# APPENDIX F
# OTHER DESIGN PROCEDURES AND ANALYSIS MODELS

There are several means, other than the *Simplified Method* analysis model with the LRFD platform, which can be used for the design of MSE walls. Several of these are summarized below. Note that some design methods can be used in either a LRFD or an ASD platform. The use of the Simplified Method analysis model with the LRFD platform is recommended for the design of transportation MSE wall structures.

## F.1 Simplified Method and ASD Platform

As previously (Section 4.1.1) noted, Engineers have been designing MSE highway walls using an ASD (allowable stress design) procedure since MSE walls were introduced in the early 1970's. All uncertainty in applied loads and material resistance are combined in a single factor of safety or allowable material stress. The advantages of progressing to a LRFD procedure were summarized in Section 4.4.1.

Future MSE walls will be designed with the LRFD procedure. Therefore, current guidance, i.e., AASHTO Standard Specifications for Highway Bridges, 17th Edition (2002) and FHWA NHI-00-043 (Elias et al., 2001), on MSE wall design using ASD procedures will not be updated. Note that the AASHTO (2002) and FHWA (2001) ASD references will <u>not</u> be updated by AASHTO or FHWA, respectively. Any designers engineering MSE walls with the ASD procedures in the future may want to refer to current LRFD procedures for any updates which may also be applicable to ASD procedure designs (e.g., seismic loading for external stability analysis).

The *Simplified Method* of analysis has been used with ASD procedures since 1996. This method was developed using FHWA research (Christopher et al., 1990) and existing design methods (i.e., coherent gravity method, tie-back wedge method) as a starting point to create a single method for agencies and vendors to use (Elias and Christopher, 1997; AASHTO, 1997; Allen et al., 2001). The simplified method uses a variable state of stress for internal stability analysis. This variable state of stress is defined in terms of a multiple of the active lateral earth pressure coefficient, $K_a$, and is a function of the type of reinforcement used and depth from the top of wall. This single method of design is applicable to all types of soil reinforcement. Thus, the simplified method offers the following advantages over other methods:

- Straight forward by avoiding iterative processes to determine the reinforcement requirements (i.e., it is simple and easy to use).
- Justified empirically in comparison to other methods available at the time of its development based on instrumented full scale structures, and the simplifications do not appear to compromise the Simplified Method's accuracy (Allen et al., 2001).

- Found to be more accurate for upper reinforcements in sloped surcharges (Allen et al., 2001).
- Eliminates variations in method to determine internal lateral stress.
- Eliminates variations in assumptions of the critical failure surface.
- Accounts for the differences in reinforcement type and is easily adapted to new MSE wall reinforcement types as they become available.

The simplified method has been adapted to LRFD procedures in AASHTO (2007) and in this manual. As noted in the introduction to this section, today, the use of the Simplified Gravity analysis model with the LRFD platform is recommended for the design of transportation MSE wall structures.

## F.2 Coherent Gravity Method

The coherent gravity method, or analysis model, has been used for several decades in the ASD procedure. It can also be used with the LRFD procedure. The 2009 AASHTO Interims note that the maximum reinforcement loads shall be calculated using the Simplified Method or the Coherent Gravity Method. For state and agencies using the Coherent Gravity Method, the load in the reinforcements shall be obtained in the same way as the Simplified Method, except: (i) for steel reinforced wall systems, the lateral earth pressure coefficient used shall be equal to $k_o$ at the point of intersection of the theoretical failure surface with the ground surface at or above the wall top, transitioning to a $k_a$ at a depth of 20.0 ft below the intersection point, and constant at $k_a$ at depths greater than 20.0 ft. and (ii) If used for geosynthetic reinforced systems, $k_a$ shall be used throughout the wall height.

AASHTO also states that other widely accepted and published design methods for calculation of reinforcement loads may be used at the discretion of the wall owner or approving agency, provided the designer develops method-specific resistance factors for the method employed. AASHTO recommends that the resistance factors recommended for the Simplified Method should also be used for the Coherent Gravity Method.

