Chapter 18

EARTH RETAINING STRUCTURES

Final

SCDOT GEOTECHNICAL DESIGN MANUAL

June 2010

Table of Contents

List of Tables

List of Figures

CHAPTER 18

EARTH RETAINING STRUCTURES

18.1 INTRODUCTION

Earth retaining structures (ERSs) are used to retain earth materials while maintaining a grade change between the front and rear of the wall (see Figure 18-1). ERSs transmit the loads (Q_1, Q_2, and p_1) to a combination of the base and the restraining element (p_2 and deadman) to maintain stability. Typically, ERSs are expensive when compared to embankments; therefore, the need for an ERS should be carefully considered in preliminary design. An effort should be made to keep the retained soil height to a minimum. ERSs are used to support cut and fill slopes where space is not available for construction of flatter more stable slopes (see Chapter 17). Bridge abutments and foundation walls are designed as ERSs since these structures are used to support earth fills.

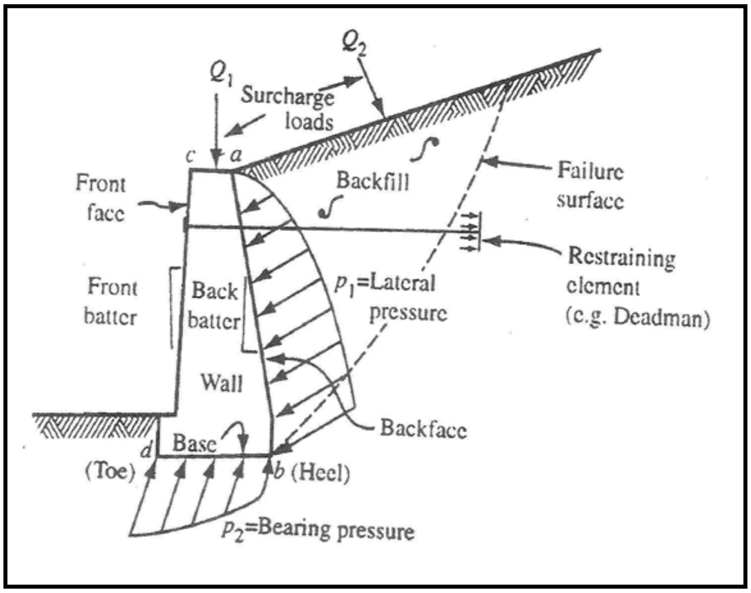

Figure 18-1, Retaining Wall Schematic
(Earth Retaining Structures – June 2008)

According to Earth Retaining Structures (FHWA-NHI-07-071) dated June 2008, ERSs are typically used in highway construction for the following applications:

- New or widened highways in developed areas
- New or widened highways at mountains or steep slopes
- Grade separations
- Bridge abutments, wing walls and approach embankments
- Culvert walls
- Tunnel portals and approaches
- Flood walls, bulkheads and waterfront structures
- Cofferdams for construction of bridge foundations
- Stabilization of new or existing slopes and protection against rockfalls
- Groundwater cut-off barriers for excavations or depressed roadways

18.2 EARTH RETAINING STRUCTURE CLASSIFICATION

There are four criteria for classifying an ERS:

- Load support mechanism (externally or internally stabilized walls)
- Construction concept (fill or cut)
- System rigidity (rigid or flexible)
- Service life (permanent or temporary)

All ERSs are classified using all four of the criteria listed above; however, the service life is not normally used since most ERSs are designed as permanent. For example, a soldier pile and lagging wall is classified as an externally stabilized flexible cut wall, while a soil nail wall is an internally stabilized flexible cut wall. The design of temporary ERSs is discussed at the end of this Chapter. Therefore, the intermediate Sections are concerned with the design of permanent ERSs. Figure 18-2 provides a partial representation of the classification of permanent ERSs; this Figure is partial in that it does not include all of the possible types of walls available.

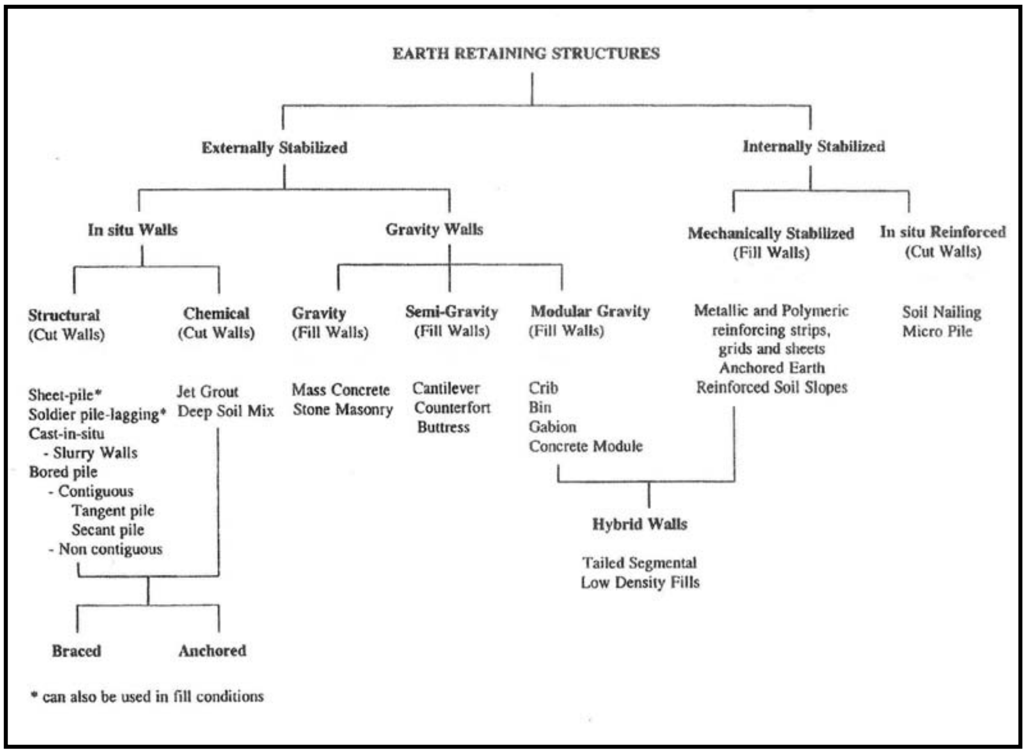

Figure 18-2, ERS Classification Chart
(Modified from Earth Retaining Structures – June 2008)

18.2.1 Load Support Mechanism Classification

The load support mechanism classification is based on whether the ERS is stabilized externally or internally. Externally stabilized ERSs use an external structure against which the stabilizing forces are mobilized. Internally stabilized ERSs use reinforcements that are installed within the soil mass and extend beyond the potential failure surface to mobilize the stabilizing forces.

18.2.2 Construction Concept Classification

ERSs are also classified based on the construction method used. The construction methods consist of fill or cut. Fill construction refers to an ERS that is constructed from the base to the top (i.e. bottom-up construction). Conversely, cut construction refers to an ERS that is constructed from the top to the base (i.e. top-down construction). It is very important to realize the cut or fill designations refer to how the ERS is constructed, not the nature of the earthwork. For example, a prefabricated bin wall could be placed in front of a "cut" slope, but the wall would be classified as a "fill" wall since the construction is from the bottom-up.

18.2.3 System Rigidity Classification

The rigidity of the ERS is fundamental to understanding the development of the earth pressures that develop behind and act on the ERS. A rigid ERS moves as a unit (i.e. rigid body rotation and/or translation) and does not experience bending deformations. A flexible ERS undergoes not only rigid body rotation and/or translation, but also experiences bending deformations. In flexible ERSs, the deformations allow for the redistribution of the lateral (earth) pressures from the more flexible portion of the wall to the more rigid portion of the wall. Most gravity type ERSs would be considered an example of a rigid wall. Almost all of the remaining ERS systems would be considered flexible.

18.2.4 Service Life Classification

The focus of this Chapter is on permanent ERS construction. According to Chapter 10, all geotechnical structures including ERS shall have a design life of 100 years. Temporary ERSs shall have a service life less than 5 years. Temporary ERSs that are to remain in service more than 5 years shall be designed as a permanent ERS. A more detailed explanation of temporary ERSs is provided at the end of this Chapter.

