Rock Embankments

Standard Specifications Section 19-6.03C, Placing and Compacting, discusses compaction and construction requirements of rock embankments.

Special consideration should be given to the type of material that will be used in rock embankments. In some areas of the state, moderately weathered to decomposed, and moderately soft to very soft rock (i.e. poorly indurated) may be encountered in cuts and used as embankment fill. Degradable fine grained sandstone and siltstone are often encountered in the cuts. The use of this material in embankments can result in significant long term settlement and stability problems as the rock degrades, unless properly compacted with heavy tamping foot rollers (Machan, et al., 1989). The type, size, durability, and layer thickness of the rocky material will need to be considered. Also, compaction of a rocky fill is generally not measured with standard compaction equipment; therefore a method specification will be required.

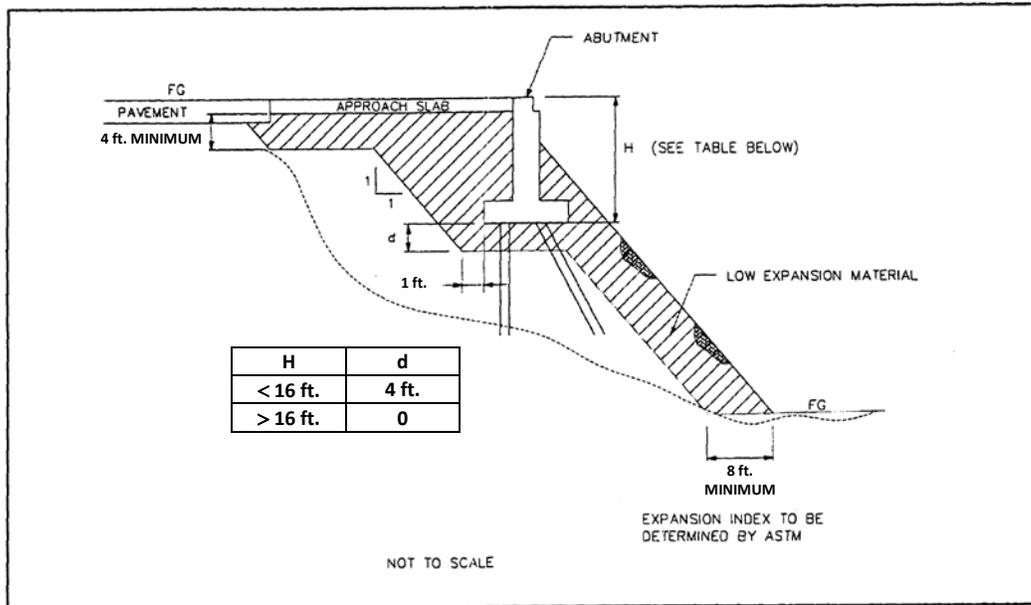
3.1.2 Earth Embankments and Bridge Approach Embankments

Two types of materials are commonly used in earth embankments: embankment fill (such as import borrow, local borrow, excavated material, lightweight imported borrow) and structure backfill.

Specifications for embankment fill and structure backfill are located in Section 19 of the Standard Specifications. Specifications for compaction of embankment fill and structure backfill are located in Section 6, Control of Materials, and Section 19, Earthwork, and also California Test Methods 216, 226, and 231.

Do not place expansive soil as part of the embankment within the limits of a bridge abutment as shown in Figure 1 for the full width of the embankment. Expansive soil materials for this requirement are defined as having either an Expansion Index (EI) (ASTM D 4829) greater than 50, or a Sand Equivalent (SE) (California Test Method 217) less than 20. This requirement is exclusive of the structure backfill and pervious backfill material requirements as shown on the plans and set forth in the Standard Specifications under Sections 19-3.02B and 19-3.03E, Structure Backfill, and 19-3.02C and 19-3.03G, Pervious Backfill Material, respectively. If you suspect that expansive soil might be available for use either locally or by import, include Figure 1 and appropriate discussion in the Foundation Report under Construction Considerations.

Figure 1: Expansive Soil Exclusion Zone



3.2 Fill Placement Below Water

If material will be placed below the water table, material that does not require compaction such as gravel or cobbles or boulders must be specified. Above the water surface, transition to standard embankment materials, using geosynthetics to prevent migration of the finer materials into the void spaces of the coarser underlying material.

