Chapter 9 - Embankments – Analysis and Design

Chapter Contents

9.1 General

This chapter addresses the analysis and design of rock and earth embankments. Also addressed are the use of lightweight fill, settlement and stability mitigation techniques. Bridge approach embankments have different requirements and are addressed specifically at the end of this chapter. For the purposes of this chapter, embankments include the following:

- Rock embankments, also known as all-weather embankments, are defined as fills in which the material is non-moisture-density testable and is composed of durable granular materials.
- Earth embankments are fills that are typically composed of onsite or imported borrow, and could include a wide variety of materials from fine to coarse grain. The material is usually moisture-density testable.

Embankments less than 10 feet high are generally designed based on past experience with similar soils and the application of engineering judgment. Embankments greater than 10 feet in height usually require a more detailed geotechnical analysis. Relatively flat (2H:1V or flatter) embankments constructed in accordance with the Standard Specifications, and not subject to submergence, would generally not require rigorous analysis. Any embankment where failure would result in large rehabilitation, on-going maintenance costs or threaten public safety should be designed using more rigorous techniques.

Common causes of embankment failures include the use of excessive slope angles, failure to address seepage, and erosion. Consideration should be given to addressing springs and seeps and establishing vegetation on the slope to prevent long-term erosion. It may be difficult to establish vegetation on slopes with inclinations steeper than 2H:1V without the use of erosion mats or other stabilization methods.

9.2 Design Considerations

9.2.1 Embankment Materials and Compaction

New embankments and embankment widening require the placement of suitable fill materials, properly compacted with correct equipment based on the material type. The *ODOT Standard Specifications for Construction* provides embankment construction methods for soil, non-durable rock and rock materials. Non-durable rock materials may require additional compaction effort beyond standard construction methods to prevent long-term deflections associated with degradation of theembankment materials. The geotechnical designer should determine during the exploration program if any of the material from planned earthwork excavations will be suitable for re-use as embankment. Consideration should be given as to whether the material is moisture sensitive and difficult to compact during wet weather.

9.2.1.1 All-Weather Embankment Materials

ODOT projects frequently require embankment fill construction during the wet-weather months (typically October through May). Clean, granular, all-weather embankment materials improve the contractor's ability to properly place and compact fill materials during the wet-weather months. *ODOT Standard Specifications* identify include two materials generally suitable for wet-weather construction: Selected Stone Backfill (*00330.15*), and Stone Embankment Material (*00330.16*).

9.2.1.2 Non-Durable Rock Materials

Special consideration should be given during design to the type of material that will be used in rock embankments. In some areas of the state, moderately weathered or very soft rock may be used as embankment fill. For embankment construction with non-durable rock materials, the following guidelines should be followed:

- Degradable fine-grained sandstone and siltstone are often encountered in the cuts and the use of these materials in embankments can result in significant long-term deformations and stability problems as the rock degrades. Avoiding this subsequent collapse requires that the embankment fill be pulverized, watered, and compactedproperly compacted with heavy tamping foot rollers (Machan, et al., 1989). The slake durability test (ASTM D4644) is required during construction to determine handling and compaction requirements of non-durable rock. The slake durability test should also be performed during design to anticipate the performance of the rock in construction.
- When the rock is found to be non-durable, it should be physically broken down and compacted as earth embankment, provided the material meets or exceeds common borrow requirements. Special compaction requirements, defined by method specification, may be needed for these materials. In general, tamping foot rollers work best for breaking down the rock fragments. The minimum size roller should be 30 tons, note this is a much larger roller than is required in the standard specifications. Specifications should include the maximum size of the rock fragments and maximum lift thickness. These requirements will depend on the hardness of the rock, and a test section should be incorporated into the contract to verify that the Contractor's methods will achieve compaction and successfully break down the material. In general, both the particle size and lift thickness should be limited to 12 inches.

9.2.2 Embankment Stability

Embankment stability design should be consistent with state-of-the-practice design guidelines, as discussed in Chapter 9. Stability design shall be evaluated using conventional limit equilibrium methods, and analyses should be performed using a state-of-the-practice slope stability computer program such as the most current versions of Slope/W® (Geo-Slope International), Slide® (Rocscience, Inc.), and/or ReSSA® (ADAMA Engineering, Inc.).

9.2.2.1 Safety Factors

For embankments adjacent to but not directly supporting structures, a maximum resistance factor of 0.75 should be used. Where embankments support structures such as bridges, approach slabs, retaining walls, and minor structures, a maximum resistance factor of 0.65

should be used. These resistance factors of 0.75 and 0.65 are generally equivalent to a safety factor of 1.3 and 1.5, respectively.

9.2.2.2 Strength Parameters

Strength parameters are required for any stability analysis. Strength parameters appropriate for the different types of stability analyses are determined based on Chapter 6 and Chapter 8. Both short and long term stability need to be assessed.