18.3 LRFD ERS DESIGN

The design of ERSs is comprised of two basic components, external and internal. External design handles stability, sliding, and bearing; while internal design handles pullout failure of soil anchors or reinforcement and structural failure of the ERS. The external stability of an ERS is checked using the procedures outlined in Chapter 17. For ERSs supported by shallow foundations, sliding and bearing are checked using Chapter 15, while those ERSs supported by deep foundations are checked using Chapter 16. All loads that affect the external stability of an ERS shall be developed using Chapter 8, as well as the procedures outlined in AASHTO LRFD Bridge Design Specifications (latest edition), Article 11.5 – Limit States and Resistance Factors. Where there is conflict, this Manual takes precedence over AASHTO. According to Earth Retaining Structures, FHWA – June 2008; "In general, use minimum load factors if permanent loads increase stability and use maximum load factors if permanent loads reduce stability." The resistance factors shall be developed using Chapter 9 for both Strength and Service limit states. Chapter 9 divides ERSs into three types of walls; Rigid Gravity, Flexible Gravity and Cantilever ERSs. Chapter 9 provides examples of the different types of common walls that fit within each group. Cantilever ERSs are a sub-class of Gravity ERSs per Figure 18-2. In accordance with Chapter 8, the Service limit state is the boundary condition for performance of the structure under service load conditions. The Service limit state is evaluated for the movements induced by the Service load combinations (see Chapter 8). The movements induced by the Service loads are compared to the performance objectives established in Chapter 10. At the end of construction, the ERS shall have a front batter that either meets the performance objectives indicated in Chapter 10 or is vertically plumb. Once all of the external designs are checked, then, the internal design is checked. ERSs comprised of MSE walls or Reinforced Soil Slopes (RSSs) use the internal resistance factors as presented in Chapter 9.

All ERS designs must meet the requirements of the basic LRFD equation

$$\mathbf{Q} = \sum \gamma_{\mathbf{i}} \mathbf{Q}_{\mathbf{i}} \leq \varphi_{\mathbf{n}} \mathbf{R}_{\mathbf{n}} = \mathbf{R}_{\mathbf{r}} \qquad \text{Equation 18-1}$$

Where,

- Q = Factored Load
- Q_i = Force Effect
- γ_i = Load factor
- R_r = Factored Resistance
- R_n = Nominal Resistance (i.e. ultimate capacity)
- φ_n = Resistance Factor

18.4 ERS SELECTION PHILOSOPHY

The selection of the type of ERS is based on numerous factors. It is possible for more than one ERS type to be applicable to a given site. Figure 18-3 provides a flow chart for determining the most appropriate type of wall for a specific location. Further, Tables 18-1 and 18-2 provide the most common cut and fill walls (see discussion above on ERS classification). The ERSs listed in Tables 18-1 and 18-2 contain walls that are typically used by SCDOT and walls that would be allowed. Written permission to use walls other than those indicated in these tables shall be obtained from the GDS and the PCS/GDS prior to designing the wall.

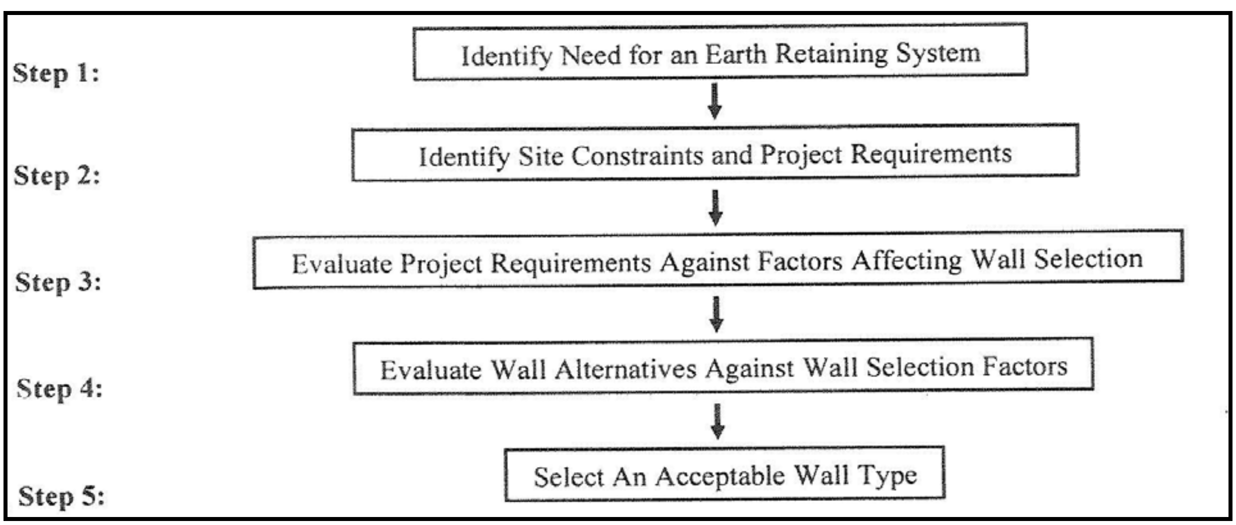

Figure 18-3, Wall Selection Flow Chart
(Earth Retaining Structures – June 2008)

Table 18-1, Cut Wall Evaluation Factors
(Earth Retaining Structures – June 2008)

	Wall Type	Application[1]	Height Range[2]	Required ROW[4]	Lateral Movements	Advantages	Disadvantages
CANTILEVERED	Sheet-pile	P/T	<16 ft	None	Large	- Rapid construction - Readily Available	- Difficult to construct in hard ground or penetrate obstructions
	Soldier Pile/Lagging	P/T	<16 ft	None	Medium	- Rapid construction - Soldier piles can be drilled or driven	- Difficult to maintain vertical tolerances in hard ground - Potential for ground loss at excavated face
	Anchored	P/T	15 - 70 ft	0.6H + abl[3]	Small-medium	- Can resist large horizontal pressures - Adaptable to varying site conditions	- Requires skilled labor and specialized equipment - Anchors may require permanent easements
IN-SITU REINFORCED	Soil-nailed	P/T	10 – 70 ft	1.0H	Small-medium	- Rapid construction - Adaptable to irregular wall alignment	- Nails may require permanent easements - Difficult to construct and design below water table
	Micropile	P	N/A	Varies	N/A	- Does not require excavation	- Requires specialty contractor

[1]P/T – Permanent and Temporary
[2]Height range based on cost effectiveness
[3]abl – Anchor Bond Length
[4]ROW requirements expressed as the distance (as a fraction of wall height, H) behind the wall face where anchorage components are installed

Table 18-2, Fill Wall Evaluation Factors
(Earth Retaining Structures – June 2008)

	Wall Type	Application[1]	Height Range[2]	Required ROW[3]	Differential Settlement Tolerance	Advantages	Disadvantages
RIGID GRAVITY	Gravity[4]	P	3 – 10 ft	0.7H	1/500	- Durable - Requires smaller quantity of select backfill as compared to MSE walls - Can meet aesthetic requirements	- Deep foundation support may be necessary - Relatively long construction time
RIGID GRAVITY	Cantilever[4]	P	6 – 30 ft	0.7H	1/500	- Durable - Requires smaller quantity of select backfill as compared to MSE walls - Can meet aesthetic requirements	- Deep foundation support may be necessary - Relatively long construction time
RIGID GRAVITY	Counterfort[4]	P	30 – 60 ft	0.7H	1/500	- Durable - Requires smaller quantity of select backfill as compared to MSE walls - Can meet aesthetic requirements	- Deep foundation support may be necessary - Relatively long construction time
FLEXIBLE GRAVITY	Gabion	P/T	6 – 30 ft	0.7H	1/50	- Does not require skilled labor or equipment	- Need adequate source of stone - Construction of wall requires significant labor
FLEXIBLE GRAVITY	MSE Wall – precast facing	P/T	10 - 100 ft	1.0H	1/100	- Does not require skilled labor or equipment - Flexibility in choice of facing	- Requires use of select backfill - Subject to corrosion in aggressive environments (metallic reinforcement)
FLEXIBLE GRAVITY	MSE Wall – modular block facing	P/T	6 – 60 ft	1.0H	1/200	- Does not require skilled labor or equipment - Flexibility in choice of facing - Blocks are easily handled	- Requires use of select backfill - Subject to corrosion in aggressive environments (metallic reinforcement) - Positive reinforcement connection to blocks is difficult to achieve
FLEXIBLE GRAVITY	MSE Wall – geotextile / geogrid / welded wire facing	P/T	6 – 50 ft	1.0H	1/60	- Does not require skilled labor or equipment - Flexibility in choice of facing	- Facing may be aesthetically pleasing -Geosynthetic reinforcement is subject to degradation in some environments
FLEXIBLE GRAVITY	MSE Wall – vegetated soil face	P/T	10 – 100 ft	1.0H	1/60	- Does not require skilled labor or equipment - Flexibility in choice of facing - Vegetation provides ultraviolet light protection to geosynthetic reinforcement	- Facing may be aesthetically pleasing -Geosynthetic reinforcement is subject to degradation in some environments - Vegetated soil face requires significant maintenance

[1]P/T – Permanent and Temporary
[2]Height range based on cost effectiveness
[3]ROW requirements expressed as the distance (as a fraction of wall height, H) behind the wall face where anchorage components are installed
[4]These walls are all constructed of cast-in-place concrete and/or standard brick and mortar

18.4.1 Necessity for ERS

As indicated in Figure 18-3, the first step in selecting an ERS type is to determine if a wall is needed. According to the SCDOT *Highway Design Manual* (HDM) (2003 with latest revisions), the need for ERSs is determined jointly by the Program Manager and the Road Design Team. Typically, ERSs are required in areas where additional Right-of-Way (ROW) cannot be obtained or there are other factors (i.e. other roads, major utilities, etc.) that limit the development of stable slopes. The need for ERSs can often be determined during the DFR (see Chapter 1).