The primary differences between the *coherent gravity method* and the *simplified method* are: (i) the coherent gravity method includes the pressure at each reinforcement elevation in the vertical pressure sum; (ii) the effect of the overturning moment caused by the retained backfill lateral earth pressure is included in the vertical pressure at each reinforcement elevation; and (iii) the lateral pressure varies from $K_o$ at the top of the soil to $K_a$ at a depth of 20 ft (6 m) below, and constant at $K_a$ below the 20 ft (6 m) depth for metallic reinforcements. This is illustrated in Figure F-1. As discussed in Chapter 4 (and illustrated in Figure 4-9), the metallic reinforcement lateral pressure varies from 1.7 $K_a$ (strips) or 2.5 $K_a$ (mats and grids) at top of soil to $K_a$ at a depth of 20 ft (6 m), and constant at $K_a$ thereafter. For comparison purposes, for a $\phi = 34^\circ$ soil, $K_o = 1 - \sin 34^\circ = 0.50$; for a $\phi = 34^\circ$ soil, $K_a = 0.283$; thus, $K_o = 1.77\ K_a$.

For geosynthetic reinforcements, the lateral pressure is constant at $K_a$ for both the coherent gravity method and the simplified method. Therefore, the *coherent gravity method* is typically used only for metallic reinforcements.

Previous research (FHWA RD-89-043) focused on defining the state of stress for internal stability, as a function of $K_a$, type of reinforcement used (geotextile, geogrid, metal strip or metal grid), and depth from the surface. The results from these efforts were synthesized in a *simplified method*, which can be used for all types of soil reinforcements. The simplified coherent gravity method is a single, logical method that can be used with LRFD or ASD procedure. As previously indicated in the Simplified Method section, there are a number of advantages to agencies. The method has been used for the past 12 years to safely design retaining walls. In comparison studies with field measured data, Allen et al. (2001) found the following:

- Overall, the Simplified Method and the FHWA Structure Stiffness Method produce a prediction that is slightly conservative, whereas the Coherent Gravity Method produces a prediction that is slightly nonconservative.
- The Coherent Gravity Method has been found to consistently provide lower predicted loads in structures with stiff reinforcement systems and in the upper reinforcements of sloped surcharges than measured field loads, while the Simplified Method more accurately predicts these reinforcement loads (Allen et al., 1993).
- The assumption that the reinforcement stress is reduced with increased reinforcement length is questionable and not supported by field measurements.

FHWA supports the use of a single method in order to maintain consistency in design. There are always concerns that designers will be confused and combine aspects of alternate methods that could produce nonconservative results. Agencies should be cognizant of the pending change to the AASHTO LRFD code and evaluate whether or not to allow the use of the Coherent Gravity Method (and/or other methods) in addition to the Simplified Method. Agencies specifications should be updated to reflect use of just the Simplified Method or the acceptance of either method.

Again, the use of the Simplified Gravity analysis model with the LRFD platform is recommended for the design of transportation MSE wall structures.

