Chapter 10
GEOTECHNICAL PERFORMANCE LIMITS

GEOTECHNICAL DESIGN MANUAL

January 2022

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CHAPTER 10

GEOTECHNICAL PERFORMANCE LIMITS

10.1 INTRODUCTION

LRFD incorporates the use of limit states as a condition beyond which a component/member or foundation of a structure ceases to satisfy the provisions for which it was designed. The Strength, Service and Extreme Event limit states have design boundary conditions for structural performance that account for some acceptable measure of structural movement throughout the structure's design life. The performance limits for geotechnical structures such as embankments and ERSs are presented in this Chapter. Although performance limits for bridge foundations are not presented, the determination of the settlement of bridge foundations is required and shall be reported to the SEOR, who will determine if the structure is capable of withstanding these deformations.

The design of embankments shall include consideration for the performance of the pavements as well as any structure located within the embankments (i.e., culverts, pipes, and ERSs). No performance objectives or limits have been established for hydraulic structures (i.e., culverts and pipes). The acceptable performance of a hydraulic structure is based on the integrity of the structure and the ability of the structure to continue to function as designed (i.e., convey water from one side of the embankment to the other). Therefore, the GEOR shall report anticipated deformations (i.e., total and differential settlement, etc.) to both the SEOR as well as the HEOR. It is the responsibility of these designers (i.e., SEOR and HEOR) to determine if the hydraulic structure will perform as designed given the anticipated deformations.

Performance limits are based on the design life of the structure. For bridge structures the design life shall be 75 years, as established by AASHTO LRFD Specifications, and for other non-bridge elements (embankments and ERSs) the design life shall be 100 years. However, it is noted that the typical design life for pavements is 20 years and that this life shall be used in the determining the amount and acceptable rate of deformation for embankments. Structures that cannot be replaced without significant expense or that may be subject to structural distress due to environmental conditions (corrosion, biological degradation, etc.) may have a design life that exceeds the typical design life. The structural performance under Strength, Service and Extreme Event loads are typically expressed in terms of settlement, settlement rate, differential settlement, vertical displacement, lateral displacements, rotations, etc.

The LRFD geotechnical design philosophy and the load factors, γ, for geotechnical engineering are provided in Chapter 8. The geotechnical resistance factors, φ, for the Strength, Service, and Extreme Event limit states are provided in Chapter 9. The design methodology to analyze structure performance shall be in accordance with AASHTO design methodology with modifications/deviations as indicated in the appropriate Chapters of this Manual. The load and resistance factors provided in this Manual shall be used. These factors were considered in the selection of the performance limits established in this Chapter.

10.2 PERFORMANCE OBJECTIVES

10.2.1 General

Transportation structures are typically thought of as being rigid and stationary, but in reality they deform throughout their service life due to various physical (loads) and environmental (temperature, degradation, etc.) conditions exerted on the structures. The deformations range from the elastic range where no permanent deformations remain after unloading, to the plastic range where deformations become permanent even after unloading, and finally to rupture where the material is permanently severed and collapse is imminent. The types of loadings that cause these deformations are discussed in Chapter 8. The deformations experienced by geotechnical structures are typically non-linear, dependent on subsurface site variability, influenced by environmental factors, and are highly dependent on soil-structure interaction due to strain compatibility (stiffness) between soil, aggregates (stone, gravel, etc.), soil reinforcements/anchors (steel or geosynthetic), and reinforced concrete, steel, etc. Soils are considerably more compressible, have essentially no tensile strength, and have shear strengths that occur at considerably larger displacements than occur in most typical structural elements. Unlike concrete and steel, soil properties are highly variable. Soils found in-place may vary significantly over short distances both vertically and horizontally because soil composition and properties are based on geologic mechanisms. When soils are engineered through material selection and construction control, soil variability in composition and density can still occur as a result of the non-uniformity of the material stockpile, weather, and construction.

Performance Limits are the result of first establishing Performance Objectives for typical structures used by SCDOT such as embankments, ERSs, bridge and hydraulic structures. Performance Objectives should be established by the design team based on guidelines established by SCDOT for each limit state the structure is being designed for. Once the Performance Objectives are established, the design team should establish Performance Limits for each structure to meet the level of functionality defined by the objectives. These Performance Objectives and Performance Limits shall have the concurrence and acceptance of the OES/SDS and the OES/GDS. This Chapter provides the Performance Objectives and Performance Limits for embankments and ERSs. The Performance Objectives and Performance Limits for bridge structures at the Strength, Service or Extreme Event limit states shall be developed by the SEOR on a project specific basis. The Performance Objectives and Performance Limits for hydraulic structures including 3-sided culverts, concrete box culverts, pipes, etc. at the Service or Extreme Event limit states shall be developed on a project specific basis by the SEOR and HEOR (see Section 10.1). When evaluating the performance of hydraulic structures, consideration of adjacent structures such as Embankments (Section 10.8) or ERSs (Section 10.9) shall be given since the Performance Objectives and Performance Limits of these geotechnical structures may not be compatible with the requirements for hydraulic structures.

The Performance Objectives define the level of functionality of the structure for the limit state loading condition being evaluated. Performance Objectives are based on:

- Limit State: Service I limit state or Extreme Event limit state load combinations defined in Chapter 8.
- Operational Classification: Bridge OC (see Seismic Specs).

Typically, there is no adjustment for variability in both the load and resistance portions of the analysis. The load (γ) and resistance (φ) factors generally used in geotechnical analyses are unity (1.0) unless indicated otherwise in Chapters 8 and 9. When load factors greater than unity ($\gamma > 1.0$) or resistance factors less than unity ($\varphi < 1.0$) are used, this is typically due to the variability or uncertainty associated with the load or resistance being computed. The design intent is to analyze the most likely behavior of the structure when subjected to typical loadings for each limit state.

Temporary (i.e., having a life of less than 5 years) embankments and structures (e.g., temporary steepened slope, temporary ERSs, etc.) shall not be designed for the EE I limit state. Project specific Performance Objectives and Performance Limits for temporary embankments and structures at the Service limit state shall be based on whether the structure is critical or is support of excavation only (see Chapters 17 and 18). The design team shall determine whether a temporary embankment or structure is for excavation support only or is critical. In addition, the Performance Objectives and Performance Limits shall be established by the design team.

The Performance Objectives and Performance Limits for both permanent and temporary structures at the EE II (collision/impact loadings only) limit state are developed on a project specific basis by the design team. The Performance Objectives and Performance Limits for this limit state check shall be established by the design team and shall have the concurrence and acceptance of the OES/SDS and the OES/GDS. For the EE II (check flood (500-yr flow event)) limit state, stability shall be maintained (i.e., a resistance factor of 1.0 (φ =1.0) shall be obtained from the analysis). See Chapters 15 through 18 for analysis procedures.

Development of Performance Objectives and Performance Limits for structures subjected to Service and Extreme Event loadings that are not included in this Chapter shall be developed by the design team on a project specific basis. These Performance Objectives and Performance Limits shall have the concurrence and acceptance of the OES/SDS and the OES/GDS.

10.2.2 Service Limit State Performance Objectives

The Performance Objective for the Service limit state requires that, with standard SCDOT maintenance, the structure remains fully functional to normal traffic for the design life of the structure. The performance of a structure under Service loads is influenced by many factors that may or may not be within the designer's control. Provided in Appendix K is a list of considerations that may influence the performance of the structure over its design life Service limit state.

10.2.3 Extreme Event Limit State Performance Objectives

The Extreme Event limit states (EE I and EE II) are load combinations that are typically in excess of the Service limit state loadings and may also be in excess of the Strength limit state. The loadings from these Extreme Events are typically the result of seismic events or the check flood (500-yr flow event) or collisions from ships, barges, or vehicles. The Extreme Event limit states have the potential to cause damage to a structure and impact the structure's functionality. Even though Extreme Event limit states typically have a low probability of occurring within the design life of the structure, these limit state loadings must be evaluated since the potential for loss of life and loss of service of the structure can be significant. Because the probability of these events occurring is relatively low, a lower safety margin is used and performance limits are less rigid than those for the Service limit state. The damage resulting from these Extreme Event loading conditions may be significant enough to warrant replacement of the structure, but the bridges should have a low probability of collapse due to seismic motions.

The Performance Objectives for the Extreme Event limit state of a structure are defined by selecting an appropriate Service Level and Damage Level for each component/member or foundation element being analyzed. For complex structures such as bridges and ERSs, performance objectives are first given to the overall structure and then component performance objectives are given to the individual component/members or foundation of the structure. Although this approach is somewhat subjective at this time, it allows for a more methodical way of evaluating each component of the structure to assure that the component meets the overall performance objective of the complete structure. The Performance Objectives for the EE I limit state for bridges are provided in the Seismic Specs. The Performance Objectives and Performance Limits for bridges for the EE II should be established by the design team.

The Performance Objectives for the EE I limit state for bridge embankments and any ERSs located within the bridge embankment are that any movements shall conform to the Performance Objectives established for the bridge in the Seismic Specs and are based on the OC of the bridge as indicated in the Seismic Specs. It should be noted that certain slopes, embankments and ERSs do not required global stability analysis during the EE I limit state, see Chapters 13 (embankments) and 14 (ERSs) for these conditions.

The Service and Damage Level descriptions are provided in the Seismic Specs and are intended to apply to bridges, roadway structures and bridge embankments. Because soils found in-place and within embankments may significantly vary within short distances both vertically and horizontally due to South Carolina geology, it is difficult to associate closure time and degree of collapse along a continuous embankment. Generally, it is not economically feasible to entirely prevent failure of a roadway embankment due to a seismic event; however, a bridge embankment can and will be improved as required to prevent the collapse of the bridge. This should not be taken as to mean that movement of the bridge or embankment is not allowed, but that movement commiserate with the Performance Objective of the bridge is permitted. Observations from past earthquakes around the world indicate that embankment failures are isolated and discontinuous after a seismic event and the accessible area along the top of the embankment has for the most part remained traversable. Based on these observations, roadway embankments that are not designed for seismic events may still be traversable even though they may exhibit significant damage that may require repair.

The EE I limit state is a load combination that is associated with a design seismic event. SCDOT uses the design seismic events listed in the Seismic Specs. Additional information concerning the design seismic events can be found in Chapters 11 and 12. The Performance Objectives and seismic design requirements for bridges are provided in the latest edition of the Seismic Specs. While the Seismic Specs limit the applicability of the 2-level design (i.e., designing using both FEE and SEE) for bridges, all bridge embankments and ERSs located within bridge embankments shall be designed for both seismic events. ERSs located in roadway embankments shall be designed for the SEE only.

The EE II limit state is associated with vehicular or vessel collision/impact and certain hydraulic events including the check flood (500-year flow event). Project specific Performance Objectives and Performance Limits shall be determined by the design team and shall have the concurrence and acceptance of the OES/SDS and the OES/GDS for vehicular or vessel collision/impact as applicable to ERSs. The Performance Objectives for the check flood shall conform to the requirements contained in this Manual. EE II (collision/impact loadings only) limit state loadings shall not be considered in the design of embankments. However, the stability of an embankment shall be determined using the EE II (check flood (500-yr flow event)).

10.3 PERFORMANCE LIMITS

The Performance Limits that are specified in this Manual are for new construction including embankment widenings required during staged bridge replacement, but do not apply to retrofitting or maintaining existing structures or embankments. For road or bridge embankments widened as part of either the widening of a road or the widening of an existing bridge, the Strength and Service limit state checks will be required. Performance Limits have been developed based on SCDOT design and construction standards of practice contained in this Manual, AASHTO LRFD Specifications, FHWA publications, BDM, Seismic Specs, and in accordance with SCDOT construction specifications and SCDOT experience. SCDOT reserves the right to modify these Performance Limits based on project specific requirements or as new research or additional experience becomes available.

The Performance Limits presented are based on the deformations that occur at the Service and EE limit states. The deformations determined at the Service limit state shall be compared to the Performance Limits contained in this Manual. If the deformations exceed the Performance Limits contained in this Manual, the GEOR shall consult with the design team to determine the impact of the deformations on the Performance Objectives. The design team shall make the determination of whether remediation is required or not. If remediation is not required the GEOR shall report the deformations and shall indicate that the design team has elected to not remediate the limit state as the Performance Objectives are still met. If remediation is required, both the SEOR and GEOR shall consider different remediation options and shall present the various options to the design team along with the anticipated cost of the remediation. The design team will select the most appropriate remediation to achieve the Performance Objectives of the project. This should include the longitudinal and transverse limits of remediation as well as the depth of remediation.

The EE limit state Performance Limits shall be considered a general guide and not a limit. The design team has the ultimate responsibility for determining performance of the project/structure during the design seismic event. The performance must meet the required Performance Objectives as described in the Seismic Specs. The design team has the responsibility to ensure that the Performance Limits are used judiciously so as not to place in jeopardy the Performance Objectives of the structure being designed. It is the GEOR's responsibility to present the geotechnical performance findings to the design team and to assist the design team in evaluating geotechnical and structural solutions for maintaining the structure's performance within the Performance Objectives and Performance Limits previously established by the design team. If the design team makes no comment concerning the geotechnical performance findings; the GEOR may assume the findings are acceptable and no remediation will be required.

The Performance Limits specified in this Chapter are specific to the type of structure being designed. The acceptable deformations specified are based on the structure's intended use as provided in the Service limit Performance Objectives for Embankments (Section 10.8) and Earth Retaining Structures (Section 10.9). Performance Limits may need to be adjusted for these structures based on any adjacent structures such as hydraulic structures, utilities (water, gas, electricity, phone, etc.), pavements, bridges, ERSs, signs, homes, buildings, etc. that may be impacted by the deformations that are deemed acceptable for the structures that are addressed in this Manual. For example, settlements that may be acceptable for an embankment may not be acceptable for an existing building within the influence of a roadway embankment. Another example where the Performance Limits provided may not be acceptable would be during global instability where deformations of an embankment may distress adjacent structures such as bridges, side ramps, or other structures beyond the Right-of-Way.

Performance Objectives and Performance Limits not covered in this Manual shall be determined by the design team and shall have the concurrence and acceptance of the OES/SDS and the OES/GDS. The design team will first establish Performance Objectives for the structure being analyzed. Once the Performance Objectives have been developed and accepted, Performance Limits shall be established that meet the Performance Objectives.