9.2.3 Embankment Settlement

Embankment settlement analysis should be based on the methods in *FHWA Soils and Foundation Reference Manual,* (Samtani and Nowatzki, 2006) and Section 10 of the *AASHTO LRFD Bridge Design Specifications*. Because primary consolidation and secondary compression can continue to occur long after the embankment is constructed (post construction settlement), they represent the principal settlement concerns for embankment design and construction. Post construction settlement can damage structures, pavement structures, and utilities located within and atop the embankment, especially if those facilities are also supported in such a way as to limit deflection, leading to differential settlements. 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.

Key parameters required to calculate the time-rate and magnitude of embankment settlement include:

- The subsurface profile including soil types, layering, groundwater levels and unit weights.
- The indices for recompression, primary and secondary compression from laboratory consolidation test data, correlations from index properties, or results from settlement monitoring programs at nearby sites with similar soil conditions.
- The geometry of proposed fill embankments, including fill unit weight and any long-term surcharge loads.

Analysis of primary consolidation and secondary compression settlements should be performed by hand-calculation, using Excel spreadsheet or MathCAD, or with a state-of-the-practice computer program such as the most current versions of FoSSA® (ADAMA Engineering, Inc.).

9.3 Stability Mitigation

A variety of techniques is available to mitigate inadequate slope stability for new embankments or embankment widening. These techniques include staged construction to allow the underlying soils to gain strength, base reinforcement, ground improvement, and construction of toe berms (counterweights) and shear keys. An overview of these instability mitigation techniques is presented below.

9.3.1 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. This approach allows for consolidation and dissipation of excess pore pressures within the compressible soils. Construction of the second and subsequent stages commences when the strength of the compressible soils is sufficient to maintain stability under the subsequent applied loads. In order to define the allowable height of fill for each stage and maximum rate of construction, detailed geotechnical analysis is required. This generally includes both limit equilibrium slope stability and time rate of settlement analyses. Field monitoring of settlement and pore water pressures should be specified for quality control during construction.

9.3.2 Base Reinforcement

Base reinforcement typically consists of placing at least two, closely spaced geogrid layers near the embankment base with a high-strength geotextile used as a separator between the embankment and foundations soils. Base reinforcement may be used to increase the factor of safety against slope failure. Base reinforcement is particularly effective where soft/weak soils are present below a planned embankment location. The base reinforcement can be designed for either temporary or permanent applications. Since the reinforcement is needed only until the foundation soil has developed sufficient shear strength to maintain stability, the base reinforcement geogrid design does not require application of the full strength reduction factor for creep effects. Holtz, et al. (1995) provides a suitable design methodology for embankment base reinforcement. It is typical when using base reinforcement to not compact the, typically soft, native grade. As such, the use of base reinforcement would typically require the development of project-specific special provisions.

9.3.3 Ground Improvement

Refer to Chapter 14 for references and information on ground improvement design. Ground improvement is typically used to address seismic performance given the relatively high cost. It may be appropriate for sites where overexcavation and/or embankment reinforcement are not feasible.

9.3.4 Toe Berms and Shear keys

Toe berms and shear keys are methods to improve the stability of an embankment by increasing the resistance along potential failure surfaces. Toe berms are typically constructed of granular materials that can be placed quickly, do not require much compaction, and have relatively high shear strength. ODOT would typically specify the use of Stone Embankment Material when toe berms and shear keys are required.

9.4 Settlement Mitigation

9.4.1 Acceleration Using Wick Drains

Wick drains, or prefabricated drains, are, in essence, vertical drainage paths that can be installed into compressible soils to decrease the overall time required for completion of primary consolidation. Wick drain design considerations, example designs, guideline specifications, and installation considerations are provided by reference in Chapter 14. Section 00435 of the *ODOT Standard Specifications* addresses installation of wick drains.

9.4.2 Acceleration Using Surcharges

Surcharge loads are additional loads placed on the fill embankment above and beyond the finish grades. The primary purpose of a surcharge is to speed up the consolidation process. Two significant design and construction considerations for using surcharges include embankment stability and re-use of the additional fill materials. New embankments over soft soils can result in stability problems. Adding additional surcharge fill could exacerbate the stability problem. Furthermore, after the settlement objectives have been met, the surcharge will need to be removed. If the surcharge material cannot be moved to another part of the project site for use as site fill or as another surcharge, it is often not economical to bring the extra surcharge fill to the site only to haul it away again. Also, when fill soils must be handled multiple times (such as with a "rolling" surcharge), it is advantageous to use gravel borrow to reduce workability issues during wet weather conditions.

The design of surcharges requires a high level of knowledge with respect to time rate of consolidation. As such, surcharge design should only be undertaken based on a rigorous laboratory testing program, including numerous consolidation tests or from fill settlement data collected from an adjacent site in the same soils. Even with such data, the design of a surcharge requires a significant amount of engineering judgement. The drainage flowpath distance is a principal driver in predicting consolidation rates and is to reliably determine from subsurface explorations.

9.4.3 Lightweight Fills

Lightweight fills can also be used to mitigate settlement issues as indicated in Section 9.3.4. Lightweight fills reduce the new loads imposed on the underlying compressible soils, thereby reducing the magnitude of the settlement. When considering the use of lightweight fills a number of significant issues must be addressed including material, cost, constructability, and buoyancy.