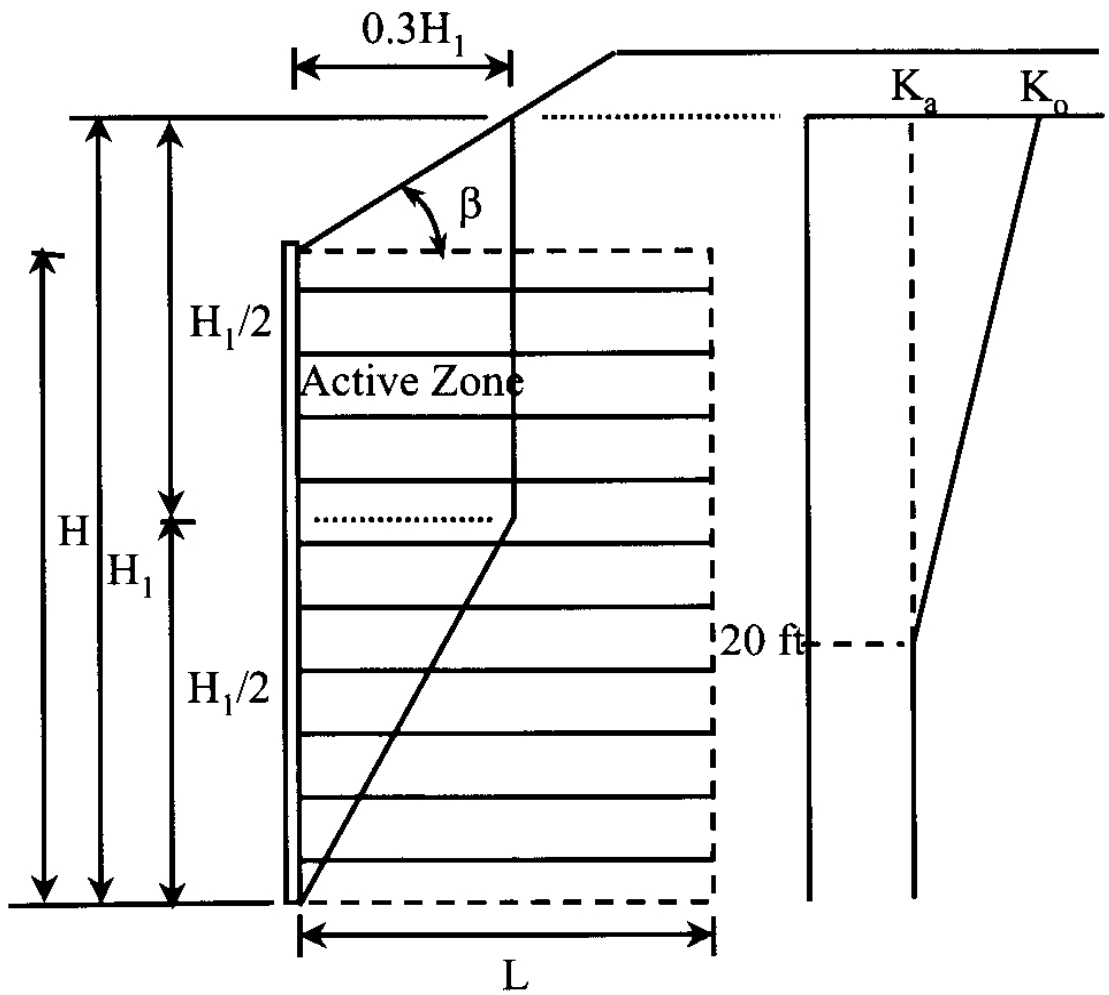


Figure F-1. Coherent gravity method lateral pressure coefficient for internal stability (2009 Interims to AASHTO, 2007).

## F.3 National Concrete Masonry Association Procedure

The National Concrete Masonry Association (NCMA) method and analysis model was developed in 1993 (Simac et al.) specifically for, and is widely used with, modular block faced (a.k.a. segmental blocks), geosynthetic reinforced soil walls. It is an ASD procedure. It was updated in 1997 (NCMA), and a third update is reportedly in-progress.

The principal differences between the NCMA method and the ASD Simplified Method are: (i) internal stability lateral pressure is set equal to the Coulomb active earth pressure coefficient, instead of the Rankine coefficient; (ii) assumed failure plane is the Coulomb active pressure wedge, instead of the Rankine active pressure wedge; (iii) the minimum reinforcement length to height ratio is 0.6, versus 0.7; and (iv) the connection strength requirements are based upon short-term testing, instead of being based upon long-term testing, as required by AASHTO.

## F.4 GRS

The Geosynthetic Reinforced Soil (GRS) analysis model is used with ASD procedure. This method was developed in Colorado specifically for geosynthetic soil reinforcements and wrap-around or block facings. The GRS design method is documented in NCHRP Report 556 (Wu et al., 2006). The GRS design method is a modification of the FHWA ASD Simplified Method (Elias et al., 2001). The soil reinforcement model is based upon closely-spaced vertically adjacent layers of reinforcement and soil arching, versus the FHWA method that this based upon a tied-back wedge model.

Addtional principal differences between the GRS method and the ASD Simplified Method are: (i) the default vertical reinforcement spacing is 8 in. (0.2 m), and maximum spacing (for abutments) is 16 in. (0.4 m); (ii) the reinforcement length may be truncated in the bottom portion of the wall where the foundation is competent; (iii) the soil reinforcement is specified on a basis of minimum ultimate tensile strength and a minimum tensile stiffness; and (iv) connection strength is not a design requirement where the maximum reinforcement vertical spacing is 8 in. (0.2 m) and reinforced fill is a compacted select fill.