10.4 DEFORMATIONS

Deformations are specified in terms of vertical and lateral displacements, whereas Performance Limits are not to exceed deformations (i.e., acceptable displacements). Displacements can be a result of direct movements such as settlement of an embankment or as a result of rotations such as embankment instability or foundation rotations due to lateral loadings. Vertical displacements that occur in a downward direction (into the ground) are referred to as settlement. Specifying a Maximum Vertical Settlement (i.e., a Performance Limit) can help to control total settlements. Damage or poor performance of a structure most often occurs as a result of excessive differential displacements. An example of this would be a bridge with foundations supported by rock and with an approach embankment supported on very compressible soils. While the bridge would remain relatively stationary vertically, the approach embankment would settle substantially relative to the bridge. The vertical differential displacements would affect vehicle rideability and add structural loads to the abutment foundations as a result of downdrag on deep foundations. Specifying a Maximum Vertical Differential Settlement would help to control the differential vertical displacements that occur between the bridge abutment and the bridge approach embankment to an acceptable level of performance. There may be situations where vertical displacements act upward, due to heave or differential movements of a structure. This condition may cause part of the structure to move up when other parts of the structure move downward (settle). The Maximum Vertical Differential Displacement limits also control these upward and downward displacements to an acceptable level of performance.

Lateral displacements (horizontal movements) are identified as occurring in either the longitudinal or transverse directions. On bridges and roadways, the longitudinal direction is parallel to the centerline, while the transverse direction is perpendicular to the centerline. Unless otherwise indicated in the performance limit description, the lateral displacements do not have sign convention and may occur in either direction.

10.5 GLOBAL INSTABILITY DEFORMATIONS

In the 9th Edition of AASHTO (2020) global stability analysis was changed from a Service limit state check to a Strength limit state check. The accepted design methodologies currently being used for evaluating the global stability of a structure at the Service limit state shall continue to be used. Global stability is evaluated at the Strength limit state using appropriate resistance factors that provide for designs that are the equivalent of ASD. This method of evaluating global stability assumes that the driving and resisting forces are maintained in equilibrium within an appropriate safety margin and therefore negligible displacements occur. Therefore, the Service limit state shall not be checked. Embankments and ERSs at the Strength limit state shall have global stability checked (Chapter 17); however, a specified resistance factor, φ (margin of safety) against instability must be achieved (i.e., deformation of the embankment or ERS is ineligible). Therefore, there are no Performance Limits for global instability at the Service limit state for either embankments or ERSs. If the required resistance factor, φ, is not achieved, then either ground improvement (see Chapter 19) will be required to maintain stability or the slope may be made flatter (i.e., decrease slope from 2H:1V to 3H:1V). Embankments and ERSs at the EE II (check flood (500-yr flow event)) limit state are required to just maintain stability (i.e., φ = 1.0); therefore, just like at the Service limit state there are no Performance Limits.

The Performance Objectives for embankments and ERSs at EE I limit state is that neither the embankments nor the ERSs adversely affect the bridge structure during the design seismic event. Bridge embankments are defined in Chapter 2 and shall include any ERSs. ERSs beyond this longitudinal limit are discussed in the following paragraphs.

Global stability analysis shall be performed to determine the portion of the embankment (i.e., bridge embankment) that will have instability during the EE I limit state and that will directly affect the bridge (i.e., typically the front slope, see Figure 10-1). Mitigation shall be limited longitudinally from the bridge to the point where the Global Performance Objectives of the Bridge System are met (see Seismic Specs). The embankment beyond this point is a roadway embankment and is not required to be seismically designed. ERSs not located within bridge embankments shall be designed for no collapse. These ERSs shall be designed to account for the surrounding area and shall be allowed to displace as necessary.

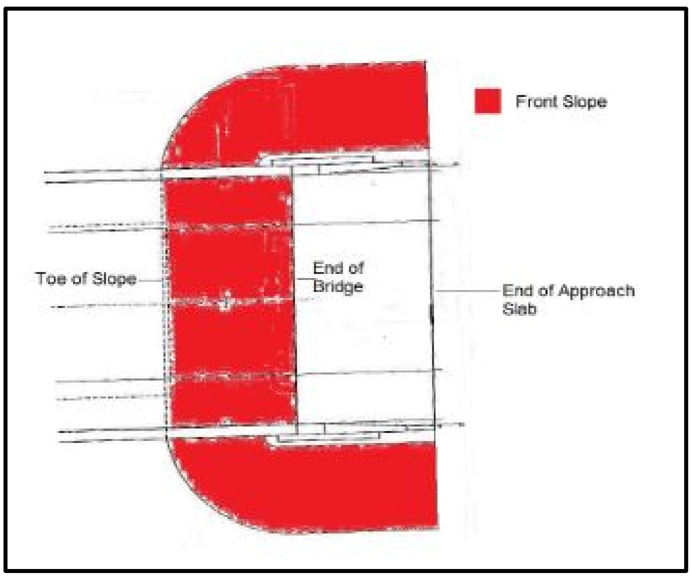


Figure 10-1, Front Slope Definition

Deformations can only occur when there is an imbalance of the driving and resisting forces within the earthen mass. Because the Performance Objectives for the EE I limit state permits an acceptable amount of deformation, global instability analyses and the subsequent deformation determination must be made for the EE I limit state. Embankment deformations associated with the EE I limit state (seismic loadings) include flow failure, lateral spread, seismic instability, and seismic settlement. Deformations associated with flow failure are assumed to exceed the Performance Limits for the EE I limit state and must be either mitigated or the bridge protected from the flow failure. In addition, flow failure also requires the presence of SSL at the project site.

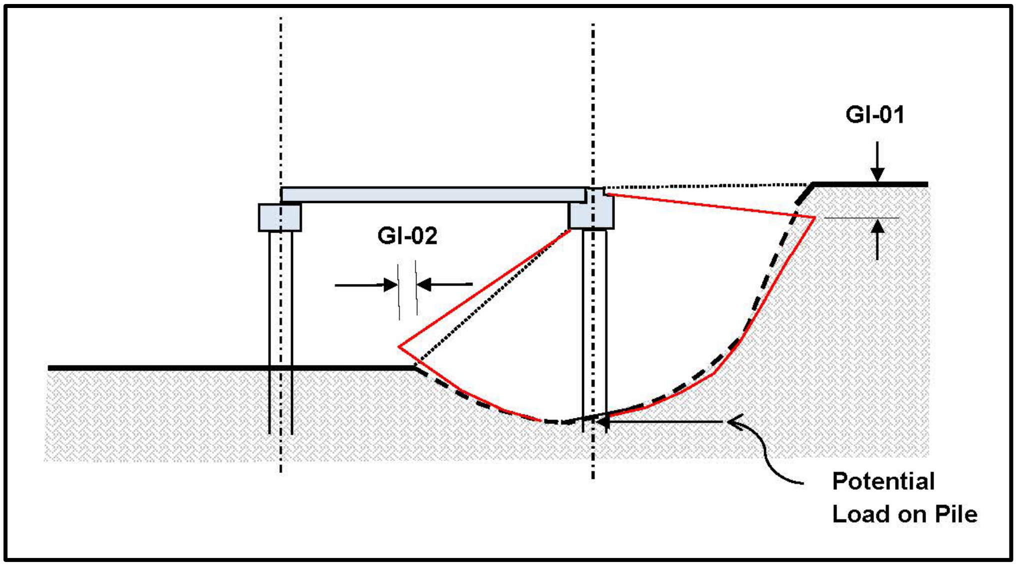
Similarly to flow failure, lateral spread also requires the presence of SSL. The deformations induced by the lateral spread shall be determined as provided in Chapter 13 and shall be discussed with the design team to determine if the bridge foundations can handle the movement (see Chapter 14). Methods of analyzing deformations due to seismic instability are provided in Chapter 13. Performance Limits for global instability have been developed that address these types of deformations and are identified in Table 10-1. The Performance Limits for seismic displacement are discussed in the following Section.

Table 10-1, Global Instability Deformations Performance Limits

Notation	Deformation ID No.	Description
Vertical Displacement, Δ_V	**GI-01**	Maximum Vertical Displacement at top of the failure surface (circular).
Lateral Displacement, Δ_L	**GI-02**	Maximum Lateral Displacement at either top or bottom of the failure surface (sliding block).

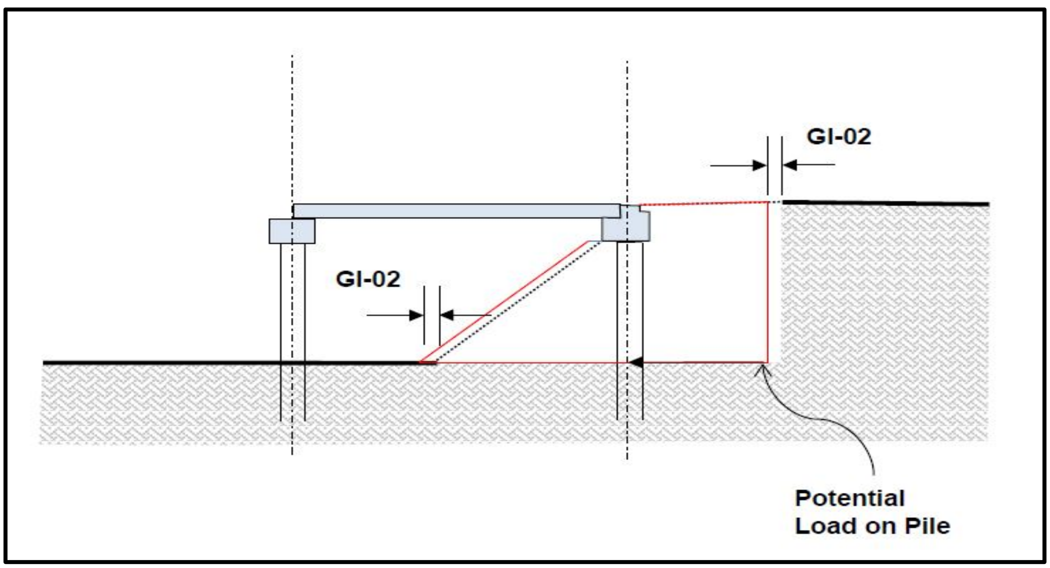
EE I limit state Performance Limits for global instability deformations associated with seismic slope instability are specified along the shear failure surface that results from the imbalance in the driving and resisting forces of the slope. The evaluation of global instability deformations is very complex and the methods (Chapter 13) that have been developed to evaluate deformations are typically either empirical or are very simplistic models that only provide an approximation of the slope instability deformations. A considerable amount of engineering judgment will be required to evaluate embankment deformations. To simplify this evaluation, it can be assumed that the soil is incompressible, that the deformations occur equally along the critical failure surface and that failing mass, whether embankment or ERS remains as a block during failure. The deformations measured along the failure surface shall be considered to be completely vertical at that top of slope for a circular failure surface (see Figure 10-2), while at the bottom of the circular failure surface the deformations shall be considered to be completely horizontal. For a sliding block failure surface the deformation shall be completely horizontal (lateral) regardless of whether the displacement is measured at the top or bottom of the slope (see Figure 10-3).

Figures 10-2 and 10-3 depict the results of global instability at the end bent of a bridge. Figure 10-2 indicates a circular failure surface, while Figure 10-3 indicates a sliding block failure surface. Please note that depending on the stiffness of the piles, the end bent may or may not move. Therefore, it is possible that the end bent could be in “air” with soil having pulled away from the end bent. Similar deformations would happen if instead of a slope, an ERS were located at the end bent.



Not to Scale

Figure 10-2, Bridge Embankment Circular Instability



Not to Scale

Figure 10-3, Bridge Embankment Sliding Block Instability

Figures 10-4 and 10-5 indicate the instability of the transverse (side) slope of an embankment located within the "bridge embankment" portion of the approach embankment. If these instabilities affect the end bent of the bridge, then either structural or geotechnical mitigation will be required. The type and amount of mitigation that will be required is based on the Performance Objectives of the bridge, which are based on the OC of the bridge. OC determination and the Performance Objectives are defined in the Seismic Specs.

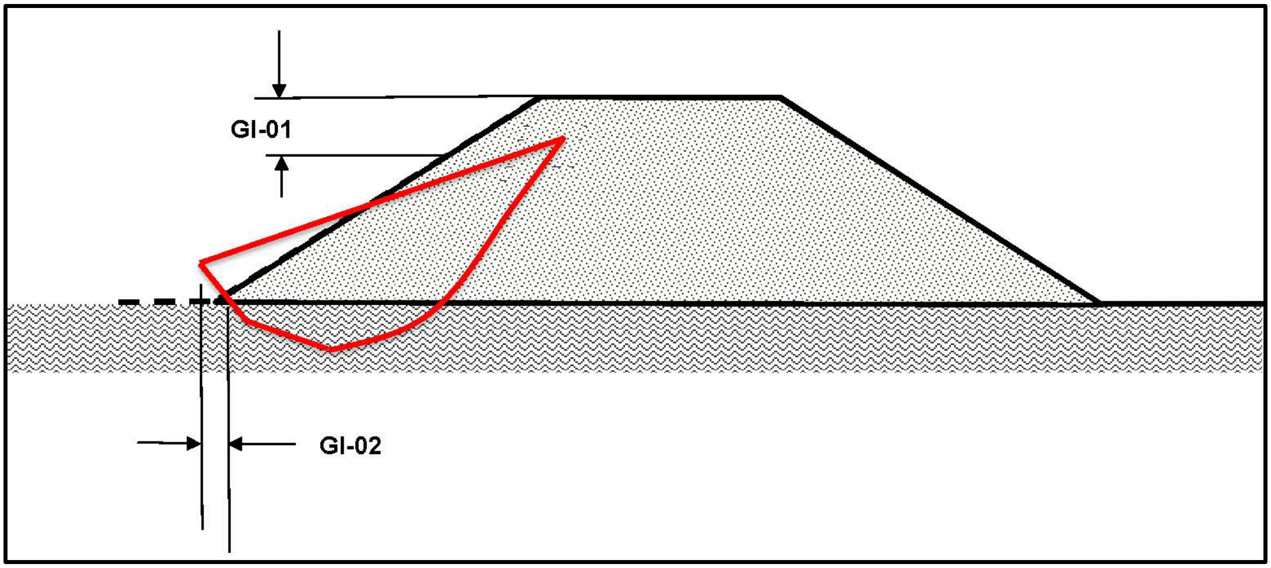


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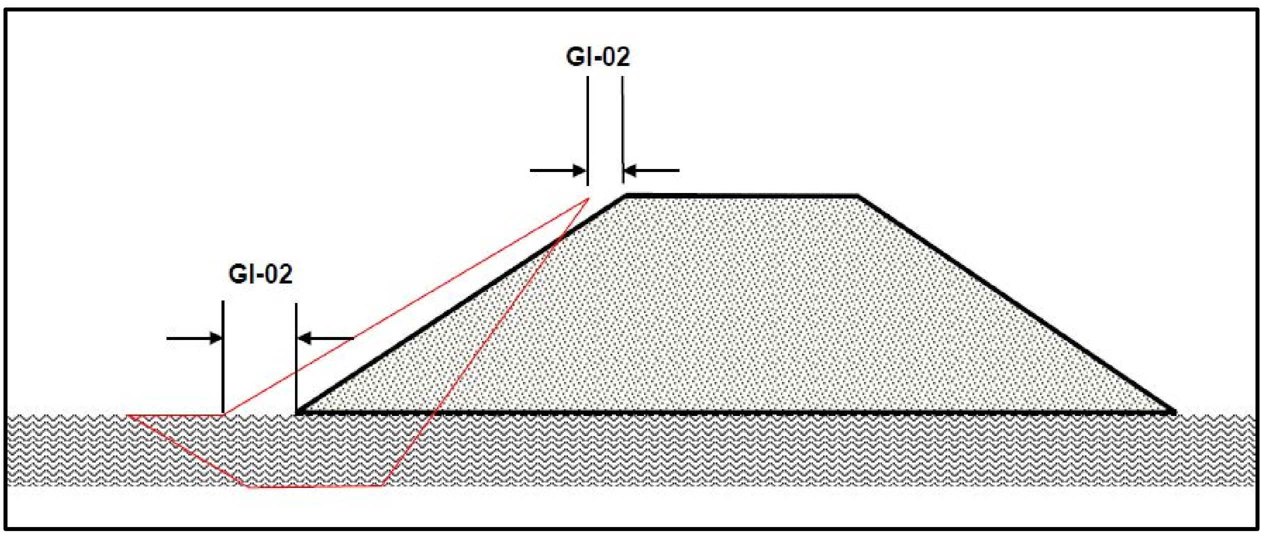
Figure 10-4, Roadway Embankment Circular Arc Instability