18.4.2 Site Constraints and Project Requirements

Once the need for an ERS is identified, then specific site constraints and project requirements need to be identified. Listed below are some items that will affect ERS selection. This list is not all inclusive.

1. Site accessibility and space restrictions
    a. Limited ROW
    b. Limited headroom
    c. On-site material storage areas
    d. Access for specialized construction equipment
    e. Traffic Disruption restrictions
2. Utility locations, both above and underground
3. Nearby structures
4. Aesthetic requirements
5. Environmental concerns
    a. Construction noise
    b. Construction vibration
    c. Construction dust
    d. On-site stockpiling, transport and disposal of excavated materials
    e. Discharge of large volumes of water
    f. Encroachment on existing waterways
6. Exposed wall face height

The relative importance of each of these items should be assessed by the Project Team for the specific project under consideration. This assessment should identify those items that should be given priority in the selection process.

18.4.3 Factors Affecting ERS Selection

Step 3 from Figure 18-3 establishes the process for evaluating project requirements against fairly common factors that affect the selection of an ERS. Twelve factors have been identified and indicated in Table 18-3. The factors are listed in no particular order. Additional factors may be considered based on the requirements of the Project Team. Each factor is evaluated based on its relevancy and importance to the project requirements and site constraints. Each factor is assigned a number rating from one, the least relevant, to three, the most relevant. The rating is termed the weighted rating (WR). Table 18-4 depicts an example of the selection factors and WR for each factor.

Table 18-3, ERS Selection Factors
(Modified from Earth Retaining Structures – June 2008)

1	Ground type	7	Environmental concerns
2	Groundwater	8	Durability and maintenance
3	Construction considerations	9	Tradition
4	Speed of construction	10	Contracting practices
5	ROW	11	Cost
6	Aesthetics	12	Displacements (lateral and vertical)

Table 18-4, Weighted ERS Selection Factors
(Modified from Earth Retaining Structures – June 2008)

Displace.	
Cost	
Contracting Practice	
Tradition	
Durability and Maintenance	
Environmental Concerns	
Aesthetics	
ROW	
Speed of Construction	
Construction Considerations	
Groundwater	
Ground Type	
	WR[1]

[1]Wieghted rating of the importance of each ERS selection factor based on project requirements and site constraints. Each factor should be rated between 1, least importance factor, and 3, most important factor.

18.4.4 Evaluate ERS Alternates

The fourth step in selecting an ERS type consists of reviewing specific ERS types versus the Weighted ERS Selection Factors presented in the previous section. A logical first step in this process is the elimination of ERS types that would be inappropriate for the specific project site. This elimination process should focus on project constraints such as ERS geometry and performance; however, the project constraints related to costs should not be included as a reason to eliminate an ERS type. In addition, the factors affecting cut (top-down construction) or fill (bottom-up construction) ERS selection should also be evaluated.

The selection issues discussed in this Section apply to permanent ERSs, selection issues for temporary cut walls are discussed later in this Chapter. Typically, permanent cut walls are designed with greater corrosion protection or with higher strength materials. In addition, these types of ERSs have permanent facing elements that consist of either cast-in-place concrete or precast concrete panels. Cut ERSs are typically either cut or drilled into the existing geomaterials at a site and require specialty contractors. If ground anchors are not required, then little or no ROW is required. However, if anchors or soil nails are used, then either additional ROW or permanent easements will be required. The taller a cut ERS becomes, the higher the unit cost of the ERS becomes. Depending on the geotechnical conditions, for ERS heights ranging from 15 to 30 feet or greater, either anchors or soil nails will be required. Cut ERSs typically used by SCDOT are provided in Table 18-1.

Fill ERSs are constructed from the bottom-up and are typically used for permanent construction. However, temporary MSE walls can also be constructed using flexible facing elements. Fill ERSs typically require more ROW than cut ERSs. Typically, the soil used for fill ERSs is comprised of granular, nonplastic, free draining geomaterials. The requirements for high quality fill materials typically increase the cost of fill ERSs. Fill ERSs typically used by SCDOT are provided in Table 18-2.

Those ERS systems not eliminated earlier in this step should be evaluated using the ERS Selection Factors (see Table 18-3). An Importance Selection Factor (ISF) rating of one to four is applied to each ERS Selection Factor for each ERS type. An ISF rating of four means the factor is most suitable for the ERS type under evaluation, while an ISF rating of one means the factor is least suitable. Any cost associated with a selection factor should be considered when developing the rating. A brief description of each selection factor is provided in the following sections.

18.4.4.1 Ground Type

According to Earth Retaining Structures, FHWA - June 2008, "An *ERS* is influenced by the earth it is designed to retain, and the one on which it rests." For ERSs that are internally supported (MSE walls and soil nail walls), the quality of the retained soil in which the reinforcement is placed is of great influence. For MSE walls, the pull-out force of the reinforcement is developed by the friction along the soil-reinforcement interface and any passive resistance that develops along transverse members of the reinforcement, if any are present. Typically, MSE walls require high quality granular fill materials with relatively high friction angles. Plastic fine-grained soils (i.e. cohesive) are not used in MSE wall design or construction. For soil nail walls used to support excavations, the possible saturation and creep associated with plastic fine-grained soils can have a negative impact on the performance of the structure. For externally supported ERSs (gravity, semi-gravity and modular gravity), the influence of the retained soil is less important. However, for soils that undergo large vertical and horizontal displacements, a flexible ERS (i.e. gabion) should be used in lieu of a more rigid ERS. A rigid ERS will attempt to resist the movements, thereby placing more stress on the structural members.

18.4.4.2 Groundwater

The groundwater table behind ERSs should be lowered for the following reasons:

1. To reduce the hydrostatic pressures on the structure
2. To reduce the potential for corrosion of metal reinforcing in the retained soil
3. To reduce the potential for corrosion of metal reinforcing in facing elements
4. To prevent saturation of the soil
5. To limit displacements that can be caused by saturated soils
6. To reduce the potential for soil migration through or from the ERS

Typically, fill ERSs are constructed with free-draining backfill, while the ERS face contains numerous weep holes or other means for water to be removed from behind the structure. Drainage media is also installed in cut walls. An SCDOT ERS shall never be designed to retain water. If the necessity for water retention is mandated on a project, the PCS/GDS should be contacted for instructions and guidance.

18.4.4.3 Construction Considerations

Construction considerations that need to be accounted for in the selection of an ERS are material availability, site accessibility, equipment availability and labor considerations. The availability of construction materials can affect selection of an ERS. For example, the use of a gabion wall in Charleston would not be practical since all stone for the gabion would have to be hauled in, while on the other hand a gabion wall in Cherokee could be successfully used. Limited site accessibility could limit the type of ERS that could be constructed. Another construction consideration is the requirement for specialized equipment and is the equipment locally or at least regionally available. The final construction consideration is the labor force to be used to build the wall (i.e. does the labor force require specialized training?).

18.4.4.4 Speed of Construction

Another factor to be considered is the speed at which the ERS can be constructed. The more rapidly an ERS can be constructed, the more rapidly the project can be completed.

18.4.4.5 Right-of-Way

The amount or need for additional Right-of-Way (ROW) should be considered when selecting an ERS wall type. The question that needs to be asked is whether the ERS is being used to support the transportation facility or to support an adjacent owner. ERSs supporting the transportation facility should require limited to no additional ROW, while ERSs supporting an adjacent owner may require either additional ROW or an easement to install ground anchors, etc.