3.3 Stability Assessment

In general, embankments 10 feet or less in height with 2H:1V or flatter side slopes, may be designed based on past precedence and engineering judgment provided there are no known problem soil conditions such as organic soils, soft/ loose soils, potentially unstable soils, such as Bay Mud or peat, or liquefiable sands. Embankments over 10 feet in height or any embankment on soft soils, in unstable areas/soils, or those comprised of lightweight fill require more in-depth stability analyses, as do any embankments with side slope inclinations steeper than 2H:1V. Moreover, any fill placed near or against a bridge abutment or foundation, or that can impact a nearby buried or above-ground structure, will likewise require stability analyses.

Prior to the start of the stability analysis, determine key issues that need to be addressed, such as:

- Is the site underlain by soft silt, clay or peat? If so, a staged stability analysis may be required.

- Are site constraints such that slopes steeper than 2H:1V are required (1.5:1 embankments are common in mountainous areas)? If so, a detailed slope stability assessment is needed to evaluate the various alternatives.
- Is the embankment temporary or permanent? Factors of safety for temporary embankments may be lower than for permanent ones, depending on the site conditions and the potential for variability.
- Will the new embankment impact nearby structures or bridge abutments? If so, more elaborate sampling, testing and analysis are required.
- Are there potentially liquefiable soils at the site? If so, seismic analysis to evaluate this may be warranted and ground improvement may be needed. For a structure approach embankment or if seismic distress to the embankment would impact a bridge or building, then liquefaction (settlement, lateral spreading, and deformation) must be evaluated and the embankment should be designed to remain stable during seismic events. It is not common perform liquefaction mitigation for highway embankments due to the high cost of applying such a policy uniformly to all highway embankments statewide. In the latter case, if liquefaction is identified, a risk discussion must be held with the Project Development Team (PDT).

3.3.1 Safety Factors

The minimum Factor of Safety (FS) to be used in stability analyses for an embankment depends on many factors such as:

1. The degree of uncertainty in the stability analysis inputs
2. The level of investigation and data collection
3. Costs of constructing the slope to be more stable
4. Costs, risks to the travelling public, risks to the roadway, and other consequences should the slope fail
5. Whether the slope is temporary or permanent

Use the FS values below; however, higher or lower values may be appropriate, depending on specifics of the project and considerations listed above.

- Highway embankments (embankments that neither support nor potentially impact structures) should have a minimum factor of safety of 1.25. When repairing an embankment slide or slipout, and a factor of safety for the embankment can be reliably calculated, a minimum factor of safety of 1.15 may be used.
- Highway embankments supporting or potentially impacting structures should have a minimum factor of safety of 1.3.
- Bridge Approach Embankments and embankments supporting important (see MTD 20-1) structures should have a minimum factor of safety of 1.5.
- Under seismic conditions, only those portions of the new embankment that could impact an adjacent structure such as bridge abutments and foundations or nearby buildings require an overall minimum factor of safety of 1.1 using a pseudo-static

analysis. Utilize $1/3$ PGA or 0.2 g (maximum) for the horizontal pseudo-static coefficient.

- Temporary embankments, i.e. short term conditions during construction can be lower than long term factor of safety, typically about 1.1 to 1.2, but no lower than 1.1. Refer to considerations above.

3.3.2 Strength Parameters

Strength parameters are required for both stability and settlement analyses. Use FHWA Geotechnical Engineering Circular No. 5 (Sabatini, et al., 2002), the Soils Correlations Module, or other appropriate references for guidance on the selection of needed strength parameters. Obtain the parameters by a combination of laboratory testing and in-situ testing; in some cases for low risk situations, soil correlations may be appropriate.

Tables 2 and 3 present the typical field and laboratory tests used to determine soil strength parameters. These tables are not exhaustive but do contain the most common tests.

Consider the applicable operating ranges of these tests, and that the values that these tests yield are dependent upon various rates and types of loading, boundary conditions, and stress history, etc.