## F.5 FHWA Structure Stiffness Method (from Allen et al., 2001; Christopher et al., 1990)

The Structure Stiffness Method was developed as the result of a major FHWA research project in which a number of full-scale MSE walls were constructed and monitored. Combined with an extensive review of previous fully instrumented wall case histories (Christopher et al., 1990; Christopher, 1993), small-scale and full-scale model walls were constructed and analytical modeling was conducted (Adib, 1988). This method is similar to the Tieback Wedge Method, but the lateral earth pressure coefficient is determined as a function of depth below the wall top, reinforcement type, and global wall stiffness, rather than using $K_a$ directly. Furthermore, the location of the failure surface is the same as is used for the Coherent Gravity Method (Figure 3) for MSE walls with inextensible soil reinforcement. It is a Rankine failure surface for MSE walls with extensible soil reinforcement. The design methodology is summarized in equations 8, 9, and 10. Note that because the reinforcement stress, and the strength required to handle that stress, varies with the global wall stiffness, some iteration may be necessary to match the reinforcement to the calculated stresses.

$$T_{max} = S_v\, R_c\, K_r\, (\gamma Z + S + q)$$

$$K_r = K_a\,(\,\Omega_1\,(1 + 0.4\,(S_r / 47880))\,(1 - Z/6) + \Omega_2\, Z/6) \quad \text{if } Z \leq 6 \text{ m}$$

$$K_r = K_a\, \Omega_2 \qquad \text{if } Z > 6 \text{ m}$$

$$Sr = EA / (H/n)$$

Where, $K_r$ is the lateral earth pressure coefficient,

$S_r$ is the global reinforcement stiffness for the wall (i.e., the average reinforcement stiffness over the wall face area),

$\Omega_1$ is a dimensionless coefficient equal to 1.0 for strip and sheet reinforcements or equal to 1.5 for grids and welded wire mats,

$\Omega_2$ is a dimensionless coefficient equal to 1.0 if $S_r$ is less than or equal to 47880 kPa or equal to $\Omega_1$ if $S_r$ is greater than 47880 kPa, EA is the reinforcement modulus times the reinforcement area in units of force per unit width of wall,

H/n is the average vertical spacing of the reinforcement, and n is the total number of reinforcement layers.

This stiffness approach was based on numerous full-scale observations that indicated that a strong relationship between reinforcement stiffness and reinforcement stress levels existed, and it was theoretically verified through model tests and numerical modeling.

## F.6 K-Stiffness Method

The K-Stiffness Method, or analysis model, is relatively new method that may be used with the ASD or LRFD procedure. This method was researched and developed by Allen and Bathurst (2003), Allen et al. (2003), Allen et al. (2004) and was calibrated against measurements of loads and strains from a large database of full-scale geosynthetic and full-scale steel reinforced soil walls. The method is targeted to accurately predict working loads in the soil reinforcement, though wall behavior near failure of some of the walls by excessive deformation or rupture was considered in the development of the design model (see Allen et al., 2003) to insure that such behavior would be precluded if the K-Stiffness Method is properly used and design parameters properly selected. From that research, the K-Stiffness method defined a design limit state that has not been considered in the other design models – a soil failure limit state. This is especially important for geosynthetic walls, since the geosynthetic reinforcement continues to strain and gain tensile load long after the soil has reached its peak strength and begun dropping to a residual value. Therefore, if the strain in the soil is limited to prevent it from going past peak to a residual value, failure by excessive deformation or rupture is prevented and equilibrium is maintained. This is a key design philosophy in the K-Stiffness design model.

An analysis of the K-Stiffness predictions relative to the full scale measurements indicate that the K-Stiffness method is a more accurate method for estimating loads in the soil reinforcements than other currently available design models and thereby has the potential to reduce reinforcement requirements and improve the economy of MSE walls (Allen et al., 2003 and 2004). The improvement (i.e., economy) is significant for both geosynthetic and steel reinforcement, though more pronounced for geosynthetic reinforcements. A couple of geosynthetic reinforced walls have been designed using the K-Stiffness Method, built, and fully instrumented by the Washington State Department of Transportation (WSDOT). Because they were designed with the K-Stiffness Method, the amount of soil reinforcement in the wall was reduced by a third to one-half of the reinforcement required by the AASHTO Simplified Method. Results reported by Allen and Bathurst (2006) for the largest wall (36 ft high, 600 ft long) indicate that the K-Stiffness method accurately predicted the strains in the reinforcement, and the wall has performed well since its construction. The other wall has also performed well, and full results for both walls will be available in a forthcoming WSDOT research report. The K-Stiffness Method's ability to accurately predict reinforcement strains provides promise for having the ability to accurately predict wall deformations for the serviceability limit state. See Allen and Bathurst (2003) for additional details on this issue.