Not to Scale

Figure 10-5, Roadway Embankment Sliding Block Instability

As indicated previously the global instability assumes that the ERS maintains integrity (i.e., the ERS functions as a unit) during the instability. If the anticipated failure surface passes through the ERS, the ERS will need to be increased in size (i.e., the reinforcement material should be longer for MSE walls or the heel of the wall of a cantilevered gravity retaining wall should be increased). For ERSs located at the end bent of a bridge, global instability will be handled similarly to the embankment instability as discussed previously. ERSs located within the portion of the roadway embankment shall meet the Performance Objectives and Performance Limits established for ERSs. Figure 10-6 depicts the effect of localized global instability that does not affect the full length of the ERS. Section B-B is depicted in Figures 10-7 and 10-8, which indicate the anticipated movements for a circular and sliding block failure surface, respectively. The Performance Limits for global instability presented in this Chapter only apply to Rigid and Flexible Gravity ERSs (see Table 10-6). A global stability check is required for all Cantilevered ERSs as discussed in Chapter 18.

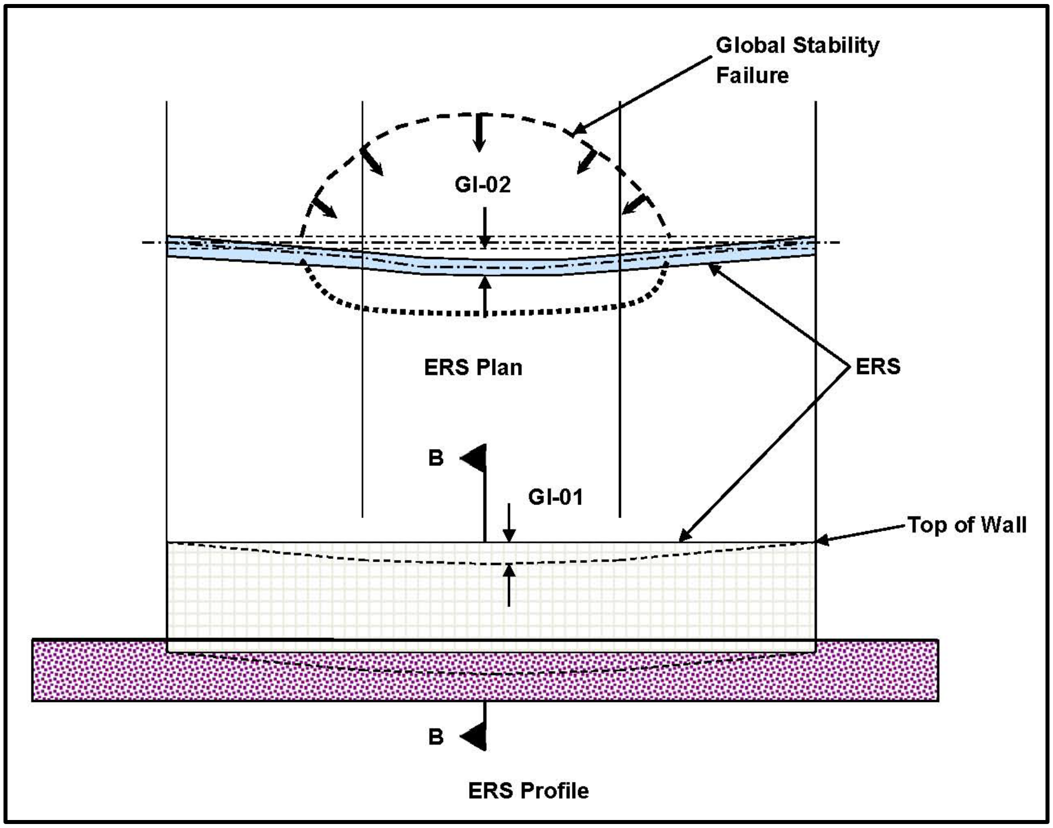


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Figure 10-6, ERS Global Instability

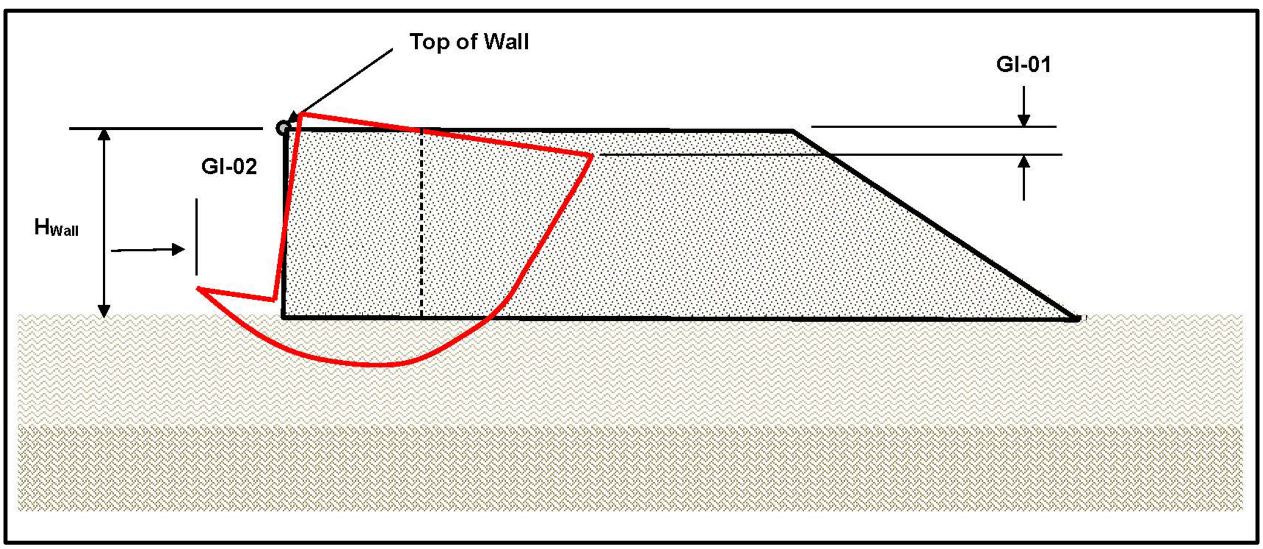

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Figure 10-7, ERS Circular-Arc Instability (Section B-B)

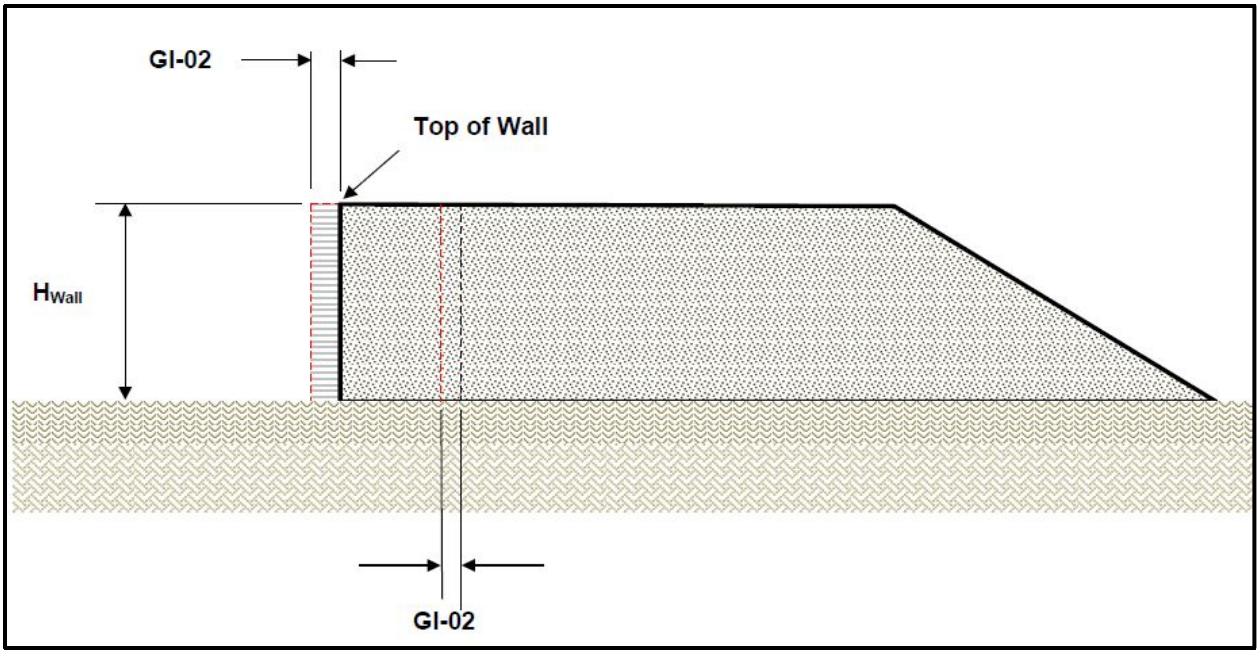

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Figure 10-8, ERS Sliding-Wedge Instability (Section B-B)

10.6 EMBANKMENT DEFORMATIONS

10.6.1 Embankment Terminology and Deformation Notations

Embankment design with respect to global stability and settlements (deformations) is discussed in Chapter 17. Terminology used to specify geotechnical performance limits for embankments along roadways and at bridge approaches is presented in Chapter 2. RSSs as well as reinforced embankments are included with unreinforced embankments.

Embankment deformation notations are listed in Table 10-2. Embankment deformations where Performance Limits are specified can be categorized as follows:

- Embankment Settlement
- Embankment/Bridge Transition Settlement
- Embankment Widening Settlement

Table 10-2, Embankment Deformation Notations

Notation	Description
δ_V	Vertical Differential Settlement
Δ_V	Total Vertical Displacement / Settlement
Δ_L	Lateral Displacement
L_{SLAB}	Longitudinal Length of the approach slab
ΔL	Deformation occurring along the critical failure surface due to slope instability
L_L	Longitudinal distance of area affected by the compressive soils producing embankment settlements.
L_T	Transverse distance that defines the span of maximum differential settlement from the existing embankment (no settlement or minimal settlement) to the location of maximum settlement for the portion of new embankment that has been widened.

10.6.2 Embankment Settlement

Embankment vertical settlements are typically due to embankments being constructed over compressible soils that experience soil deformation (elastic compression, primary consolidation, and secondary compression) under constant load. It is anticipated that elastic compression will be completed prior to the placement of pavement; however, the total settlement (elastic compression, primary consolidation, and secondary compression) shall be determined. The total settlement shall be used in the development of static downdrag loads (see Chapter 16), if required. Settlement analysis methods are provided in Chapter 17. The vertical settlements that are evaluated under the Service limit state are as indicated below.

- Maximum Settlement from Elastic compression + Primary consolidation + Secondary Compression (i.e., total settlement occurring during construction)
- Maximum Settlement from Primary consolidation + Secondary Compression (i.e., total settlement after paving)
- Maximum Differential Settlement from Primary Consolidation + Secondary Compression (occurs after paving)

The maximum settlement shall be based on a 20-year design life which is used to match the typical repaving schedule anticipated by SCDOT.

Under the EE I limit state, performance limits for embankment settlement are specifically those caused by geotechnical seismic hazards that may affect the embankment or subgrade during or after a seismic event especially at the transition between the embankment and bridge. Methods of analyzing geotechnical seismic hazards due to soil SSL of the subgrade or seismic settlement of the embankment and subgrade are discussed in Chapter 13. It is noted that there is no limit on the amount of vertical settlement that can occur at the end bent of a bridge during EE I. Instead the vertical movements are converted into downdrag loads that are determined as discussed in Chapter 16. The maximum differential settlement may be determined under the EE I limit state analysis. The differential settlements may be either between the end of the approach slab and the bridge, between a point on the embankment and the end of the approach slab or between 2 points along the embankment. The longitudinal differential settlement of the embankment and the bridge should not be determined if an approach slab is present.

Performance limits for embankment settlements are identified in Table 10-3.

Table 10-3, Embankment Settlement Performance Limits

Notation	Deformation ID No.	Description
Vertical Settlement, Δ_v	**EV-01A**	Maximum Settlement from Elastic Compression + Primary Consolidation + Secondary Compression along the profile grade[1] that occurs during the duration of the construction of the embankment and commences at the start of construction and terminates just prior to paving operations. This deformation is used to adjust borrow requirements, if necessary
	EV-01B	Maximum Settlement from Primary Consolidation + Secondary Compression along the profile grade[1] over the design life[2] of the embankment. The design life begins after the pavement has been placed (i.e., the settlement that occurs after EV-01A).
Vertical Differential Settlement, δ_v	**EV-03**	Maximum Differential Settlement from Primary Consolidation + Secondary Compression occurring longitudinally along the profile grade after the roadway has been paved. Determined either between the end of the approach slab and a point on the embankment or between 2 points on the embankment that may affect rideability.