18.4.4.6 Aesthetics

Depending on the location of the ERS, the aesthetics of the wall can be of great importance in final selection. Typically, the aesthetics of wall is more important in populated areas than in non, or limited, populated areas. In more environmentally sensitive areas, the ERS may need to blend in with the surrounding environment. This need for blending should be accounted for in ERS selection.

18.4.4.7 Environmental Concerns

ERSs can both cause, as well as alleviate, environmental concerns. ERSs cause environmental concerns if contaminated soil must be removed prior to or during the construction of the structure. In addition, noise and vibration from certain ERS wall installations can have a negative impact on the environment around the project. In addition, the fascia of some ERSs may allow for the bouncing or echoing of traffic noise; therefore, in cases where this may become a concern, an alternate fascia material may need to be selected. ERSs may alleviate environmental concerns by allowing for smaller footprints in environmentally sensitive areas; therefore, eliminating the need for environmental permits.

18.4.4.8 Durability and Maintenance

Depending on the environmental conditions (corrosiveness) of materials the ERS is founded on or is constructed of, certain ERS types may not be satisfactory. The ERS must be durable for the life of the structure (100 years) or must have definitive maintenance procedures that will need to be identified. These maintenance procedures should also clearly indicate the time periods that maintenance should be performed.

18.4.4.9 Tradition

Tradition (i.e. what is normally done) can impact what type of ERS is selected. Traditionally, SCDOT uses the following wall types:

1. MSE
2. RSS
3. Cantilever (concrete or standard brick/block)
4. Soil Nail
5. Sheetpile (cantilever or anchored)
6. Soldier pile and lagging (cantilever or anchored)
7. Gabion
8. Gravity

18.4.4.10 Contracting Practices

The use of sole source or patented ERSs should be avoided at all times. If sole source or patented ERSs cannot be avoided, a written justification is required. The written justification shall be maintained in the project file and shall include the endorsement (approval) of the Regional Production Engineer.

18.4.4.11 Cost

The total cost of the ERS should include the structure (structural elements and backfill materials, if any), ROW (acquisition or easement), excavation and disposal of unsuitable or contaminated materials, mitigation costs of environmental impacts (such as additional noise) and the time value of construction delays. Credits for eliminating environmental permits or speeding up construction should as be factored into the decision.

18.4.4.12 Displacements

The amount of displacement (horizontal and vertical) that an ERS may be required to handle also affects the selection process. Some walls are more flexible than others. An idea of the amount of displacement that an ERS is anticipated to endure should also be known prior to making the final ERS selection.

18.4.5 Selection of Acceptable ERS Type

The final step in selecting an ERS is to determine the most acceptable type. This determination is made based on the ISF rating and the weighted rating each of the above selection factors is given for each ERS type. A score is arrived at by multiplying the ISF and the WR for each selection factor and summing all of the results. The ERS with the highest score is most acceptable type and should be developed in design. Other highly scored walls may be included in the Contract Documents as acceptable alternatives. Table 18-5 provides an example of this process.

Table 18-5, Wall Selection Matrix
(Modified from Earth Retaining Structures – June 2008)

	Ground	Groundwater	Construction Considerations	Speed of Construction	ROW	Aesthetics	Environmental Concerns	Durability and Maintenance	Tradition	Contracting Practice	Cost	Displacement	Total Score
ISF[1]	3	2	2	3	1	1	2	2	3	1	3	3	
MSE Wall – Precast Facing	4	1	3	3	1	4	4	3	4	2	3	2	77
Gabion Wall	3	1	3	1	4	1	4	4	1	3	1	4	62
Cast-in-place Concrete Gravity Wall	4	1	1	1	1	4	2	4	3	4	1	2	58

[1]Importance selection factor (ISF) for each ERS are based on project requirements and site constraints. Each factor should rated be between 1, least importance factor, and 3, most important factor.

18.5 EARTH PRESSURE THEORY

Earth pressures act on the rear face of an ERS and are caused by the weight of the soil (backfill or retained fill), seismic loads and various surcharge loads. The ERS is designed to resist these loads, as well as, any water (pore) pressures that may build up on the rear of the wall. There are three different lateral pressures used in the design of ERSs (see Table 18-6).

Table 18-6, Earth Pressure Definitions

Earth Pressure	Symbol	Definition
Active	K_a	The lateral pressure that is developed when the wall moves away from the backfill resulting in a decrease in pressure on wall relative to the at-rest pressure
At-Rest	K_o	The lateral pressure that exists in level ground for condition of no lateral deformation
Passive	K_p	The lateral pressure that is developed when the wall moves toward the backfill resulting in an increase in pressure on wall relative to the at-rest pressure

The general horizontal earth pressure is expressed by the following equation.

$$\sigma_h = K\sigma_v \qquad \text{Equation 18-2}$$

Where,

σ_h = Horizontal earth pressure at a specific depth on an ERS
K = Earth pressure coefficient
σ_v = Vertical earth pressure (overburden stress) at a specific depth on an ERS

The active and passive earth pressure coefficients are a function of the soil shear strength, backfill geometry, the geometry of the rear face of the ERS and friction and cohesion that develop along the rear face as the wall moves relative to the retained backfill. The active earth pressure condition is developed by a relatively small movement of the ERS away from the retained backfill, while the movements required to develop the passive earth pressure condition are on the order to approximately ten times larger than the movements required to develop active conditions (see Figure 18-4).

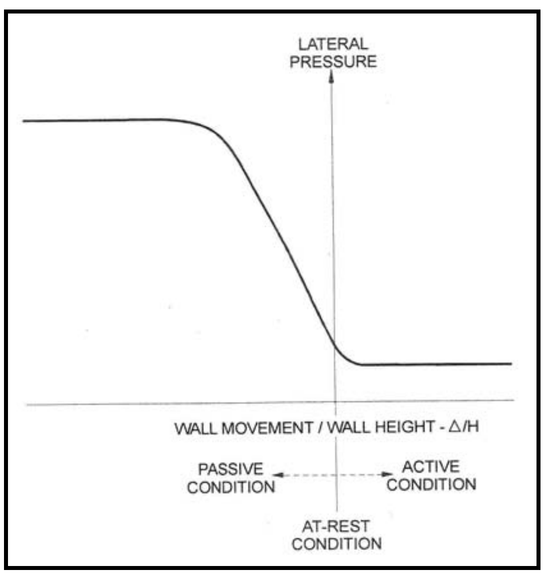

Figure 18-4, Relative Magnitude of Displace. Required to Develop Earth Pressures (Earth Retaining Structures – June 2008)

18.5.1 Active Earth Pressure

As indicated previously, the active earth pressure condition exists when the ERS is free to rotate away from the retained backfill. There are two earth pressure theories available for determining the earth pressure coefficients; Rankine and Coulomb earth pressure theories. Rankine earth pressure makes several assumptions concerning the wall and the backfill. The first assumption is that the retained soil has a horizontal surface, secondly, that the failure surface is a plane and finally that the wall is smooth (i.e. no friction). Rankine earth pressure theory is the preferred method for developing the active earth pressure coefficient; however, under the appropriate conditions Coulomb earth pressure theory may be used. The use of Rankine theory will cause a slight over estimation of K_a, therefore, increasing the pressure on the wall resulting in a more conservative design. The equations for developing the active earth pressure coefficient for cohesionless and cohesive soils, respectively, are indicated below:

$$K_a = \tan^2\left(45 - \frac{\varphi'}{2}\right) \quad \text{Equation 18-3}$$

$$K_a = \tan^2\left(45 - \frac{\varphi'}{2}\right) - \frac{2c'}{\sigma'_v}\tan^2\left(45 - \frac{\varphi'}{2}\right) \quad \text{Equation 18-4}$$

Where,

φ' = Effective friction angle
c' = Effective cohesion
σ'_v = Effective overburden pressure at bottom of wall

ERSs used on SCDOT projects shall be designed to prevent the buildup of pore water pressures behind the wall. The effective active pressure on an ERS shall be determined using the following equations for cohesionless and cohesive soils, respectively:

$$p_a' = K_a(\gamma z - u) \quad \text{Equation 18-5}$$

$$p_a' = K_a(\gamma z - u) - 2c'\sqrt{K_a} \quad \text{Equation 18-6}$$

Where,

γ = Total unit weight of soil
z = Depth of interest
u = Static pore water pressure
K_a = Active earth pressure coefficient
c' = Effective cohesion