9.4.4 Subexcavation

Subexcavation refers to excavating the soft compressible or unsuitable soils from below the embankment footprint and replacing these materials with higher quality, less compressible material. Because of the costs associated with excavating and disposing of unsuitable soils as well as the difficulties associated with excavating below the water table, sub excavation and replacement typically only makes economic sense under certain conditions. Some of these conditions include, but are not limited to:

- The area requiring over excavation 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, sub excavation depths greater than about 10 ft. are in general not economical);
- Temporary shoring and dewatering are not required to support or facilitate the excavation and;
- Suitable materials are readily available to replace the over-excavated unsuitable soils.

9.5 Unusual Foundation Soils

Deposits of unusual foundation soils are present throughout Oregon. These include highly organic soils such as peat deposits and diatomaceous formations. In some instances, conventional consolidation theory is not applicable since an underlying assumption of consolidation theory is that the soil grains are incompressible. Detailed evaluation of unusual formations should be based on published research and practices as well as past experience in the area.

9.6 Bridge Approach Embankments

The FHWA publication “Soils and Foundations Reference Manual”, (Samtani, 2006) should be referenced for guidance in the analysis and design of bridge approach embankments. New embankments placed for bridge approaches should be evaluated for short term (undrained) and long term (drained) conditions.

Bridge end slopes are designed at 2H:1V. Bridge treatments often include slope paving and hydraulic countermeasures are designed and stable at 2H:1V slopes. If steeper end slopes are anticipated, close coordination with the bridge and hydraulic engineers needs to occur. Regardless of slope inclination, the slopes are evaluated for stability and designed to meet the required resistance for static and seismic load cases. Ground improvement should not be used as a mitigation to use steeper sloeps.

The evaluation of slope stability using limit equilibrium methods is addressed in detail in Chapter 8. For overall stability, the minimum static factor of safety for bridge approach embankments is 1.5. This includes the consideration of abutment spread footings or retaining walls supported directly on the proposed embankments. Dynamic (seismic) slope stability, settlement, and lateral displacements are discussed in Chapter 7.

As specified in Article 11.6.2.3 of the AASHTO, the evaluation of the overall stability of earth slopes with foundation units shall be evaluated at the Service I limit state and a resistance factor, φ_{os}, of 0.65, which corresponds to a factor of safety of 1.5. The analysis will address the impact of a maximum bearing stress equal to the specified service limit state bearing resistance.

If the foundation is located on the slope such that the foundation load contributes to slope instability, the designer shall establish a maximum footing load that is acceptable for maintaining overall slope stability for Service, and Extreme Event limit states. If the foundation is located on the lower portion of the slope such that the foundation load increases slope stability, overall stability of the slope shall be evaluated ignoring the effect of the footing on slope stability.

In general, approach embankments should be designed to limit long-term settlement to less than 1” in 20 years. Refer to the ODOT BDM for additional approach fill settlement limitations regarding integral abutments. If estimated post-construction settlements are more than 1” report this value in the Geotechnical Report and consider implementing the techniques discussed in Section 9.4. An additional option to consider is relocating the bridge end bents, if doing so would result in markedly reduced embankment settlement. An additional consideration specific to bridge embankments is settlement-induced down drag loads on piles and drilled shafts.

9.6.1 Approach Slab

The standard practice at ODOT is to provide bridge approach slab (20’ in length) at each end bent location for bridges constructed on the State Highway system. Post construction embankment settlement frequently occurs at this transition point and approach slab assist in eliminating a potentially dangerous traffic hazard. They further reduce the impact of traffic loads to the bridge. Although approach slabs are effective in mitigating minor levels of movement, excessive levels of embankment settlement will still require expensive mitigation. Such excessive settlement is typically the result of poorly compacted embankment fills or long-term consolidation of the foundation soils.

Eliminating the end panels may be considered if the following geotechnical conditions are met:

- Foundation materials are nominally incompressible (e.g., bedrock or very dense granular soils)
- Post-construction settlement estimates are negligible (<0.25”)
- Provisions are made to ensure the specifications for embankment and backfill materials, placement and compaction are adhered to (increased inspection and testing QC/QA)

The elimination of approach slab requires a geotechnical and structural evaluation and an approved Bridge deviation. The final decision on whether or not to eliminate approach slabs shall be made by the ODOT State Bridge Engineer after consideration of the geotechnical and structural evaluations.

In addition to geotechnical criteria, other issues such as average daily traffic (ADT), design speed, or accommodation of certain bridge structure details may supersede the geotechnical reasons for eliminating approach slabs. Approach slabs shall be used for all ODOT bridges with stub, or integral abutments to accommodate bridge expansion and contraction. Approach slabs are used in all cases which result in excessive fill settlement due to seismic loads and failure to meet the performance criteria described in the BDM.

9.7 References

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Samtani, N. and Nowatzki, E. (2006), Soils and Foundation Reference Manual, Volumes I and II, Report No. FHWA NHI-06-088.

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