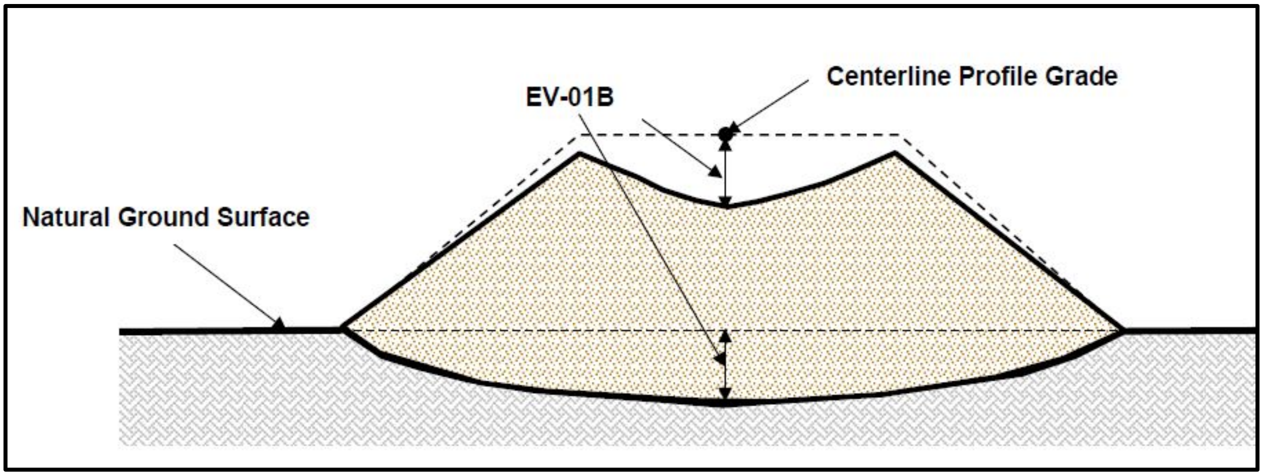
[1]The longitudinal location of EV-01(A or B) shall be noted (i.e., at end bent, at end of approach slab, at Sta. XX+XX, etc.)

[2]Design life of 20 years shall be used.

The roadway profile grade (P.G.) for non-divided highways (highways without medians) is typically located at the center of the roadway as indicated in Figure 10-9. Figure 10-9 is designated as Section A-A and corresponds to an embankment cross-section taken transverse to the travel lane as indicated in Figure 10-11. Provide a settlement profile that extends from toe to toe for all embankments including new or widened embankments. For widened embankments include both new portion as well as the existing portion in the profile. The GEOR should attempt to locate settlement profiles near to or at the locations of crossline culverts or pipes. The profile should either be continuous or should consist of the settlements at the following locations:

- Centerline of the embankment
- A distance halfway between the centerline and the shoulder break
- The shoulder break
- A distance halfway between the shoulder break and the toe of slope
- Toe of slope

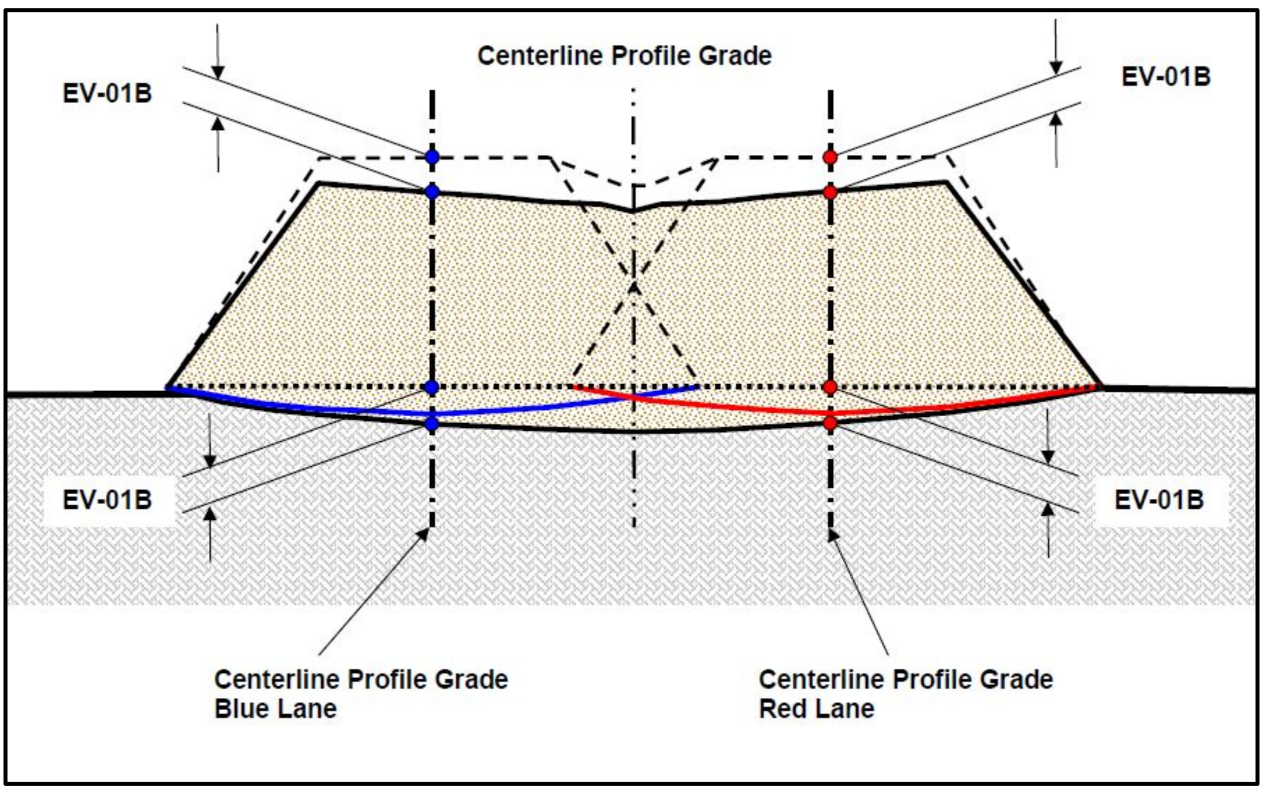
The locations indicated above should extend both right and left of centerline. These are the minimum number points on the profile, additional points may be added by the GEOR. The developed settlement profile should be provided to the HEOR and SEOR to determine whether the crossline culvert or pipe will perform as required.



Not to Scale

Figure 10-9, Embankment Settlement (Section A–A)

Divided highways may have a P.G. elevation for each travel direction as indicated in Figure 10-10. Figure 10-10 is designated as Section A-A and corresponds to an embankment cross-section taken transverse to the travel lane as indicated in Figure 10-11. To differentiate the divided profile grades the color Blue was used to designate the roadway on the left and the color Red was used to designate the roadway on the right. Divided highways should be evaluated separately for each P.G. Settlement analyses must take into account the total embankment cross-section and the construction sequencing.

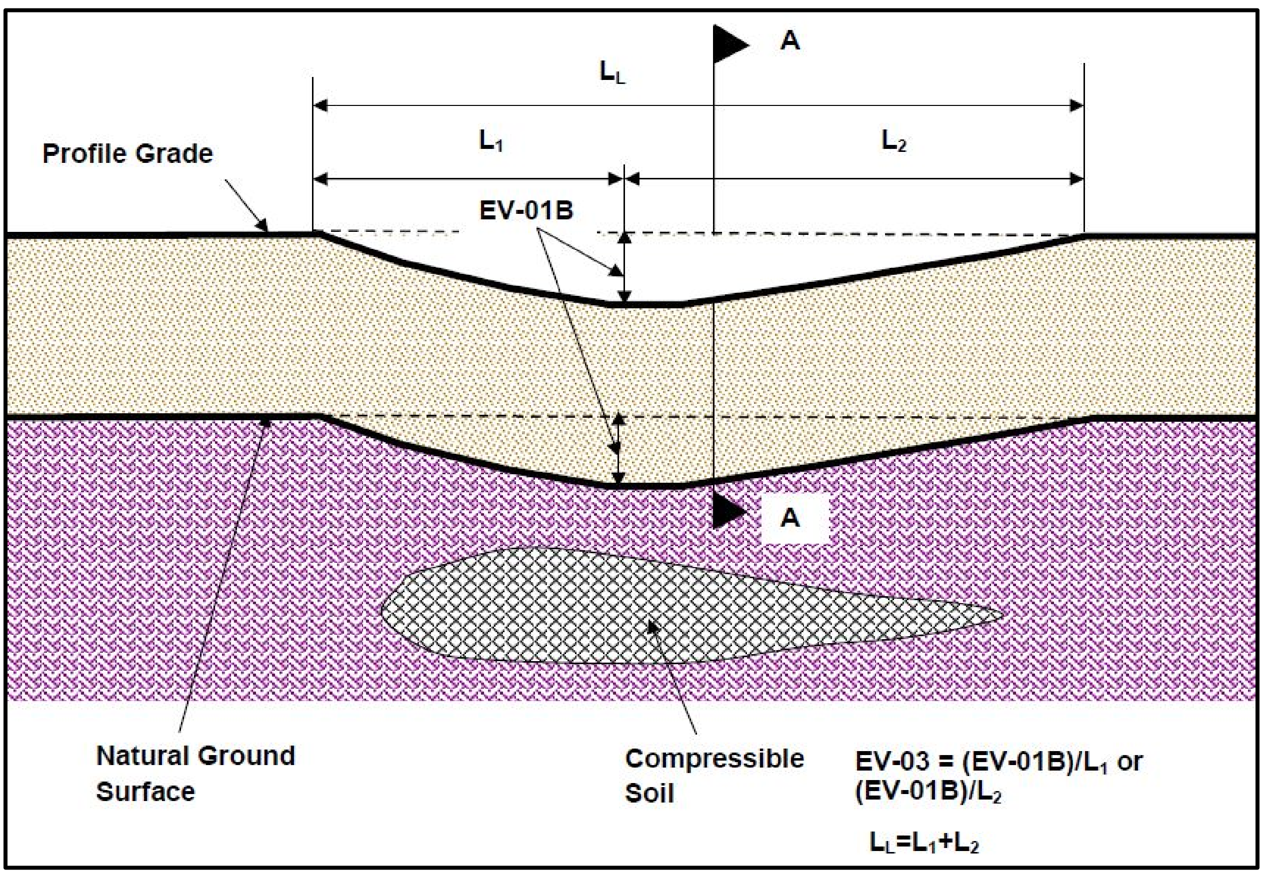


Not to Scale

Figure 10-10, Divided Highway (Section A-A)

The Performance Limit EV-01A is for maximum settlement (Δ_V) that occurs at the profile grade during the construction of the embankment that begins immediately after construction starts and ends immediately prior to paving and may be determined at any specified point along the length of the embankment. Because this deformation also includes elastic compression, EV-01A should be used to adjust borrow quantities as required. The Performance Limit EV-01B is for Δ_V that occurs at the profile grade over the design life (20 years) of the embankment that begins after the pavement has been placed and may be determined at any specified point along the length of the embankment.

Performance Limit EV-03 is specified as the maximum differential settlement (δ_V) occurring longitudinally along the profile grade. The differential settlement is specified over a distance of 50 feet, measured longitudinally along the embankment. It is anticipated that Performance Limit EV-03 will be determined only if there is concern about the rideability of the roadway surface. Performance EV-03 should only be determined from end of the approach slab and another point along the profile grade of the roadway or between 2 points located along the profile grade. If vertical displacements are encountered at an isolated location such as shown in Figure 10-11, the differential settlement performance limit EV-03 may be pro-rated so that at any point along the distance, L_L, the tolerances specified are not exceeded. The distance L_L shall never exceed 50 feet. There are no Performance Limits for differential settlements (δ_V) that occur perpendicular (transverse) to the alignment for new embankments since these types of displacements are relatively small due to the relatively uniform loading and the assumed low soil variability in the transverse direction (not typically investigated). If excessive transverse differential settlement is anticipated to affect the performance of the roadway, refer to Section 10.6.3.



Not to Scale

Figure 10-11, Embankment Settlement Profile

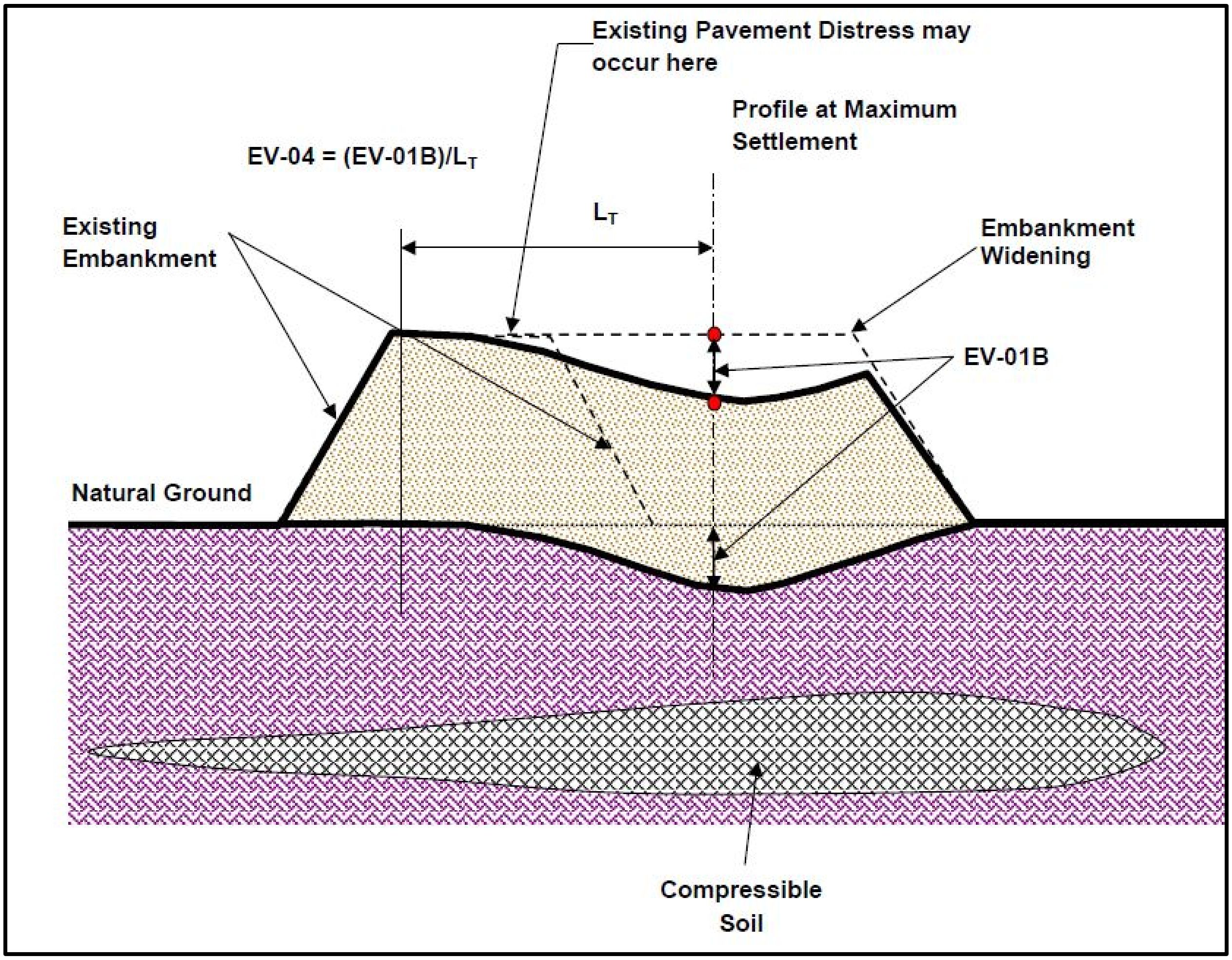
10.6.3 Embankment Widening Differential Settlements