The active pressure may also be expressed in terms of total stress by adding the pore pressure to the effective active pressure. This condition will only exist immediately after the completion of construction. If the soil has $c=s_u$ and $\varphi=0$, then total active pressure equation becomes:

$$p_a = \gamma z - 2s_u \qquad \text{Equation 18-7}$$

18.5.2 At-Rest Earth Pressure

In the at-rest earth pressure (K_o) condition, the top of the ERS is not allowed to deflect or rotate; therefore, requiring the wall to support the full pressure of the soil behind the wall. The at-rest earth pressure coefficient is related to the OCR (Chapter 7) of the soil. The following equation is used to determine the at-rest earth pressure coefficient:

$$K_o = (1 - \sin\varphi')(OCR)^{\Omega} \qquad \text{Equation 18-8}$$

$$\Omega = \sin\varphi' \qquad \text{Equation 18-9}$$

While all soils can be overconsolidated, the ability to accurately determine the OCR for cohesionless soil is not cost effective; therefore, the OCR for all cohesionless materials shall be taken as 1.0. Therefore for cohesionless materials, Equation 18-8 may be rewritten as:

$$K_o = 1 - \sin\varphi' \qquad \text{Equation 18-10}$$

Flexible walls are not typically designed to withstand the at-rest earth pressure condition. In this case, the effective at-rest earth pressure is determined using the following equation for both cohesionless and cohesive soils:

$$p_o' = K_o(\gamma z - u) \qquad \text{Equation 18-11}$$

18.5.3 Passive Earth Pressure

The development of passive earth pressure requires the ERS to move into or toward the soil. As with the active earth pressure, Rankine earth pressure is the preferred method to be used to develop passive earth pressure coefficient. Coulomb earth pressure theory may be used if the appropriate conditions exist at a site; however, the designer is required to understand the limitations on the use of Coulomb earth pressure theory as applied to passive earth pressures. The use of Rankine theory will cause an under estimation of K_p, therefore resulting in a more conservative design. The equations for developing the passive earth pressure coefficient for cohesionless and cohesive soils, respectively, are indicated below:

$$K_p = \tan^2\left(45 + \frac{\varphi'}{2}\right) \qquad \text{Equation 18-12}$$

$$K_p = \tan^2\left(45 + \frac{\varphi'}{2}\right) + \frac{2c'}{\sigma'_v}\tan^2\left(45 + \frac{\varphi'}{2}\right) \qquad \text{Equation 18-13}$$

Where,

φ' = Effective friction angle

c' = Effective cohesion

σ'_v = Effective overburden pressure at bottom of wall

ERSs used on SCDOT projects shall be designed to prevent the buildup of pore water pressures behind the wall. The effective passive pressure on an ERS shall be determined using the following equations for cohesionless and cohesive soils, respectively:

$$p_p' = K_p(\gamma z - u) \quad \text{Equation 18-14}$$

$$p_p' = K_p(\gamma z - u) + 2c'\sqrt{K_p} \quad \text{Equation 18-15}$$

Where,

- γ = Total unit weight of soil
- z = Depth of interest
- u = Static pore water pressure
- K_p = Passive earth pressure coefficient
- c' = Effective cohesion

The passive pressure may also be expressed in terms of total stress by adding the pore pressure to the effective passive pressure. This condition will only exist immediately after the completion of construction. If the soil has $c=s_u$ and $\varphi=0$, then total passive pressure equation becomes:

$$p_p = \gamma z + 2s_u \quad \text{Equation 18-16}$$

18.6 GRAVITY RETAINING WALLS

Gravity ERSs are externally stabilized fill walls and consist of the wall types provided in Table 18-7. Gravity wall types can be subdivided into three categories; gravity, semi-gravity and modular gravity. The limited details of each wall type are discussed in the following Sections. The design of gravity retaining walls is also discussed.

Table 18-7, Gravity Wall Types

Gravity	Semi-Gravity	Modular Gravity
Mass Concrete	Cantilever	Gabion
Stone	Counterfort	Crib
Masonry	Buttress	Bin

18.6.1 Gravity Retaining Walls

Gravity walls are typically trapezoidal in shape; although for shorter walls, the walls are more rectangular (SCDOT Standard masonry walls) (see Figure 18-5). Gravity walls are constructed of either mass concrete with little or no reinforcement or masonry or stone walls. These types of walls tend to behave rigidly and depend on the weight (mass) of concrete to resist overturning and sliding.

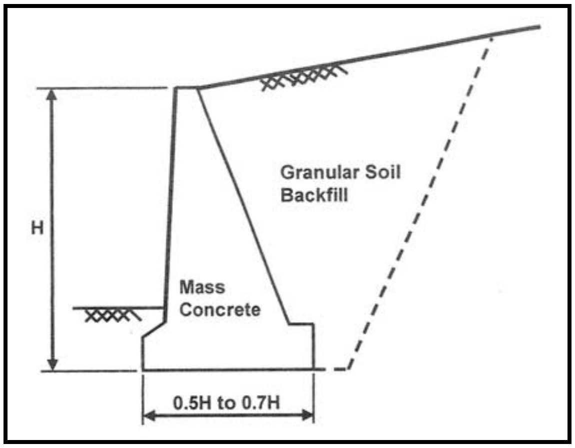

Figure 18-5, Gravity Retaining Wall
(Earth Retaining Structures – June 2008)

18.6.2 <u>Semi-Gravity Retaining Walls</u>

Semi-gravity walls are comprised of cantilevered, counterfort or buttress walls (see Figure 18-6). Semi-gravity walls are constructed of reinforced concrete, with the reinforcing in the stem designed to withstand the moments induced by the retained soil. Typically, cantilevered walls are limited to heights less than 30 feet. The counterforts (buttress within the retained soil mass) or buttresses (buttress on exposed face of the wall) are used when the moments are too large requiring a thicker stem and more reinforcing. Typically, these types of walls are used when the cantilevered wall height exceeds 30 feet.

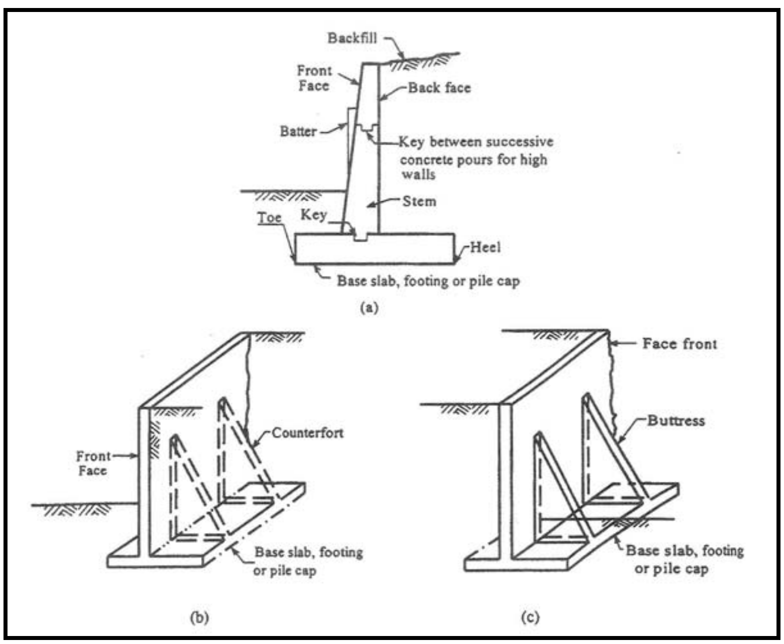

Figure 18-6, Semi-Gravity Retaining Wall
(Earth Retaining Structures – June 2008)
(a) Cantilever; (b) Counterfort; (c) Buttress

18.6.3 Modular Gravity Walls

Modular gravity walls are comprised of gabion, crib or bin walls (see Figure 18-7). Gabion walls are rock filled wire baskets. Gabion walls are used in locations where rock is plentiful. These types of walls are labor intensive to construct. Gabion walls are often used in applications that will experience cycles of inundation from streams. Currently SCDOT does not use crib or bin walls. The use of crib or bin walls must be approved in writing by the GDS and the PCS/GDS prior to commencing design.