Table 2 - Strength Parameters by Field Testing

Field Test	Parameter	Remarks
Standard Penetration Test (SPT)	Internal Angle of Friction	Values indirectly obtained by correlation (see Correlation Module). Only good for cohesionless soils. Discrete testing.
Cone Penetration Test (CPT)	Internal Angle of Friction, Undrained Shear Strength	Values indirectly obtained by correlation (see CPT module). Good for both cohesive and cohesionless soils. Continuous testing. No samples retrieved for lab testing.
Pocket Penetrometer	Undrained Shear Strength	Only good for cohesive soils. Good for estimating shear strength ranges. PP values may be confirmed with lab tests.
Torvane	Undrained Shear Strength, Residual undrained shear strength	Only good for cohesive soils. Good for estimating shear strength ranges. TV values may be confirmed with lab tests.
Vane Shear	Undrained Shear Strength, Residual undrained shear strength	Limited to soft and stiff clays.

Table 3 - Strength Parameters and Stress History by Laboratory Testing

Laboratory Test	Parameter	Remarks
Unconfined Compressive Strength	Undrained Shear Strength, (S_u)	Good for Clays and Silty soils; $S_u = C_u = q_u/2$
Triaxial	Undrained Shear Strength, (S_u), Effective Stress Parameters (c' and ϕ')	Good for both cohesive and cohesionless soils. Requires careful field sampling techniques. Most commonly, UU and/or CUE.
Direct Shear	Effective Stress Parameters (c' and ϕ')	Good for both cohesive and cohesionless soils. Requires careful field sampling/handling techniques. Shearing occurs over a pre-defined plane.
One-dimensional Consolidation	Overconsolidation Ratio (OCR), Preconsolidation Stress (σ'_p), Compression and Recompression Indices (C_c & C_r), Swelling Index (C_s), secondary compression (C_α), and Time-rate settlement values	Requires engineering judgment/experience to determine parameters.

If the critical stability is under drained conditions, such as in sand or gravel, then effective stress analysis using a peak friction angle is appropriate and should be used for stability assessment. In the case of over-consolidated fine grained soils, the residual strength based on remolded down-hole vane shear or remolded lab tests, may be appropriate. This is especially true for soils that exhibit strain softening or are particularly sensitive to shear strain.

If the critical stability is under undrained conditions, such as in most clays and silts, a total stress analysis using the undrained cohesion value, based on a combination of field and laboratory tests, with no friction, should be used for stability assessment.

For staged construction, both short (undrained) and long term (drained) stability need to be assessed. At the start of a stage the input strength parameter is the undrained cohesion. The total shear strength of the fine-grained soil increases with time as the excessive pore water dissipates.

3.4 Embankment Settlement Assessment

New embankments, as is true of almost any new construction, will add load to the underlying soils and cause those soils to settle. The total settlement has up to three potential components: 1) immediate settlement, 2) consolidation settlement, and 3) secondary compression.

Settlement must be assessed for all embankments. Even if the embankment has an adequate overall stability factor of safety, the performance of a highway embankment can be adversely affected by excessive differential settlement at the road surface.

Settlement analyses for embankments over soft soils require the compression index parameters for input. These parameters are typically obtained from standard one-dimensional oedometer tests of the fine-grained soils. For granular soils, these parameters can be estimated empirically. Oedometer tests (consolidation tests) and the load increment ratios required for the tests must be determined/performed according to the American Society for Testing and Materials standard; ASTM D2435/D2435M – 11.

3.4.1 Settlement Impacts

Because primary consolidation and secondary compression can continue to occur long after the embankment is constructed, they represent the major settlement concerns for embankment design and construction. Post construction settlement can damage structures and utilities located within the embankment, especially if those facilities are also supported by adjacent soils or foundations that do not settle appreciably, leading to differential settlements. Embankment settlement near an abutment could create an unwanted dip in the roadway surface, or downdrag and lateral squeeze forces on the foundations.

If the primary consolidation is allowed to occur prior to placing utilities or building structures that would otherwise be impacted by the settlement, the impact is essentially mitigated. However, it can take weeks to years for primary settlement to be essentially complete, and significant secondary compression of organic soils can continue for decades. Many construction projects cannot absorb the scheduling impacts associated with waiting for primary consolidation and/or secondary compression to occur. Therefore, estimating the time rate of settlement is often as important as estimating the magnitude of settlement.

To establish the target settlement criteria, the tolerance of potentially affected structures or utilities to differential settlement that will be impacted by the embankment settlement must be determined. Lateral movement (i.e., lateral squeeze) caused by the embankment settlement and its effect on adjacent structures, including light, overhead sign, and signal foundations, must also be considered. If structures or utilities are not impacted by the embankment settlement, settlement criteria are likely governed by the long-term maintenance needs of the roadway surfacing. In that case, the target settlement criteria must be established with consideration of the effect differential settlement will have on the pavement life and surface smoothness.