Existing embankments are often widened to accommodate additional traffic lanes or are widened in order to accommodate a re-alignment of a new bridge being constructed adjacent to an existing bridge. These Performance Limits are used on roadways where differential settlement due to widening of the roadway or to soil variability could adversely affect both the existing and proposed roadway pavement. The embankment subject to transverse differential embankment settlement shall be designed for the Performance Limits indicated in Table 10-3 (EV-01A, EV-01B, and EV-03), and transverse differential embankment settlement Performance Limit (EV-04) provided in Table 10-4. Further the GEOR should provide a continuous settlement profile that extends from the existing toe (away from the widening) to the new toe of fill. If possible the GEOR shall try to obtain this profile in the location of any crossline pipes or culverts within the widening. It is noted that transverse differential settlement should be anticipated between a widened portion of the embankment and the existing embankment. The widened embankment will induce loading on the existing embankment that will in turn cause settle of the existing embankment. This settlement may potentially cause damage to the existing embankment. The GEOR should note on the plans if damage is anticipated and that the Contractor is responsible for maintaining the existing travelway. In addition, the GEOR will coordinate with Construction to determine the quantities required to maintain the existing travelway.

Table 10-4, Embankment Widening Settlement Performance Limits

Notation	Deformation ID No.	Description
Differential Settlement, δ_V	**EV-04**	Maximum Vertical Differential Settlement occurring transverse to the adjusted profile grade between the existing embankment and the new widened embankment after the roadway has been paved.

When existing embankments are widened, a parallel profile grade is established at the location of maximum vertical settlement for the embankment widening as shown in Figure 10-12. Figure 10-12 is designated as Section A-A and corresponds to an embankment widening cross-section taken transverse to the travel lane as indicated in Figure 10-11. The performance limits, EV-01A, EV-01B, and EV-03, are computed in the same manner as discussed in Section 10.6.2 except that the settlements are computed along the profile of maximum settlement. The maximum vertical differential settlement (EV-04) limits the differential settlements between the existing embankment and the embankment widening section that may affect the paved roadway surface. The differential settlements transverse to the embankment are computed at distance "L_T" between the existing embankment (where zero or minimal settlement occurs) and the new embankment at point of maximum settlement as indicated in Figure 10-12. For RSSs and reinforced embankments the differential settlement between the face of the slope and the end of the reinforcement should be determined. This differential movement should be determined using the procedure to determine RV-06A and RV-06B as indicated in Table 10-10 and depicted in Figure 10-17.



Not to Scale

Figure 10-12, Embankment Widening Settlement (Section A-A)

10.6.4 Embankment/Bridge Transition Settlement

At the transition between the bridge approach embankments and the bridge ends there is a potential for large differential vertical settlement (δ_V). The vertical differential settlement can be significant in magnitude because the bridge end bents are typically supported on deep foundations that are relatively stationary in the vertical direction as compared to the approach embankment. If the new bridge approach embankments are placed over compressible soils the approach embankments tend to settle significantly more than the bridge ends. Performance Limits for the Embankment/Bridge transition settlement are identified in Table 10-5.

Table 10-5, Bridge/Embankment Transition Settlement Performance Limits

Notation	Deformation ID No.	Description
Vertical Differential Settlement, δ_V	**EV-05A**	Maximum Differential Settlement (δ_V) between the bridge End Bent and the end of the Approach Slab after the roadway has been paved at the end of the pavement design life (20 yrs).
	EV-05B	Maximum Differential Settlement (δ_V) between the bridge End Bent and a point 1 foot from either the "begin" or "end" of bridge, for bridges without approach slabs after the roadway has been paved at the end of the pavement design life (20 yrs).

Differential vertical settlements between the bridge ends and the approach embankments can significantly affect the roadway rideability at the bridge abutment and at the end of the approach slab as shown in Figures 10–13 and 10-14.

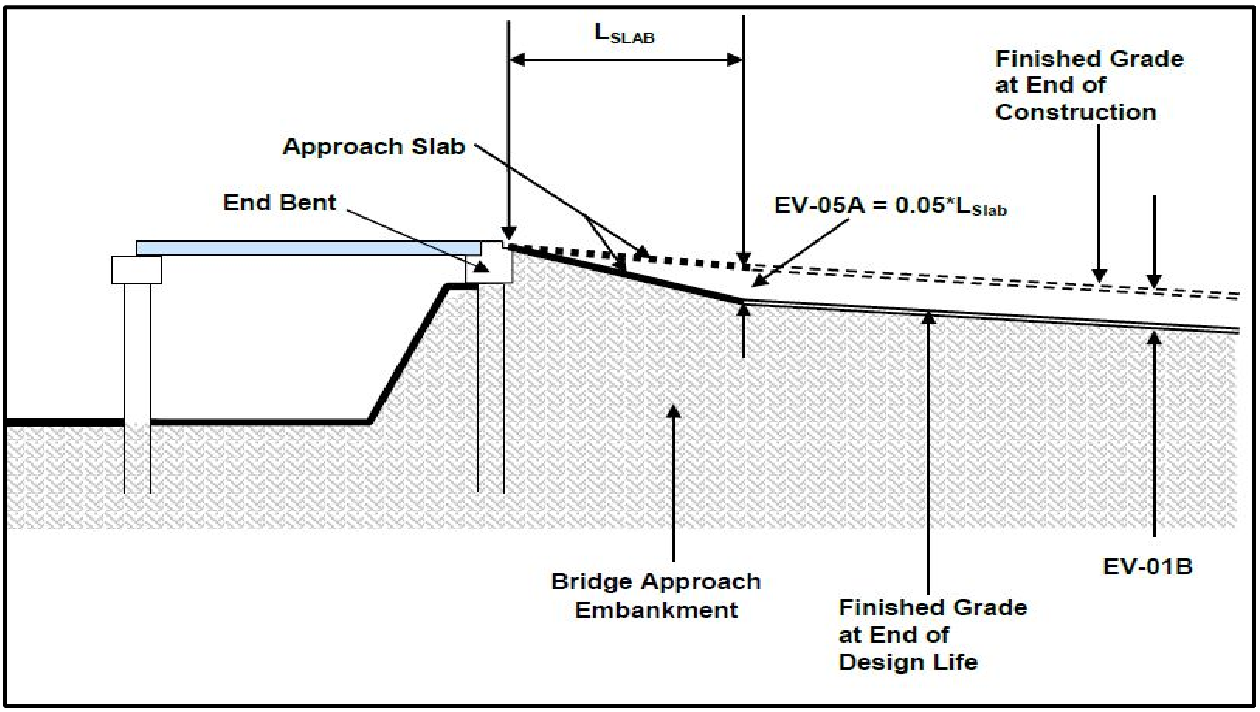


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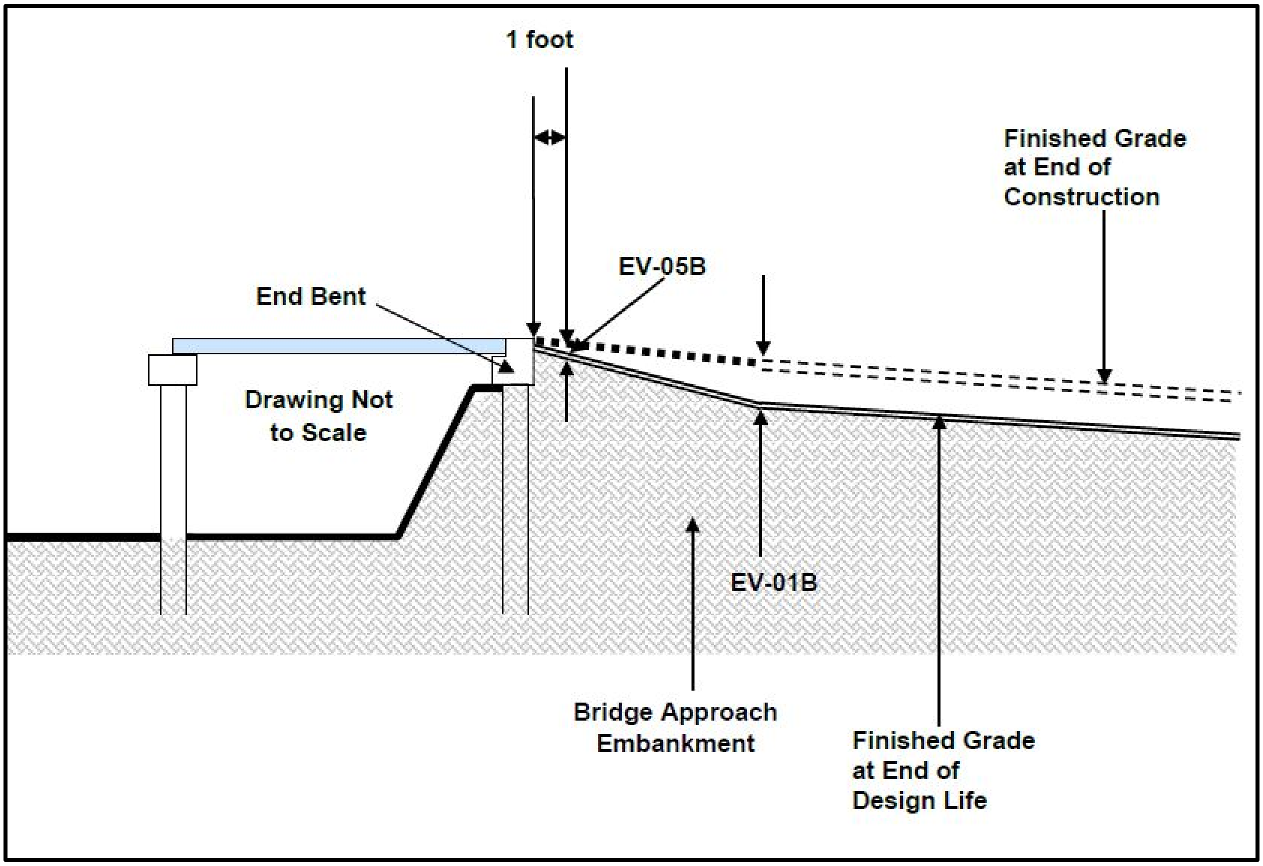
Figure 10-13, Bridge-Embankment Transition Settlement with Approach Slab



Not to Scale

Figure 10-14, Bridge-Embankment Transition Settlement without Approach Slab

Performance Limit EV-05A is specified as a percentage of the length of the approach slab (L_{SLAB}) in feet. EV-05B shall be used to determine the differential settlement between the end of the bridge and the bridge embankment across a distance of 1 foot from the bridge, for bridges that do not have approach slabs. EV-03 shall not be used to determine the longitudinal differential displacement between the bridge and the bridge embankment. For purposes of the transition from the bridge embankment to the bridge EV-05A or EV-05B shall be used, depending on whether the bridge has an approach slab or not. The differential settlement (δ_V) is the absolute value of the difference between the settlement at the end of the approach slab and the settlement of the End Bent. The vertical settlement at the End Bent shall be used in the development of static downdrag and is discussed in Chapter 16. The Performance Limit at the Service limit state is used to minimize the displacements typically observed at the bridge ends that are typically referred to as the "bump at the end of the bridge." The EE I limit state Performance Limit is used to obtain the Performance Objectives of the bridge by maintaining the Damage and Service Levels required for the design earthquake.

10.7 EARTH RETAINING STRUCTURE DEFORMATIONS

10.7.1 Earth Retaining Structure Terminology and Deformation Notations

ERS selection and design methodologies are discussed in Chapter 18. For the purposes of defining Performance Limits, ERSs have been classified based on the construction method. A cut ERS refers to a retaining system that is constructed from the top of the wall to the base of the wall concurrent with excavation operations of the in-place soil in front of the wall. A fill ERS refers to a retaining system that is constructed from the base of the wall to top of the wall with the retained soil being placed during construction. Terminology used to specify geotechnical Performance Limits for ERSs is presented in Chapter 2.

Fill ERSs and Cut ERSs that are commonly used by SCDOT have been grouped by categories as indicated in Tables 10-6 and 10-7, respectively.

Table 10-6, Fill – Earth Retaining Structures (ERS)

Wall Type	Category	Type
Rigid Gravity Walls	**Rigid Walls**	Concrete Barrier Walls, Concrete Retaining Walls
	Semi-Rigid Walls	Concrete Stem Walls
Flexible Gravity Walls	**Prefabricated Modular Gravity Wall**	Gabion Wall
	Mechanically Stabilized Earth Walls	MSE (Full Height Panel Facing) MSE (Modular Block Facing) MSE (Precast Panel Facing) MSE (Gabion Facing)

Table 10-7, Cut – Earth Retaining Structures (ERS)

Category	Type
Cantilever Walls	Sheet Pile Wall, Soldier Pile Wall, Tangent/Secant Pile Wall,
Cantilever Walls with Anchors	Sheet Pile Wall w/ Anchor, Soldier Pile and Lagging Wall w/ Anchor, Tangent/Secant Pile Wall w/ Anchors
In-Situ Reinforced Earth Walls	Soil Nailed Wall

The Performance Limits for Fill and Cut ERSs are based on the intended use and the type of wall being considered. There are many types of walls and each wall has its own limitations, advantages, and disadvantages with respect to economics, construction, and performance. Proper ERS selection (see Chapter 18) is essential for the retaining system to meet the Performance Limits required. Unless otherwise indicated, the deformations that are described in this Section apply to both Fill and Cut type ERSs. ERS deformation notations are listed in Table 10-8.