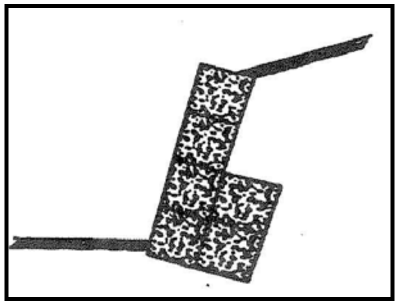

Figure 18-7, Gabion Retaining Wall
(Earth Retaining Structures – June 2008)

18.6.4 Gravity Wall Design

The design of gravity ERSs includes the overall (global) stability, bearing and deformation, sliding and overturning. The overall (global) stability and deformation analyses are performed using the procedures presented in Chapter 17. The bearing, sliding and overturning analyses are performed using the procedures discussed in Chapter 15, if shallow foundations are used. If deep foundations are required, then the procedures presented in Chapter 16 should be used. Table 18-8 provides the design steps for gravity walls. For additional details on the design of gravity walls refer to Earth Retaining Structures, FHWA - June 2008. The loads placed on gravity retaining walls should be developed in accordance with Section 11 – Abutments, Piers and Walls of the latest version of the AASHTO LRFD Bridge Design Specifications and Chapter 8 of this Manual. Resistance Factors and Performance Limits shall be developed in accordance with Chapters 9 and 10 of this Manual.

Table 18-8, Gravity Wall Design Steps
(Earth Retaining Structures – June 2008)

Step	Action
1	Establish project requirements including all geometry, external loading conditions (transient and/or permanent, seismic, etc.), performance criteria and construction constraints.
2	Evaluate site subsurface conditions and relevant properties of in-situ soil and rock parameters and wall backfill parameters.
3	Evaluate soil and rock parameters for design and establish resistance factors.
4	Select initial base dimension of wall for Strength limit state (external stability) evaluation.
5	Select lateral earth pressure distribution. Evaluate water, surcharge, compaction and seismic pressures.
6	Evaluate factored loads for all appropriate loading groups and limit states.
7	Evaluate bearing resistance (Chapter 15).
8	Check eccentricity (Chapter 15).
9	Check sliding (Chapter 15).
10	Check overall stability at the Service limit state and revise wall design if necessary (Chapter 17).
11	Estimate maximum lateral wall movement, tilt, and wall settlement at the Service limit state. Revise design if necessary.
12	Design wall drainage systems.

18.7 IN-SITU STRUCTURAL WALLS

In-situ structural walls have structural elements (i.e. sheetpile or soldier pile and lagging) installed to provide resistance of the applied lateral loads (see Figure 18-8). These types of walls are externally stabilized cut (top-down construction) walls. In-situ structural walls may develop resistance to the applied lateral loads through cantilever action, anchors or internal bracing (see Figure 18-9). In typical SCDOT applications, the use of exterior bracing is not normally used and will therefore not be discussed. Two different design methods are required for in-situ structural walls depending if the wall is cantilevered or supported by anchors. Typically, cantilevered in-situ structural walls can have exposed heights of up to 15 feet. Cantilevered in-situ structural walls taller than this will require anchors to resist the bending moments induced by the soil on the structural elements. The anchors may be either deadman or tendon type, depending on the method of construction, the amount of ROW available, etc. Table 18-9 provides the design steps for a cantilevered in-situ structural wall. Anchored in-situ structural walls are designed using the steps provided in Table 18-10. For additional details on the design of in-situ structural walls refer to Earth Retaining Structures, FHWA - dated June 2008. The loads placed on in-situ structural retaining walls should be developed in accordance with Section 11 – Abutments, Piers and Walls of the latest version of the AASHTO LRFD Bridge Design Specifications and Chapter 8 of this Manual. Resistance Factors and Performance Limits shall be developed in accordance with Chapters 9 and 10 of this Manual.

Table 18-9, Cantilevered In-Situ Structural Wall Design Steps (Earth Retaining Structures – June 2008)

Step	Action
1	Establish project requirements including all geometry, external loading conditions (transient and/or permanent, seismic, etc.), performance criteria and construction constraints.
2	Evaluate site subsurface conditions and profile, water profile, and relevant properties of in-situ soil and rock parameters.
3	Evaluate soil and rock parameters for design and establish resistance factors.
4	Select lateral earth pressure distribution. Evaluate water, surcharge, compaction and seismic pressures.
5	Evaluate factored total lateral pressure diagram for all appropriate limit states.
6	Evaluate embedment depth of vertical wall element and factored bending moment in the wall.
7	Check flexural resistance of vertical wall elements. Check combined flexural and axial resistance (if necessary).
8	Select temporary lagging (for soldier pile and lagging wall).
9	Design permanent facing (if required).
10	Estimate maximum lateral wall movements and ground surface settlement at the Service limit state. Revise design if necessary.

Table 18-10, Anchored In-Situ Structural Wall Design Steps (Earth Retaining Structures – June 2008)

Step	Action
1	Establish project requirements including all geometry, external loading conditions (transient and/or permanent, seismic, etc.), performance criteria and construction constraints.
2	Evaluate site subsurface conditions and relevant properties of in-situ soil and rock parameters.
3	Evaluate soil and rock parameters for design and establish resistance factors and select level of corrosion project for the anchor.
4	Select lateral earth pressure distribution acting on back of wall for the final wall height. Evaluate water, surcharge, and seismic pressures.
5	Evaluate factored total loads for all appropriate limit states.
6	Calculate horizontal ground anchor loads and subgrade reaction force. Resolve each horizontal anchor load into a vertical force component and a force along the anchor. Evaluate horizontal spacing of anchors based on wall type and calculate individual factored anchor loads.
7	Evaluate required anchor inclination based on right-of-way limitations, location of appropriate anchoring strata, and location of underground structures.
8	Select tendon type and check tensile resistance.
9	Evaluate anchor bond length.
10	Evaluate factored bending moments and flexural resistance of wall.
11	Evaluate bearing resistance of wall below excavation subgrade. Revise wall section if necessary.

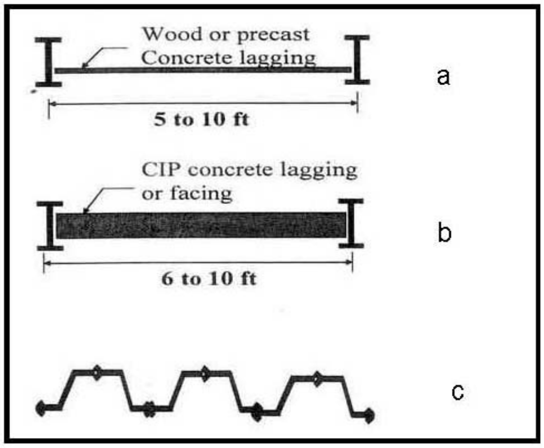

Figure 18-8, In-Situ Structural Walls
(Modified from Earth Retaining Structures – June 2008)
a and b Soldier pile and lagging; c Sheetpile

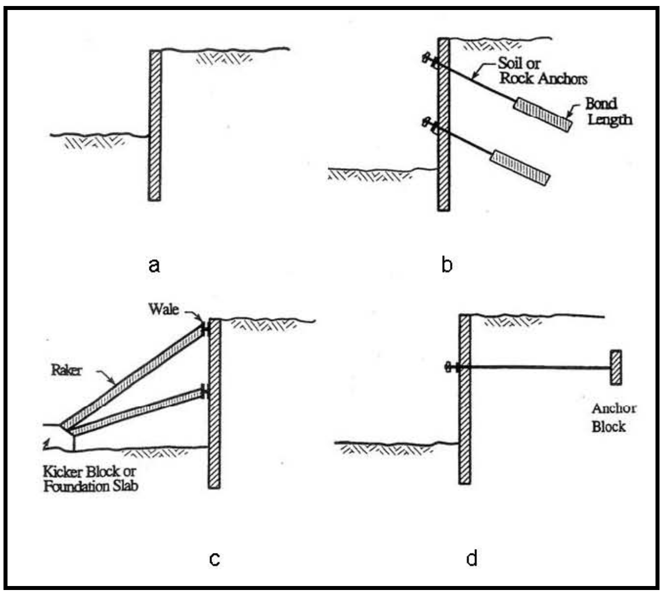

Figure 18-9, Wall Support Systems
(Modified from Earth Retaining Structures – June 2008)
a Cantilever; b Anchored; c Braced; d Deadman Anchored

18.8 MECHANICALLY STABILIZED EARTH WALLS

Mechanically Stabilized Earth (MSE) Walls are internally stabilized fill walls that are constructed using alternating layers of compacted soil and reinforcement (i.e. geogrids, metallic strips or metallic grids) (see Figure 18-10). As indicated in Table 18-2, there are four MSE Wall face alternatives that may be used when necessary. MSE Wall with precast panel facing shall be used at bridge end bent locations. However, other face options may be used with written permission of the GDS and the PCS/GDS. Table 18-11 provides the design steps that are used in the design of MSE Walls. Appendix C provides a detailed design procedure. The loads placed on in-situ structural retaining walls should be developed in accordance with Section 11 – Abutments, Piers and Walls of the latest version of the AASHTO LRFD Bridge Design Specifications and Chapter 8 of this Manual. Resistance Factors and Performance Limits shall be developed in accordance with Chapters 9 and 10 of this Manual. The external stability of the MSE Wall is the responsibility of the geotechnical engineer-of-record. The internal stability of the MSE Wall is the responsibility of either the structural designer or the MSE Wall supplier.