The amount of total and differential settlement that can be tolerated during and following embankment construction should be evaluated. The PDT (district designer, structure designer and geoprofessional) will determine the applicable design criteria on a project by project basis.

3.4.2 Settlement Analysis

Perform settlement analysis according to the NHI Soil, Slopes, and Embankment design Manual, Chapter 4.

3.5 Stability Mitigation

A variety of techniques are available to mitigate inadequate slope stability for new embankments or embankment widenings. These techniques include staged construction to allow for the underlying soils to gain strength, base reinforcement, ground improvement, use of lightweight fill, and construction of toe berms and shear keys.

3.5.1 Staged Construction

Where soft compressible soils are present below a new embankment location and it is not economical to remove and replace these soils with compacted fill, the embankment can be constructed in stages to allow the strength of the compressible soils to increase under the weight of the new fill. For stability analysis for staged construction, refer to the NHI manual, Chapter 8.6, Embankments on Soft Ground and WSDOT Geotechnical Design Manual, 9.3.1 Staged Construction and its example in Appendix 9-A.

3.5.2 Base Reinforcement

Base reinforcement may be used to increase the factor of safety against slope failure. Base reinforcement typically consists of placing a geotextile or geogrid at the base of an embankment prior to constructing the embankment. Base reinforcement is particularly effective where soft/weak soils are present below a planned embankment. The base reinforcement can be designed for either temporary or permanent applications. Most base reinforcement applications are temporary, in that the reinforcement is needed only until the underlying soil's shear strength has increased sufficiently as a result of consolidation under the weight of the embankment. Therefore, the base reinforcement does not need to meet the same design requirements as permanent base reinforcement regarding creep and durability. Use the creep reduction factors outlined in the WSDOT Geotechnical Design Manual, 9.3.2, Base Reinforcement and WSDOT Standard Practice T925.

The design of base reinforcement is similar to the design of a reinforced slope in that limit equilibrium slope stability methods are used to determine the strength required to obtain the desired safety factor. The design procedures by Holtz, et al. (1995) should be used for embankments utilizing base reinforcement.

Base reinforcement materials should be placed in continuous longitudinal strips in the direction of main reinforcement. Joints between pieces of geotextile or geogrid in the strength direction (perpendicular to the slope) should be avoided. All seams in the geotextiles should be sewn and not lapped. Likewise, geogrids should be linked with mechanical fasteners or pins and not simply overlapped. Where base reinforcement is used, the use of gravel, from imported or local borrow sources, may also be appropriate in order to increase the embankment shear strength.

3.5.3 Ground Improvement

Ground improvement can be used to mitigate inadequate slope stability for both new and existing embankments, as well as reduce settlement. The primary ground improvement techniques to mitigate slope stability fall into two general categories, namely densification and altering the soil composition. The Ground Improvement Module should be reviewed for a more detailed discussion and key references regarding the advantages and disadvantages of these techniques, applicability for the prevailing subsurface conditions, construction considerations, and costs. In addition to the two general categories of ground improvement identified above, Prefabricated Vertical Drains (PVD) (also known as "wick" drains) may be used in combination with staged embankment construction to accelerate strength gain and improve stability, in addition to accelerating primary consolidation. PVD reduce the drainage path length, thereby accelerating the rate of strength gain. Other ground improvement techniques such as stone columns can function to accelerate strength gain in the same way as PVD, though the stone columns also reduce the stress applied to the soil, thereby reducing the total

strength gain obtained. See the Ground Improvement Module for additional guidance and references to use if these techniques are to be implemented.

3.5.4 Lightweight Fills

Lightweight fill is another means of improving embankment stability. Lightweight fills are generally used for two conditions: the reduction of the driving forces contributing to instability, and the reduction of potential settlement resulting from consolidation of compressible foundation soils. Situations where lightweight fill may be appropriate include conditions where the construction schedule does not allow the use of staged construction, where existing utilities or adjacent structures are present that cannot tolerate the magnitude of settlement induced by placement of typical fill, and at locations where post-construction settlements may be excessive under conventional fills.