Table 10-8, ERS Deformation Notations

Notation	Description
δ_V	Vertical Differential Settlement
Δ_V	Total Vertical Displacement / Settlement
Δ_{VR}	Maximum Vertical Displacement of soil reinforcement
δ_L	Lateral Differential Displacement along the top of the wall
Δ_L	Lateral Displacement
L	Distance used to denote boundaries for differential settlement computations
L_E	Distance along the face that an ERS deforms away from the retained soil. Deformations are caused by lateral earth pressures.
L_L	Longitudinal distance of area affected by the compressive soils producing ERS settlements.
L_R	Transverse distance that defines the length of the reinforcement over which the maximum settlement of the reinforcement is measured and the transverse maximum differential settlement if determined.

ERS vertical settlements are typically due to ERSs being constructed over compressible soils that experience soil deformation (elastic compression, primary consolidation, and secondary compression) under constant load. It is anticipated that elastic compression will be completed prior to the placement of pavement; however, the total settlement (elastic compression, primary consolidation, and secondary compression) anticipated to occur during construction of the ERS shall be determined (RV-01A). The total settlement (primary consolidation and secondary compression) after paving (RV-01B) shall be used in the determination of the Performance Limit for all ERSs constructed in a single stage. For all ERSs constructed in 2 or more stages, the settlement remaining after completion of the ERS shall be used in determining the Performance Limits. In addition for ERSs located at the end bent of a bridge, the total settlement shall be used in the development of static downdrag loads (see Chapter 16), if required. The vertical settlements that are evaluated under the Service limit state are as indicated below. The Performance Limits for ERSs are specified for the following types of deformations:

- Longitudinal Settlement Deformation
- Transverse Settlement Deformation
- Lateral Displacements

The maximum settlement shall be based on a 20-year design; however, the structural design life (i.e., the structural components) shall be 100 years. The 20-year design life is used to match the anticipated repaving schedule anticipated by SCDOT. Methods to evaluate stability and deformations are provided in Chapters 13, 17 and 18.

10.7.2 Settlement Deformation – Longitudinal

ERS settlements are typically due to fill ERSs being placed over compressible soils. This type of settlement is typically due to elastic compression, primary consolidation and secondary compression of the compressible soils. ERS settlements can also be due to seismic hazards such as soil SSL of the subgrade during or after a seismic event. ERS settlements are evaluated at the top of the wall adjacent to the wall facing where differential settlements are likely to cause the most distress to the wall facing. Performance Limits for settlements occurring longitudinally (along the wall profile) are identified in Table 10-9. As indicated previously, whether the ERS is completed in a single stage or multiple stages will affect how the maximum vertical total and differential settlement will be determined. Methods to evaluate settlements are provided in Chapters 13 and 17.

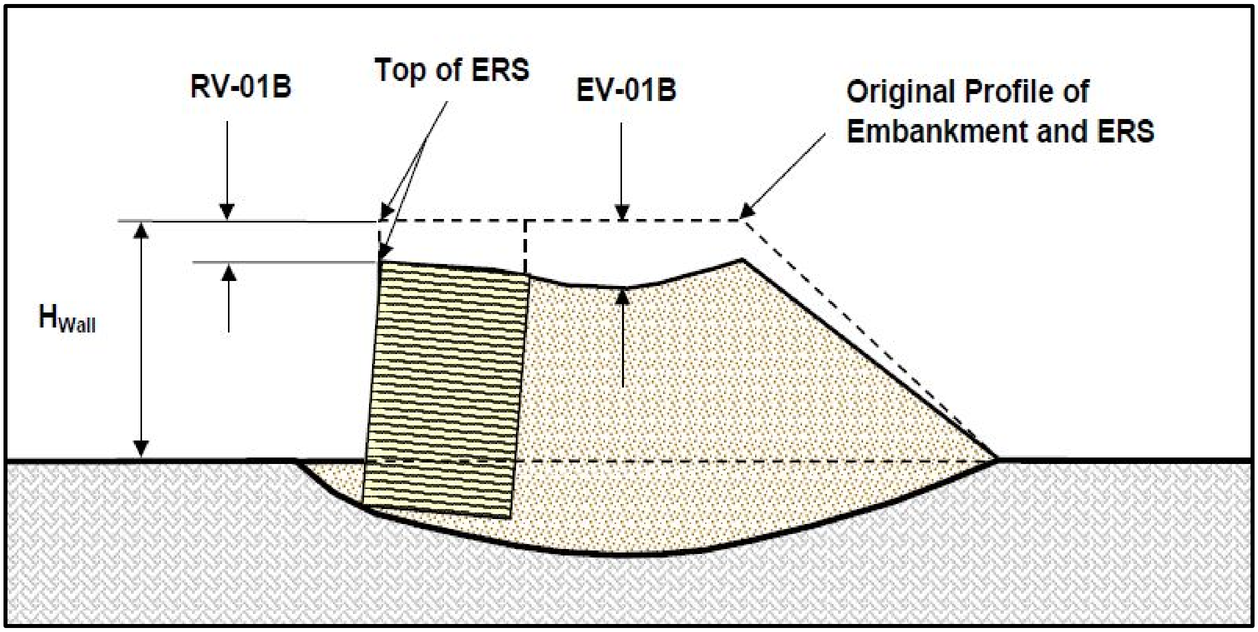
Table 10-9, ERS Settlement (Longitudinal) Performance Limits

Notation	Deformation Limit ID No.	Description
Vertical Settlement, Δ_V	RV-01A	Maximum Settlement from Elastic Compression + Primary Consolidation + Secondary Compression along the top of wall profile grade[1] that occurs during the construction of the ERS and commences immediately after construction begins and terminates just prior to paving operations. This deformation is used to adjust borrow and ERS height requirements, if necessary.
	RV-01B	Maximum Settlement from Primary Consolidation + Secondary Compression along the profile grade[1] over the design life[2] of the pavement behind the ERS. The design life begins after the pavement has been placed (i.e., the settlement that occurs after RV-01A).
Vertical Differential Settlement, δ_V	RV-03A	Maximum Differential Settlement from Elastic Compression + Primary Consolidation + Secondary Compression occurring longitudinally along the ERS profile grade (i.e., top of ERS) during construction.
	RV-03B	Maximum Differential Settlement from Primary Consolidation + Secondary Compression occurring longitudinally along the ERS profile grade (i.e., top of ERS) post construction.

[1]The longitudinal location of RV-01 shall be noted (i.e., at ERS Sta. XX+XX)

[2]Design life of 20 years shall be used.

The Performance Limit, RV-01A is the maximum settlement that occurs at the face at the top of the wall profile during construction. RV-01B is the maximum settlement that occurs at the face of the top of the wall over the design life of the pavement on top of the ERS as indicated in Figure 10-15.



Not to Scale

Figure 10-15, ERS Settlement (Section B–B)

Wall distress due to settlements along the top of the wall profile, are limited by specifying a Performance Limit, RV-03 for the maximum differential settlement (δ_V) observed longitudinally along the top of the wall profile. The Performance Limit RV-03A is determined from the differential displacements that are anticipated to occur during the construction of the wall and should be used to assist in the determination of whether the wall should be built in more than 1 stage. The Performance Limit RV-03B is differential displacement anticipated to occur after the ERS has been constructed. The differential settlement is specified over a distance of 50 feet, measured longitudinally along the top of the wall profile. If vertical displacements are encountered at an isolated location such as shown in Figure 10–16, the differential settlement Performance Limit, RV-03, may be pro-rated so that at any point along the distance, L_L, the tolerances specified are not exceeded. The distance L_L shall never exceed 50 feet.

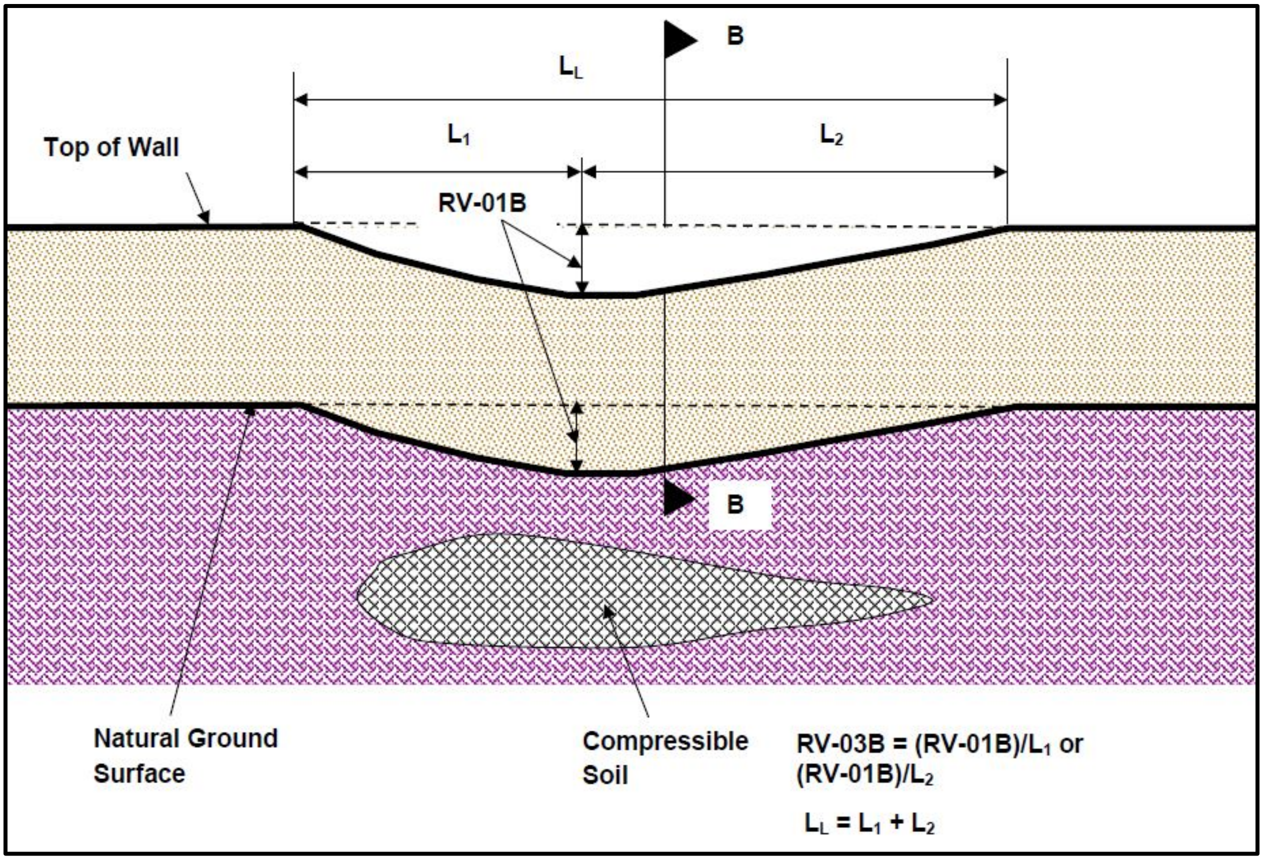


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Figure 10-16, ERS Settlement Profile

10.7.3 Settlement Deformation – Transverse

This Performance Limit is used for differential settlements (δ_V) that occurs perpendicular to the wall alignment and is only applicable to retaining walls that have discrete soil reinforcements (geosynthetic reinforcement, steel reinforcement, soil anchors, etc.) extending perpendicular to the wall facing to the end of the length of the reinforcement, L_R. The Performance Limit for settlement occurring perpendicular to the wall profile (transverse direction) is identified in Table 10-10.

Table 10-10, ERS Settlement (Transverse) Performance Limits

Notation	Deformation Limit ID No.	Description
Vertical Differential Settlement, δ_{VR}	**RV-04A**	The absolute value of the Maximum Differential Settlement observed perpendicular (transverse) to the top of the wall profile during construction of the wall.
	RV-04B	The absolute value of the Maximum Differential Settlement observed perpendicular (transverse) to the top of the wall profile after construction of the wall.
Vertical Settlement, Δ_{VR}	**RV-06A**	Maximum Settlement from Elastic Compression + Primary Consolidation + Secondary Compression at the termination of the reinforcement that occurs during the construction of the ERS and commences immediately after construction begins and terminates just prior to paving operations.
	RV-06B	Maximum Settlement from Primary Consolidation + Secondary Compression at the termination of the reinforcement that occurs over the design life[1] of the pavement behind the ERS. The design life begins after the pavement has been placed (i.e., the settlement that occurs after RV-06A).

[1]Design life of 20 years shall be used

Examples of ERSs with reinforced soil (MSE walls) and ERSs with tieback anchors (cantilever walls w/ tieback anchors) are shown in Figures 10-17 and 10-18, respectively. A cantilevered ERS should not have a tip elevation above a compressible layer as shown in Figure 10-18, unless unavoidable. Contact the OES/GDS prior to designing a cantilevered ERS above a compressible layer. Excessive differential settlements (transverse) may cause distress and even wall collapse from the added load induced to the wall facing and soil reinforcements. The Performance Limit, RV-04(A or B) is the maximum differential settlements perpendicular (transverse) to the adjusted profile over a distance, L_R, as indicated in Figure 10-17 and 10-18 and is determined both for vertical displacements that occur during construction as well as for post construction displacements. Performance Limit, RV-04(A or B) is computed along maximum increments of 5 feet.