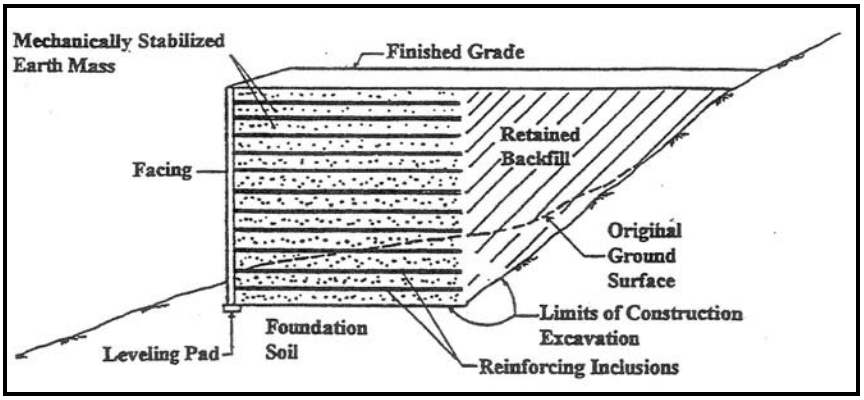

Figure 18-10, MSE Wall
(Earth Retaining Structures – June 2008)

Table 18-11, MSE Wall Design Steps
(Earth Retaining Structures – June 2008)

Step	Action
1	Establish project requirements including all geometry, external loading conditions (transient and/or permanent, seismic, etc.), performance criteria and construction constraints.
2	Evaluate existing topography, site subsurface conditions, in-situ soil/rock parameters and wall backfill parameters.
3	Based on initial wall geometry, estimate wall embedment depth and length of reinforcement.
4	Estimate unfactored loads.
5	Calculate factored loads for all appropriate limit states (external stability).
6	Check eccentricity (Appendix C).
7	Check sliding resistance (Appendix C).
8	Check bearing resistance (Appendix C).
9	Estimate critical failure surface based on reinforcement type (i.e. extensible or inextensible) for internal stability design at all appropriate Strength limit states.
10	Calculate factored horizontal stress at each reinforcement level.
11	Calculate maximum factored tensile stress in each reinforcement.
12	Check reinforcement pullout resistance.
13	Calculate nominal long-term reinforcement design strength and check reinforcement tensile resistance.
14	Check overall stability at the Service limit state (Chapter 17). Revise design if necessary.
15	Estimate vertical and lateral wall movements at the Service limit state. Revise design if necessary.
16	Design wall drainage systems.

18.9 IN-SITU REINFORCED WALLS

In-situ reinforced walls are internally stabilized cut walls that involve the insertion of reinforcing elements into the in-situ soils to create a composite ERS (see Figure 18-11).

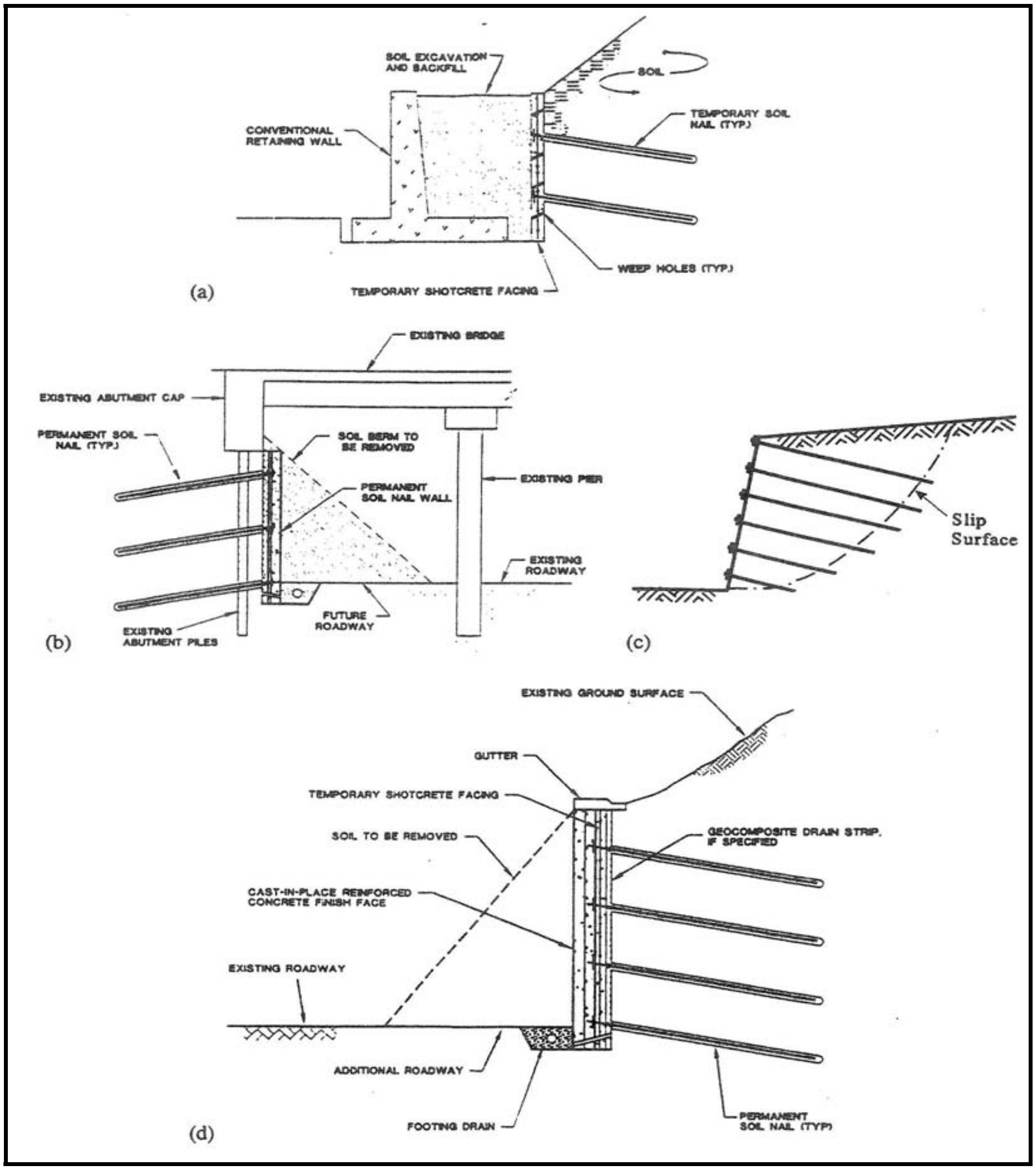

Figure 18-11, In-Situ Reinforced (Soil Nail) Walls
(Earth Retaining Structures – June 2008)

a Temporary shoring; b Roadway widening under existing bridge;
c Slope stabilization; d Roadway cut

The design steps for a soil nail wall are provided in Table 18-12. For detailed requirements of design, please refer to Earth Retaining Structures, FHWA - June 2008. An alternate detailed design source is Soil Nail Walls, FHWA - March 2003. The loads placed on in-situ structural retaining walls should be developed in accordance with Section 11 – Abutments, Piers and Walls of the latest version of the AASHTO LRFD Bridge Design Specifications and Chapter 8 of this Manual. Performance Limits and Resistance Factors shall be developed in accordance with Chapters 10 and 9 of this Manual. The external stability of the soil nail wall is the responsibility of the geotechnical engineer-of-record. The internal stability of the soil nail wall is the responsibility of either the structural designer or the soil nail wall contractor.