Lightweight fill consists of a variety of materials including polystyrene blocks (geofoam), lightweight aggregates (rhyolite, expanded shale, blast furnace slag, fly ash), wood fiber, tire derived aggregate (TDA), and other materials. Lightweight fills are infrequently used due to either high costs or other disadvantages with using these materials. Refer to the Ground Improvement Module for more information.

3.5.5 Toe Berms, Shear keys, and Stabilization Trenches

Toe berms and shear keys improve the stability of an embankment by increasing the resistance along potential failure surfaces. As implied by the name, toe berms are constructed near the toe of the embankment slopes where stability is a concern. The toe berms are often inclined flatter than the fill embankment side slopes, but the berm itself should be checked for stability. The use of berms may increase the magnitude of settlements as a consequence of the increased size of the loaded area. Toe berms may be constructed using compacted earth embankment or from granular materials that can be placed quickly, do not require much compaction, but have relatively high shear strength. Use of compacted earth embankment may be warranted due to cost savings from using local borrow as compared to importing granular materials.

Toe berms increase the shearing resistance by:

- Adding weight, and thus increasing the shear resistance of granular soils below the toe area of the embankment;
- Adding high strength materials for additional resistance along potential failure surfaces that pass through the toe berm; and creating a longer failure surface, thus more shear resistance, as the failure surface now must pass below the toe berm if it does not pass through the berm.

Shear keys function in a manner similar to toe berms, except instead of being adjacent to and incorporating the toe of the fill embankment, the shear key is placed under the fill embankment—frequently below the toe of the embankment. Shear keys are best suited to

conditions where they key can be embedded into a stronger underlying formation. Shear keys typically range from 5 to 15 feet in width and extend 4 to 10 feet below the ground surface. They are typically backfilled with quarry spalls or similar materials that are relatively easy to place below the groundwater level, require minimal compaction, and have high internal shear strength. Like toe berms, shear keys improve the stability of the embankment by forcing the potential failure surface through the strong shear key material or along a much longer path below the shear key.

Stabilization trenches function to key an embankment into competent foundation material and facilitate drainage within an embankment foundation. The specified trenches significantly reduce the amount of excavation of poor foundation materials that might otherwise be required. See Section 8.B.8, Slope Stability and Foundation Investigation, 1973 for more stabilization trench details.

3.6 Settlement Mitigation

3.6.1 Over-excavation

Over-excavation simply refers to excavating the soft compressible soils from below the embankment footprint and replacing these materials with higher quality, less compressible soil. Over-excavation (remove and replace) should be assessed prior to consideration of other mitigation strategies, such as PVD, surcharges and lightweight fills. Because of the high costs associated with excavating and disposing of unsuitable soils as well as the difficulties associated with excavating below the water table, over-excavation and replacement typically only makes economic sense under certain conditions. Some of these conditions include:

- The area requiring overexcavation is limited;
- The unsuitable soils are near the ground surface and do not extend very deep (typically, even in the most favorable of construction conditions, over-excavation depths greater than about 10 feet are in general not economical);
- Temporary shoring and dewatering are not required to support or facilitate the excavation;
- The unsuitable soils can be wasted on site;
- Suitable excess fill materials are readily available to replace the over-excavated unsuitable soils.

3.6.2 Acceleration Using PVD

The Ground Improvement Module should be reviewed for a more detailed discussion of this method.

3.6.3 Acceleration Using Surcharges

The Ground Improvement Module should be reviewed for a more detailed discussion of this method.

3.6.4 Lightweight Fills

The Ground Improvement Module should be reviewed for a more detailed discussion of this method.

4 Instrumentation

Some of the more common instrumentation methods used to design and construct embankments includes the following:

- Piezometers – standpipe, vibrating wire
- Time Domain Reflectometry
- Slope Inclinometers
- Survey Hubs
- Settlement Platforms

The geoprofessional should place as many instruments as needed to ensure that foundation soils provide adequate bearing for the embankment prism. Likewise, the embankment prism should be sufficiently instrumented to ensure settlement is complete during construction.

A more comprehensive discussion of these and other monitoring techniques is available in the Geotechnical Instrumentation for Monitoring Field Performance (Dunnicliff, 1993) and Geotechnical Instrumentation Reference Manual, NHI Course No. 13241 FHWA-HI-98-034 (Dunnicliff, 1998).

5 Reporting

Present planning phase embankment recommendations for highways and approach embankments in the District Preliminary Geotechnical Report (DPGR).