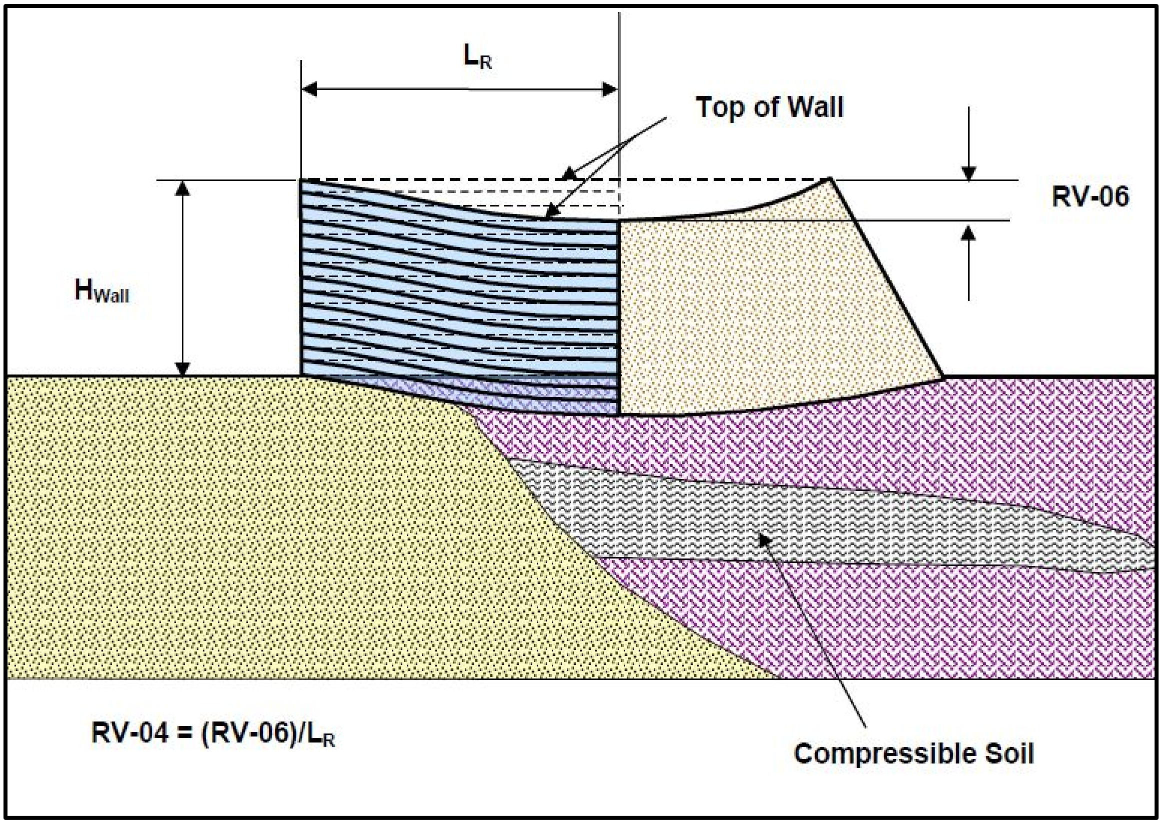

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Figure 10-17, ERS Reinforced Soils - Transverse Differential Settlement

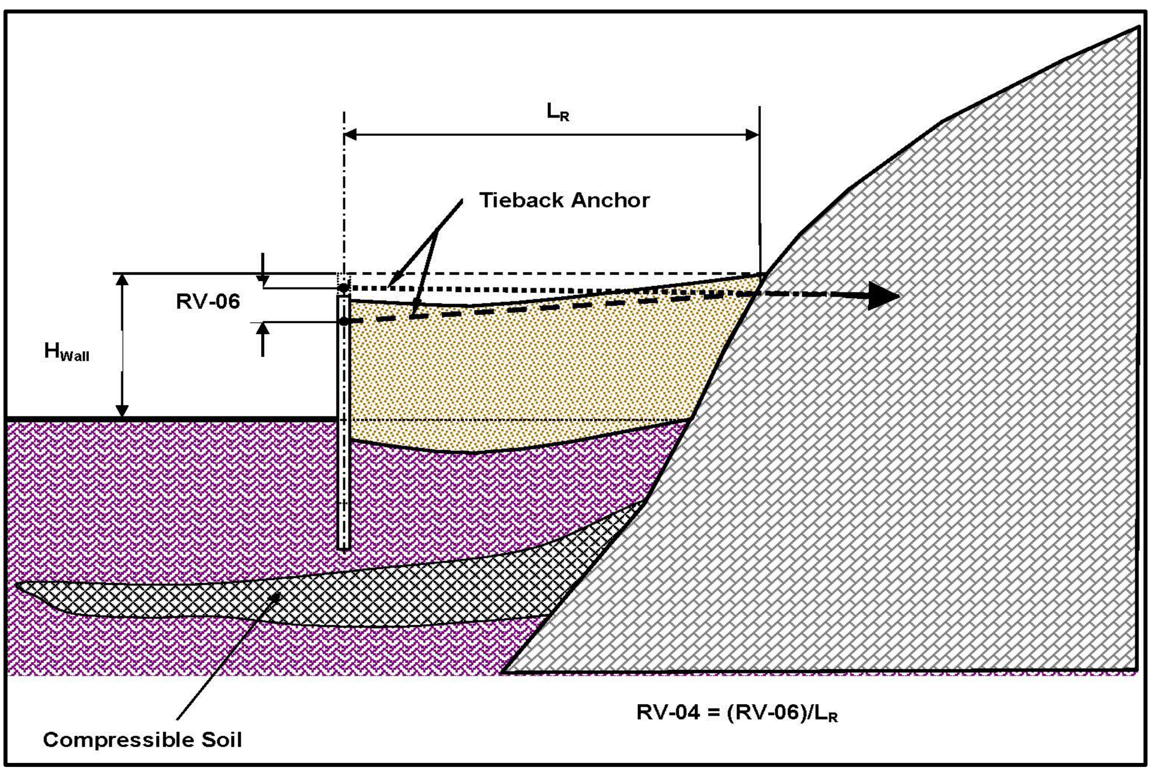

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Figure 10-18, ERS Tieback Anchor - Transverse Differential Settlement

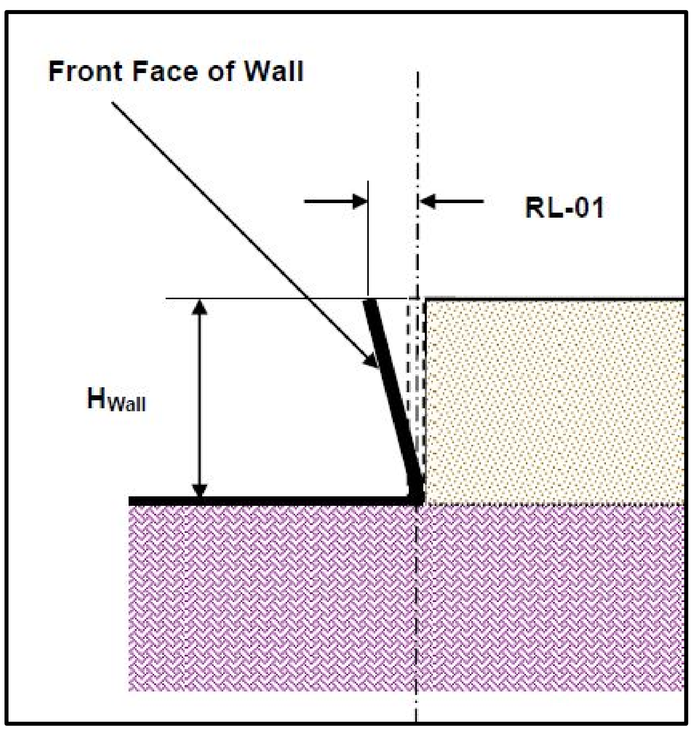
10.7.4 Lateral Displacements

ERS lateral displacements are those movements that occur as a result of lateral soil pressures. Lateral soil pressure loadings produce displacements of the structural members of the wall system and also displacements of the soil (soil-structure interaction). ERS lateral displacements can also occur as a result of active seismic loadings that are transmitted laterally to the ERS. These lateral displacements are not the same as those caused by global instabilities as discussed previously. The Performance Limits for lateral displacements occurring perpendicular to the wall profile (transverse direction) are identified in Table 10-11.

Table 10-11, ERS Lateral Performance Limits

Notation	Deformation ID No.	Description
Lateral Displacement, Δ_L	**RL-01**	Maximum Lateral Displacement at the top of the wall.
Lateral Differential Displacement, δ_L	**RL-02**	Maximum Differential Lateral Displacement longitudinally along the top of the wall. This performance limit is typically referred to as wall "bulging."

The Performance Limit, RL-01 is the maximum lateral displacement that occurs at the top of the wall over the design life of the structure. For this Performance Limit the design life shall be 100 years, since this displacement has more to do with the structural performance of the ERS. ERS Performance Limit, RL-01 is evaluated at the top of the wall as indicated in Figure 10-19.

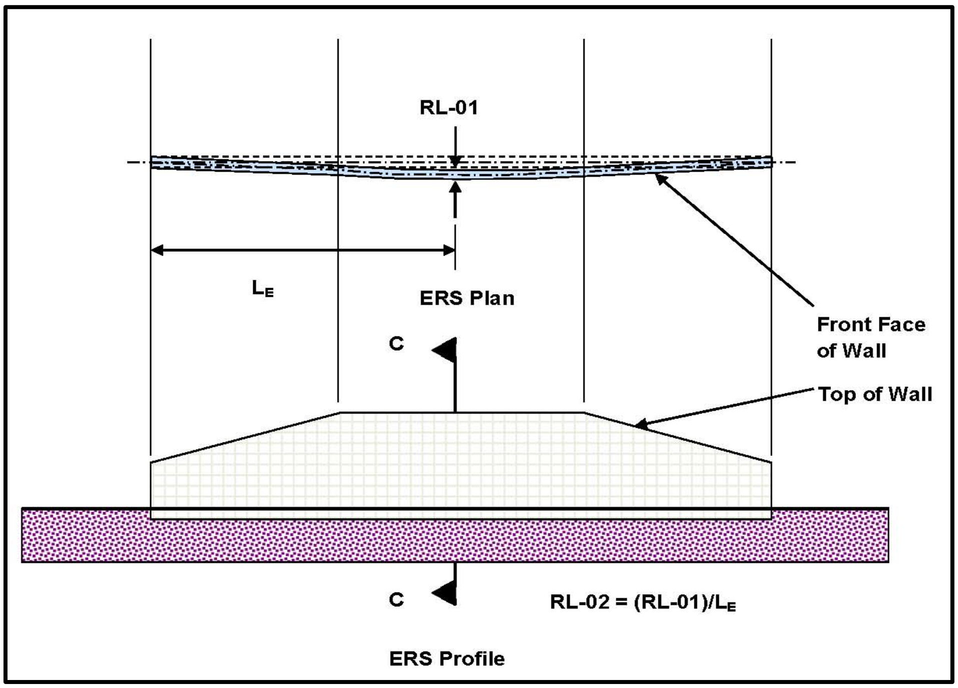


Not to Scale

[1]Front face of wall shown has negative batter, negative batter is not allowed at the SLS.

Figure 10-19, ERS Lateral Deformation (Section C-C)

Lateral wall distress (bulging), due to differential lateral displacement along the top of the wall profile, is limited by specifying a Performance Limit, RL-02 for the maximum differential lateral displacement observed longitudinally along the top of the wall profile after the ERS has been constructed as shown in Figure 10-20. The differential lateral displacement is specified over a distance of 50 feet and measured longitudinally along the top of the wall profile. If lateral displacements are encountered at an isolated location, the differential lateral displacement Performance Limit, RL-02 may be pro-rated so that at any point along the distance, L_E, the tolerances specified are not exceeded.



Not to Scale

[1]Front face of wall shown has negative batter, negative batter is not allowed at the SLS.

Figure 10-20, ERS Lateral Deformations

10.8 PERFORMANCE LIMITS FOR GLOBAL INSTABILITY

10.8.1 <u>Strength Limit State</u>

10.8.1.1 Performance Objective

The embankment and ERS Performance Objectives for global stability at the Strength limit state is that instability is not allowed. Therefore, no Performance Limits are established.

10.8.2 <u>Extreme Event I Limit State</u>

10.8.2.1 Performance Objective

The Performance Objectives for bridge embankments and ERSs at EE I limit state is that neither the bridge embankments nor ERSs adversely affect the bridge structure during the design seismic event. "Bridge embankments" are defined in Chapter 2. ERSs not located in "bridge embankments" shall not collapse at the EE I limit state. Collapse shall mean adversely affecting either area in front or behind the ERS a distance of 1.1 times the height of the wall. In addition, the seismic design of the ERS shall comply with the requirements of Chapter 14.

10.8.2.2 Performance Limits

The design team has the ultimate responsibility for development of Performance Limits of the structure during the design Extreme Event and for assuring that the Performance Objectives of the structure are met. The Performance Limits established by the design team shall conform to the Deformation ID No. and the Performance Limit description contained in Table 10-1. The design team shall supply this information to and have the concurrence and acceptance of the OES/SDS and the OES/GDS. The GEOR shall provide the anticipated displacements caused by global instability using the Deformation ID No. contained in Table 10-1 to the design team.

10.8.3 Extreme Event II Limit State

10.8.3.1 Performance Objective

The embankment and ERS Performance Objectives for global stability at the EE II (check flood (500-yr flow event)) limit state is that instability is not allowed. Therefore, there are no Performance Limits established. As indicated previously, EE II (collision/impact loadings only) shall not be used in the design of embankments or ERSs; therefore, no Performance Objectives or Performance Limits are established.

10.9 PERFORMANCE LIMITS FOR EMBANKMENTS

10.9.1 Service Limit State

10.9.1.1 Performance Objective

The Performance Objectives for permanent embankments at the Service limit state are that the embankment remains fully functional for the design life of the pavement structure (20 years) and that through periodic maintenance any deformations can be adjusted for in order to maintain the serviceability requirements of the roadway pavement. Temporary embankments (i.e., widened embankments) may induce settlements that are in excess of the Performance Limits established for transverse differential settlement for short periods (less than 1 year). If this condition exists on a project site, the GEOR is required to include notes and quantities on the plans that instruct the Contractor to maintain the rideability and safety of the existing pavement section. See Section 10.2.1 for additional requirements that were used to develop the Performance Limits.

10.9.1.2 Performance Limits

The following embankment Performance Limits have been developed to meet the Performance Objective indicated in Section 10.9.1.1. The embankment Performance Limits at the Service limit state are presented in Tables 10-12 to 10-14. Embankment deformation descriptions are found in Section 10.6.

Table 10-12, Embankment (Pavement) Performance Limits

Deformation ID No.	**Service Limit State Performance Limit Description**	
	Minimum Design Life (Years)	20
EV-01A	Maximum Settlement from Elastic Compression + Primary Consolidation + Secondary Compression along the profile grade[1] that occurs during the duration of the construction of the embankment commences at the start of construction and terminates just prior to paving operations. This deformation is used to adjust borrow requirements, if necessary	NL
EV-01B	Maximum Settlement from Primary Consolidation + Secondary Compression along the profile grade[1] over the design life[2] of the embankment. The design life begins after the pavement has been placed (i.e., the settlement that occurs after EV-01A).	3"
EV-03	Maximum Differential Settlement from Primary Consolidation + Secondary Compression occurring longitudinally along the profile grade after the roadway has been paved. Differential ratio is shown in parenthesis for informational purposes. (Inches per 50 Feet of Embankment Longitudinally)	1" (1/600)

[1]The longitudinal location of EV-01 shall be noted (i.e., at end of approach slab, at Sta. XX+XX, etc.)