Table 18-12, Soil Nail Wall Design Steps
(Earth Retaining Structures – June 2008)

Step	Action
1	Establish project requirements including all geometry, external loading conditions (transient and/or permanent, seismic, etc.), performance criteria, aesthetic requirements, and construction constraints.
2	Evaluate site subsurface conditions and relevant properties of in-situ soil and rock.
3	Develop initial soil nail wall design criteria.
4	Perform preliminary design using simplified design chart solutions.
5	Evaluate external stability including global stability (Chapter 17), sliding and bearing capacity (Chapter 15).
6	Evaluate internal stability including nail pullout resistance and tensile resistance.
7	Perform facing design including: a) evaluation of nail head load; b) selection of temporary and permanent facing materials and thicknesses; c) evaluation of facing flexural resistance; d) evaluation of facing punching shear resistance; and, e) evaluation of facing stud tensile resistance.
8	Estimate maximum lateral wall movements.
9	Design wall subsurface and surface drainage systems

18.10 HYBRID WALLS

Hybrid walls are composed of two or more different types of walls or slopes (see Figure 18- 12). These kinds of walls allow a reduction in the ROW required for the construction of a project. The use of hybrid walls will require special attention from the design engineer. The various components of the hybrid wall may require different deformations to develop adequate resistance to the external loads. These differences can lead to incompatible deformations at the face of wall. The continuity of the drainage system must be maintained in both components of the hybrid wall. Finally, while the performance and design information for each component is known, the performance of the hybrid wall system is typically not known.

The combining of cut and fill walls should be performed with extreme care, since most cut walls require small strains to develop resistance, while most fill walls require larger strains to develop the same resistance. If the walls move (displace) different amounts to develop the required resistances, the face of the wall may display unaesthetic differential movements, even if the wall is structurally sound. The fact that the face shows displacement can cause the general public to consider the wall failing. In addition, the higher strains required to develop the resistance of one portion of the wall can induce higher loads in other portion of the wall causing failure of the wall.

In most cases, the hybrid wall consists of a stacked system (see Figure 18-12) with one wall or slope on top of another. The overall stability of the entire system must be checked in accordance with Chapter 17. Then, each individual wall component should be checked for stability. The lower wall should include the weight of the upper wall as a surcharge load. The design of the upper wall should include the movements (vertical and lateral) of the lower wall in design (see Chapter 17). The design engineer should have a clear understanding of how each different wall component will perform prior to selecting the use of a hybrid wall.

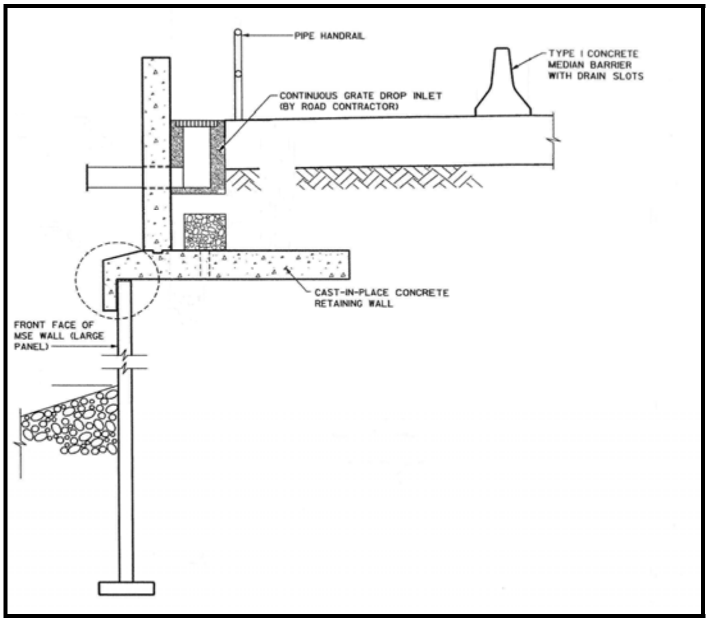

Figure 18-12, Hybrid Wall – Cantilever Concrete over MSE Wall

18.11 REINFORCED SOIL SLOPES

Steepened Reinforced Soil Slopes (RSS) are a transitional geometry between conventional (unreinforced) soil slopes and ERSs. Typically, RSSs have slopes ranging from 2H:1V to 1H:1V. Slopes flatter than 2H:1V are typically unreinforced, while structures with slopes greater than 1H:1V are considered to be ERSs. RSSs consist of reinforcement arranged in horizontal planes in the reinforced mass to resist the outward movement of this mass. The reinforcement allows the reinforced mass to act more rigid than in an unreinforced soil slope. Facing treatments can range from vegetated to flexible armor systems that are applied to prevent unraveling and sloughing of the face (see Figure 18-13). Appendix D contains detailed design methodologies for RSSs. Table 18-13 provides the design steps that are used in the design of RSS.

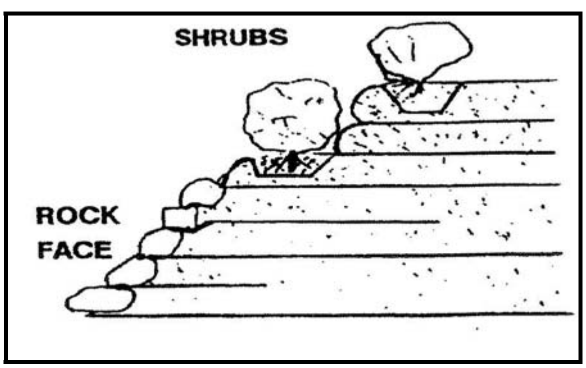

Figure 18-13, Reinforced Soil Slope
(Mechanically Stabilized Earth Walls and
Reinforced Soil Slopes Design and Construction – March 2001)

Table 18-13, RSS Design Steps
(modified from Mechanically Stabilized Earth Walls and
Reinforced Soil Slopes Design and Construction – March 2001

Step	Action
1	Establish project requirements including all geometry, external loading conditions (transient and/or permanent, seismic, etc.), performance criteria and construction constraints.
2	Evaluate existing topography, site subsurface conditions, and in-situ soil/rock parameters.
3	Determine properties of available fill materials.
4	Evaluate design parameters for the reinforcement.
5	Check unreinforced stability.
6	Design reinforcement to provide stable slope.
7	Determine type of reinforcement.
8	Check external stability.
9	Evaluate requirements for subsurface and surface water control.

The overall design of RSSs is similar to unreinforced slopes (see Chapter 17). However, there are three possible modes of slope failure (see Figure 18-14):

I. Internal – failure plane passes through reinforced soil mass
II. External – failure plane passes behind and underneath reinforced soil mass
III. Compound – failure plane passes behind and through reinforced soil mass

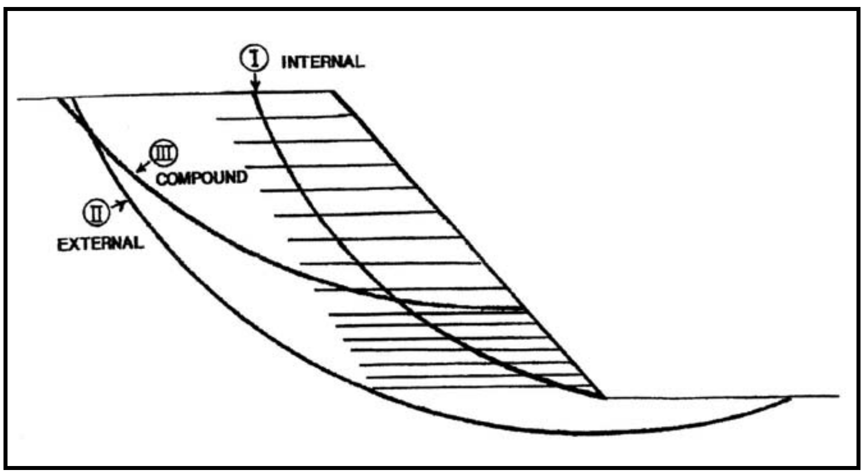

Figure 18-14, Reinforced Soil Slope Failure Modes
(Mechanically Stabilized Earth Walls and
Reinforced Soil Slopes Design and Construction – March 2001)

18.12 TEMPORARY WALLS

Temporary shoring walls are used to support a temporary excavation that is required to allow construction to proceed. Temporary shoring walls have a service of less than 5 years. Any shoring wall with a service life of greater than 5 years shall be designed as a permanent ERS.

Another major distinction between permanent and temporary ERSs is an increase in the resistance factor allowed in design. Temporary walls may be subdivided into two classes "support of excavation" (SOE) and "critical." SOE walls typically support just the excavation while the critical temporary walls support critical structures (i.e. existing roadway and traffic, bridge end bent fill, etc.). The resistance factors and performance limits established (see Chapters 9 and 10) are for critical temporary walls. The PCS/GDS should be contacted for the resistance factors and performance limits for SOE temporary walls. The design of temporary walls uses the same methodologies as the permanent walls.

18.13 REFERENCES

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