Present embankment recommendations for highways and approach embankments in the Geotechnical Design Report. The recommendations for the approach embankments should be summarized in the Foundation Report so the structure designer is provided information as to any settlement, stability, waiting periods, PVD, etc. This will assist with any design impacts to the structure, structure approach slab design and structure specification development. The details for the approach embankment mitigation are typical put together by district design.

Present methodologies used and results for slope and foundation stability and settlement, and seepage if applicable. Present findings, conclusions and recommendations. For clarity, provide tables and/or figures such as plan views, elevations, and cross-sections, to detail the limits of specific recommendations so the client can prepare accurate plans, specifications, and estimates. Communicate regularly with district design units during PS&E process. Review the plans and specifications to ensure that they are prepared

correctly and reflect the intent of the recommendations. Section 5.3 lists issues that need to be checked during the PS&E review.

5.1 Information to Provide for each Type of Recommendation

5.1.1 Loading rates

- Allowable height of fill for each stage and maximum rate of construction.
- Geotechnical instrumentation to monitor field performance and provide information relevant to decisions regarding the rate of construction.
- If instrumentation is required to control the rate of fill placement, explain how this will be done and how the readings will be used to control the contractor's operation. This information is typically presented in a non-standard special provision (NSSP) produced by the geoprofessional.

5.1.2 Preloading, Surcharges (heights and periods)

- Geometry (size and limits of surcharge).
- Rate(s) of loading (1-ft per week, etc.).
- When the surcharge will be removed.

5.1.3 Settlement

- Settlement waiting period (duration).
- Whether construction of adjacent structures be delayed during embankment settlement period.
- Need for monitoring of adjacent structures.
- Provide magnitude and time of settlement with and without recommended measures.
- State whether settlement mostly completed during construction and estimate amount of settlement that is expected to continue after embankment construction, post construction total and differential settlements.
- Provide locations that have significant differential settlement that can affect the performance of highway embankment.
- Discuss post construction settlement and potential effect to structures and utilities located within the embankment, especially if those facilities are also supported by adjacent soils or foundations that do not settle appreciably.
- Discuss potential settlement of existing structure foundations as the new embankment is placed.
- Discuss time periods that the settlement should be monitored and the frequency of observations.
- List types of monitoring such as survey hubs, monuments, and settlement plates for vertical and lateral movement.
- List type of piezometers for pore pressure monitoring.

5.1.4 Over-excavation

- Location and geometry (depths, limits of removal).
- Backfill materials.
- Geosynthetic materials used for separation and/or reinforcement.

5.1.5 Lightweight Fill

- Type (s) of lightweight fill.
- Construction requirements.
- Geometric limits.
- Other needed materials and details (geosynthetic, drainage, etc).

5.1.6 Stabilization trenches

- Trench configuration and geometry, depth to and description of competent material.
- Backfill material and whether excavated material can be used as backfill.
- Location and dimension of drainage blanket, drainage material, pipe.
- Geosynthetic materials.

5.1.7 Buttresses/Berms

- Geometry (limits, height, width, slopes, cross-sections).
- Backfill materials.
- Drainage materials and details.
- Geosynthetic materials.

5.1.8 Surface Drainage

- Geometry (slopes, plans and cross-sections).
- Surface drainage design may include sheet flow, swales, ditches, catchment areas, and erosion control/slope protection.

5.1.9 Subdrainage

Trenches

- Geometry, size, type of geotextile, drainage pipe, type of trench back fill materials.

Horizontal Drains

- Location, length, vertical and horizontal angle, spacing, type of pipe and geotextile.

Drainage Blanket

- Slope, thickness, type of geotextile, size and type of drainage pipes.

Relief Wells and Drainage Galleries

- Location, spacing, diameter, depth, bottom bell out.
- Backfill material.
- Methods of water disposal i.e., pumping and discharge channels, or horizontal drains.

5.2 Specifications

General specifications for embankment construction are provided in the Standard Specifications and Standard Special Provisions.