[2]Design life of 20 years shall be used.

NL – No Limit; however EV-01A shall be reported.

Table 10-13, Embankment Widening Performance Limits

Deformation ID No.	**Service Limit State Performance Limit Description**	
	Minimum Design Life (Years)	20
EV-04	Maximum Vertical Differential Settlement occurring transverse to the adjusted profile grade between the existing embankment and the new widened embankment after the roadway has been paved. (Inches per 5 Feet of Embankment Transverse)	0.2" (1/300)

Table 10-14, Bridge/Embankment Transition Settlement Performance Limit

Deformation ID No.	**Service Limit State Performance Limit Description**	
EV-05A	Maximum Differential Settlement (δ_V) between the bridge End Bent and the end of the Approach Slab after the roadway has been paved at the end of the pavement design life (20 yrs). The Approach Slab length (L_{Slab}) is measured in feet.	$0.05 \times L_{Slab}$
EV-05B	Maximum Differential Settlement (δ_V) between the bridge End Bent and a point 1 foot from either the "begin" or "end" of bridge after the roadway has been paved at the end of the pavement design life (20 yrs).	0.5"

10.9.2 Extreme Event I Limit State

10.9.2.1 Performance Objective

The Performance Objective for embankments at the EE I limit state is that bridge embankments do not adversely affect bridge structures during the design seismic event. Mitigation may be required to meet the required Performance Objectives. Mitigation shall be limited longitudinally to that extent which is required to satisfy the Bridge (Global) Seismic Performance Objectives (Seismic Specs). For a more detailed discussion of Performance Objectives during the design seismic event see Section 10.2.

10.9.2.2 Performance Limits

If vertical displacement is the only anticipated movement (i.e., there is no global instability), there are no limits to the amount of settlement that can occur within the embankment; however the amount of settlement induced by the EE I within the bridge embankment shall be reported. The only Performance Limit related to settlement established in this Manual will be at the transition from the embankment to the bridge. It is noted that the settlements provided in Table 10-15 are a guide only and that the actual Performance Limits shall be established by the design team based on the Performance Objectives. All Performance Limits shall be submitted to SCDOT for review and concurrence by the OES/SDS and OES/GDS. The remaining embankment Performance Limits shall be developed by the design team to meet the Performance Objective indicated in Section 10.9.2.1. However, the settlement anticipated at the end bent shall be converted into downdrag loads as described in Chapter 16 and shall be included in the design of the end bent foundations. Embankment deformation descriptions are found in Section 10.6. For a more detailed discussion of Performance Objectives during the design seismic event see Section 10.2.

Table 10-15, Bridge/Embankment Transition Settlement Performance Limit

Deformation ID No.	EE I Limit State Performance Limit Description	Design EQ	OC		
			I	II	III
EV-05A	Maximum Vertical Differential Settlement between the bridge End Bent and the End of the Approach Slab (Inches). The Approach Slab length (L_{Slab}) is measured in feet.	FEE	0.200 L_{Slab}	0.400 L_{Slab}	NL
		SEE	0.400 L_{Slab}	NL	NL
EV-05B	Maximum Differential Settlement (δ_V) between the bridge End Bent and a point 1 foot from either the "begin" or "end" of bridge.	FEE	2"	8"	NL
		SEE	8"	NL	NL

NL – No limit; low probability of collapse; anticipated displacement shall be reported and considered by the design team

10.9.3 Extreme Event II Limit State

10.9.3.1 Performance Objective

The embankment Performance Objectives at the EE II (check flood (500-yr flow event)) limit state is that settlement is not determined. Therefore, there are no Performance Limits established. Performance Objectives for the EE II (collision/impact loadings only) is not required since embankments are not typically effected by collision or impact loading. However, Performance Objectives and Performance Limits may be established by the design team, if the necessity is determined by the design team, and shall have the concurrence and acceptance of the OES/SDS and the OES/GDS.

10.10 PERFORMANCE LIMITS FOR EARTH RETAINING STRUCTURES

10.10.1 Service Limit State

10.10.1.1 Performance Objective

The Performance Objectives for ERSs at the Service limit state are that the ERS remains fully functional for the design life (20 years shall be used for determining movements of the ERS; however 100 years shall be used for the design life of the structural components) and that through periodic maintenance any deformations can be adjusted to maintain the serviceability requirements. See Section 10.2.1 for additional requirements that were used to develop the Performance Limits.

10.10.1.2 Performance Limits

Geotechnical Performance Limits have been developed for Fill ERSs and Cut ERSs in Tables 10-16 and 10-17, respectively. These Performance Limits have been developed to meet the Performance Objective indicated in Section 10.10.1.1. ERS deformation descriptions are defined in Section 10.7. It should be noted that at no time will negative batter (i.e., the ERS leans outward from plumb) be acceptable under Service limit state conditions. All ERSs shall be designed and constructed with positive batter that shall be large enough to account for any movements required to develop full active earth pressures.

Deformation ID No.			Service Limit State Performance Limit Description			
Settlement		RV-01A	Maximum Settlement from Elastic Compression + Primary Consolidation + Secondary Compression along the top of wall profile grade that occurs during the construction of the ERS and commences immediately after construction begins and terminates just prior to paving operations. This deformation is used to adjust borrow and ERS height requirements, if necessary. (Inches)			NL[1]
Settlement		RV-01B	Maximum Settlement from Primary Consolidation + Secondary Compression along the top of wall profile grade over the design life[2] of the pavement behind the ERS. The design life begins after the pavement has been placed (i.e. the settlement that occurs after RV-01A). (Inches)			2”
Settlement	Longitudinal	RV-03A	Maximum Differential Settlement from Elastic Compression + Primary Consolidation + Secondary Compression occurring longitudinally along the ERS profile grade (i.e. top of ERS) during construction. (Inches/50 feet along the length of ERS regardless of ERS type)			NL
Settlement	Longitudinal	RV-03B	Maximum Differential Settlement from Primary Consolidation + Secondary Compression occurring longitudinally along the ERS profile grade (i.e. top of ERS) post construction. (Inches/50 feet along the length of ERS) (Maximum settlement ratio indicated in parenthesis for informational purposes only)	Rigid/Semi-Rigid walls		1” (1/600)
				MSE w/Full Height Panel Facing		1” (1/600)
				MSE Panel Facing	Joint Spacing $\geq$ 1/2 inches	2” (1/300)
				MSE w/Block or Gabion Facing		2-1/2” (1/240)
				Gabion Wall		6” (1/100)
Settlement	Transverse	RV-04A[3]	The absolute value of the Maximum Differential Settlement observed perpendicular (transverse) to the top of the wall profile during construction of the wall.			NL
Settlement	Transverse	RV-04B[3]	The absolute value of the Maximum Differential Settlement observed perpendicular (transverse) to the top of the wall profile after construction of the wall.[4])			0.150 L_{Reinf}
Settlement		RV-06A[3]	Maximum Settlement from Elastic Compression + Primary Consolidation + Secondary Compression at the termination of the reinforcement that occurs during the construction of the ERS and commences immediately after construction begins and terminates just prior to paving operations.			NL
Settlement		RV-06B[3]	Maximum Settlement from Primary Consolidation + Secondary Compression at the termination of the reinforcement that occurs over the design life[1] of the pavement behind the ERS. The design life begins after the pavement has been placed (i.e. the settlement that occurs after RV-06A).			14”
Lateral Displ.[5]		RL-01	Maximum Lateral Displacement at the top of the wall.[6] (Inches)	All Earth Retaining Structures		0.050 H_{Wall}
Lateral Displ.[5]		RL-02	Maximum Differential Lateral Displacement longitudinally along the top of the wall. (Inches/50 feet of wall)	All Earth Retaining Structures		1”

NL – No limit; however, displacements shall be reported; anticipated displacements shall be considered by the design team.
[1]A limit of 12 inches shall be used for all MSE walls with rigid facing elements as the demarcation between single stage and multi-stage construction.
[2]The Minimum Design Life is based on an anticipated repaving cycle of 20 years.
[3]RV-04 and RV-06 apply only to MSE Walls w/Panel, Block or Gabion Facing, and Reinforced Soil Slopes
[4]The soil reinforcement length (L_{Reinf}) is measured in feet.
[5]At no point in time will negative batter be acceptable.
[6]The wall height (H_{Wall}) is measured in feet. For the reinforced soil slopes the H_{Wall} is the vertical distance from the toe of the slope to shoulder edge.

Table 10-16, Fill ERS Performance Limits at Service Limit State

Deformation ID No.			Service Limit State Performance Limit Description	
Settlement		RV-01A	Maximum Settlement from Elastic Compression + Primary Consolidation + Secondary Compression along the top of wall profile grade that occurs during the construction of the ERS and commences immediately after construction begins and terminates just prior to paving operations. This deformation is used to adjust borrow and ERS height requirements, if necessary. (Inches)	NL
Settlement		RV-01B	Maximum Settlement from Primary Consolidation + Secondary Compression along the profile grade over the design life[1] of the pavement behind the ERS. The design life begins after the pavement has been placed (i.e. the settlement that occurs after RV-01A). (Inches)	2”
Settlement	Longitudinal	RV-03A	Maximum Differential Settlement from Elastic Compression + Primary Consolidation + Secondary Compression occurring longitudinally along the ERS profile grade (i.e. top of ERS) during construction. (Inches/50 feet along the length of ERS regardless of ERS type)	NL
Settlement	Longitudinal	RV-03B	Maximum Differential Settlement from Primary Consolidation + Secondary Compression occurring longitudinally along the ERS profile grade (i.e. top of ERS) post construction. (Inches/50 feet along the length of ERS) (Maximum settlement ratio indicated in parenthesis for informational purposes only)	1-1/2” (1/400)
Settlement	Transverse	RV-04A[1]	The absolute value of the Maximum Differential Settlement observed perpendicular (transverse) to the top of the wall profile during construction of the wall.	NL
Settlement	Transverse	RV-04B[1]	The absolute value of the Maximum Differential Settlement observed perpendicular (transverse) to the top of the wall profile after construction of the wall.[3]	0.100 L_{Anchor}
Settlement		RV-06A[1]	Maximum Settlement from Elastic Compression + Primary Consolidation + Secondary Compression at the termination of the reinforcement that occurs during the construction of the ERS and commences immediately after construction begins and terminates just prior to paving operations.	NL
Settlement		RV-06B[1]	Maximum Settlement from Primary Consolidation + Secondary Compression at the termination of the reinforcement that occurs over the design life[1] of the pavement behind the ERS. The design life begins after the pavement has been placed (i.e. the settlement that occurs after RV-06A).	14”
Lateral Displ.[4]		RL-01	Maximum Lateral Displacement at the top of the wall.[5] (Inches)	0.050 H_{Wall}
Lateral Displ.[4]		RL-02	Maximum Differential Lateral Displacement longitudinally along the top of the wall. (Inches/50 feet of wall)	1”

NL – No limit; however, displacements shall be reported; anticipated displacements shall be considered by the design team.

[1]The Minimum Design Life is based on an anticipated repaving cycle of 20 years.

[2]RV-04 and RV-06 apply only to walls with In-Situ reinforcement.

[3]The soil anchor length (L_{Anchor}) is measured in feet.

[4]At no point in time will negative batter be acceptable.

[5]The wall height (H_{Wall}) is measured in feet. For the reinforced soil slopes the H_{Wall} is the vertical distance from the toe of the slope to shoulder edge.

Table 10-17, Cut ERS Performance Limits at Service Limit State

10.10.2 Extreme Event I Limit State

10.10.2.1 Performance Objective

The Performance Objective for ERSs at the EE I limit state is that ERSs located at or beneath a bridge do not adversely affect the bridge structure during the design seismic event. Mitigation may be required to meet the required Performance Objectives. Mitigation shall be limited longitudinally to that extent which is required to satisfy the Bridge (Global) Seismic Performance Objectives (Seismic Specs). The exception to this is if the ERS extends beyond bridge embankments then the mitigation may need to be extended. For those ERSs that are located completely beyond the bridge embankment, the ERS should not collapse. For a more detailed discussion of Performance Objectives during the design seismic event see Section 10.2

10.10.2.2 Performance Limits

If there is no global instability, there is no limit to the amount of settlement or lateral displacement that can occur with an ERS during the EE I. However the amount of settlement (RV-01B, RV-03B, RV-04B and RV-06B) and lateral displacement (RL-01 and RL-02) at the face of the ERS induced by the EE I within the bridge embankment shall be reported. It is anticipated that the Performance Limit related to settlement at the transition from the embankment supported by the ERS to the bridge shall govern design. The ERS Performance Limits shall be developed by the design team to meet the Performance Objective indicated in Section 10.10.2.1. However, the settlement anticipated at the end bent shall be converted into downdrag loads as described in Chapter 16 and shall be included in the design of the end bent foundations. Lateral displacements shall be used to determine structural forces on the ERS system to prevent structural failure of the system. In addition, the design team shall consider the area immediately adjacent to the wall when determining the Performance Limits. The area immediately adjacent to the wall shall begin at the either the base or the top of the wall and shall extend a minimum of 1.1 times the height of the wall (i.e., $1.1H_{Wall}$) either in front of the wall or behind the wall. ERS deformation descriptions are found in Section 10.7. For a more detailed discussion of Performance Objectives during the design seismic event see Section 10.2.

10.10.3 Extreme Event II Limit State

10.10.3.1 Performance Objective

The ERS Performance Objectives at the EE II (check flood (500-yr flow event)) limit state is that settlement is not allowed. However, Performance Objectives at the EE II (check flood (500-yr flow event)) limit state shall be established by the design team to conform to the overall requirements of the project. Therefore, the design team shall establish Performance Limits and shall have the concurrence and acceptance of the RPG/SDS and the RPG/GDS. Performance Objectives for the EE II (collision/impact loadings only) are required since an ERS is potentially affected at either the top of the ERS or at the bottom of the ERS by the collision or impact loading. However, Performance Objectives and Performance Limits shall be established by the design team, if the necessity is determined by the design team, and shall have the concurrence and acceptance of the OES/SDS and the OES/GDS. In addition, the design team shall consider the effects of the collision/impact loading on the structural elements that compose the ERS.

10.11 REFERENCES

American Association of State Highway and Transportation Officials, (2017), AASHTO LRFD Bridge Design Specifications Customary U.S. Units, 8th Edition, American Association of State Highway and Transportation Officials, Washington, D.C.

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