- State recommendations to revise or delete portions of the Standard Specifications and Standard Special Provisions as these will have to be presented as an NSSP.
- List Standard Special Provisions to be included by number and subject. Concisely state any editing to be done to the Special Provisions such as adding or deleting paragraphs. Give numbers or phrases that may be necessary to fill in blanks in certain Standard Special Provisions.
- Applications that are not addressed by the Standard Specifications or Standard Special Provisions may require an NSSP. These can be based on NSSP's used on past similar projects, FHWA generic specifications, specifications developed by U.S. Army Corps of Engineers, or specifications provided by specialty contractors. Some NSSP's used in our past projects are posted in Geotechnical Services Website.
- For instrumentation, state what instruments are needed, specify who will supply the equipment, provide the monitoring, analyze the data, and determine when the settlement is complete or when additional fill can be placed. Clearly state that any instrumentation damaged by the contractor's personnel will be repaired or replaced at no cost to the state.

5.3 PS&E Review

Review PS&E to verify that the design and construction recommendations in the report have been properly incorporated into the plans and specifications. The following issues, where applicable, should be addressed in the PS&E:

- Slope inclination required for stability.
- Embankment foundation preparation requirements, over-excavation limits shown on plans.
- Plan details for special drainage requirements such as lined ditches, interceptor trenches, drainage blankets, etc.

- Special embankment material requirements.
- Special treatment required for fill placement such as non-durable rock, plastic soil, or lightweight fill.
- Magnitude and time for settlement.
- Settlement waiting period estimated in the Special Provisions.
- Size and limits of surcharge.
- Special monitoring needs.
- If instrumentation is required to control the rate of fill placement, do the SP's clearly spell out how this will be done and how the readings will be used to control the contractor's operation?
- Special Provisions state that instrumentation damaged by contractor will be repaired or replaced at no cost to the State.
- Settlement issues with adjacent structures, should construction of structures be delayed during embankment settlement period.
- Monitoring of adjacent structures.

6 Construction

When it comes to designing and building embankments, the geoprofessionals role doesn't end once the GDR has been submitted. In fact, construction is typically where the geoprofessional's role becomes even more critical.

The geoprofessional needs to make every effort to insure that recommendations for embankment construction are constructible and that if any unforeseen construction problems arise, that they are resolved so as to not affect the schedule. A good working knowledge of the typical equipment used for embankment construction is important to constructability.

During construction geoprofessionals must make themselves available to Resident Engineers (RE's) whenever a problem with embankment construction arises. Geoprofessionals should attend relevant construction meetings called by the RE.

Typical problems that may be encountered during embankment construction include, but are not limited to, the following:

- Unexpected weak or soft soils encountered during embankment foundation preparation to receive embankment materials.
- Conflicts with placement of instrumentation (Settlement Platforms, vibrating wire piezometers, slope inclinometers, etc.).
- Conflicts with utilities or other facilities, and the equipment that a Contractor may use for a particular construction operation.
- Instrumentation data that appears erratic or unreasonable; instrumentation malfunction.

- Anticipated settlement not achieved during estimated timeframe. Items to discuss with the RE: Does increasing the settlement period become a critical path item? What are the risks? Are they acceptable?
- Problems with compaction – moisture, right equipment for the job, removal and replacement of problem soils with fabric and compacted soil.
- Springs, artesian conditions.

Construction issues, such as those above, illustrate the need for geoprofessionals to be flexible and willing to consider alternatives that will facilitate the progress and construction of an embankment.

Caltrans' Construction Manual, Construction Details, Earthwork (Section 4-19) is a good reference for construction activities performed during embankment construction.

7 **References**

1. Soil Slope and Embankment Design, FHWA-NHI-132033, September 2005.
2. Washington State Dept. of Transportation Geotechnical Design Manual, M 46-03.09, December 2013, Chapter 9 Embankments.
3. Geotechnical Instrumentation Reference Manual, NHI Course No. 13241 FHWA-NHI-98-034 (Dunnicliff, 1998).
4. Geotechnical Instrumentation for Monitoring Field Performance (Dunnicliff, 1993)
5. Subsurface Investigations – Geotechnical Site Characterization Reference Manual, NHI Course No. 132031 FHWA-NHI-01-031 (Mayne, Christopher, and De Long).
6. Caltrans' Construction Manual, Construction Details, Earthwork (Section 4-19), June 2012.
7. Slope Stability and Foundation Investigation, California Division of Highways, September 1973 (Forsyth and McCauley).
8. WSDOT Standard Practice T925, January 2009
9. ASTM D2435/D2435M-11; Standard Test Methods for One-Dimensional Consolidation Properties of Incremental Loading; American Society for Testing and Materials International (2011.05.01)