The K-Stiffness method has been adapted to LRFD design procedure by the Washington DOT, and load and resistance factors to use with this method are detailed in the WSDOT Geotechnical Design Manual (2006), as well as step-by-step procedures for use of the K-Stiffness Method for design of MSE walls. The method begins with a prediction of the total lateral load to be resisted by the soil reinforcement which is consistent with the approach used by the Simplified Method. The K-Stiffness Method then takes that total lateral load and adjusts it empirically based on the effects of global reinforcement stiffness, local reinforcement stiffness, facing stiffness/toe restraint, facing batter, soil shear strength, and distribution of the total lateral force to the individual layers based on observations from many full scale wall case histories. The formulation of global reinforcement stiffness is consistent with that used in the FHWA Structure Stiffness Method (Christopher et al., 1990; Christopher, 1993). The soil shear strength (the plane strain shear strength is used for this method) is used as an index to correlate to the stiffness of the soil backfill, which is the real property of interest with regard to prediction of soil reinforcement loads at working stress conditions. Note that the methods used in historical practice (e.g., the Simplified Method) calculate the vertical stress resulting from gravity forces within the reinforced backfill at each level, resulting in a linearly increasing gravity force with depth and a lateral stress distribution that continuously increases with depth below the wall top. The K-Stiffness Method instead calculates the maximum gravity force resulting from the gravity forces within the reinforced soil backfill to determine the maximum reinforcement load within the entire wall reinforced backfill, $T_{mxmx}$, and then adjusts that maximum reinforcement load with depth for each of the layers using a load distribution factor, $D_{tmax}$ to determine $T_{max}$.

The method is summarized as follows:

$$\sigma_V = \gamma_p \gamma_r H + \gamma_p \gamma_f S + \gamma_{LL} q + \gamma_p \Delta\sigma_V \text{, and}$$

$$T_{\max} = 0.5 S_v K \, \sigma_V \; D_{t\max} \Phi_g \Phi_{local} \Phi_{fb} \Phi_{fs} + \gamma_p \Delta\sigma_H S_v$$

where,

$\sigma_V$ = the factored pressure due to resultant of gravity forces from soil self weight within and immediately above the reinforced wall backfill, and any surcharge loads present (KSF)

$\gamma_P$ = the load factor for vertical earth pressure EV

$\gamma_{LL}$ = the load factor for live load surcharge per the AASHTO LRFD Specifications

q = live load surcharge (KSF)

H = the total vertical wall height at the wall face (FT)

S = average soil surcharge depth above wall top (FT)

$\Delta\sigma_V$ = vertical stress increase due to concentrated surcharge load above the wall (KSF)

$S_v$ = tributary area (assumed equivalent to the average vertical spacing of the reinforcement at each layer location when analyses are carried out per unit length of wall), in FT

K = is an index lateral earth pressure coefficient for the reinforced backfill, and shall be set equal to $K_0$ as calculated per Article 3.11.5.2 of the AASHTO LRFD Specifications. K shall be no less than 0.3 for steel reinforced systems.

$D_{tmax}$ = distribution factor to estimate $T_{max}$ for each layer as a function of its depth below the wall top relative to $T_{mxmx}$ (the maximum value of $T_{max}$ within the wall)

$S_{global}$ = global reinforcement stiffness (KSF)

$\Phi_g$ = global stiffness factor

$\Phi_{local}$ = local stiffness factor

$\Phi_{fb}$ = facing batter factor

$\Phi_{fs}$ = facing stiffness factor

$\Delta\sigma_H$ = horizontal stress increase at reinforcement level resulting from a concentrated horizontal surcharge load per Article 11.10.10.1 of the AASHTO LRFD Specifications (KSF)

The WSDOT GDM (2006, or most current update) should be consulted for the details on the calculation of $T_{max}$ for each layer and how to apply this methodology to MSE wall design.

It should be noted that the K-Stiffness Method has been updated to consider a number of additional wall case histories, and additionally to consider the effect of backfill soil cohesion. See Bathurst et al. (2008) for details. While consideration of soil cohesion does help to improve the K-Stiffness Method prediction accuracy for wall backfill soil that contain a significant cohesive component to its soil shear strength, in general, it is not recommended to consider soil cohesion in the soil backfill for design purposes due to unknown long-term effect of moisture infiltration in the backfill and possibly soil creep.

## F.7 Deep Patch

The deep patch is a mitigation technique for sliding roadway sections. It is typically used on roads that suffer from chronic slide movements that are primarily the result of side cast fill construction. One of the main advantages of the deep patch technique is that it is constructed with equipment that works from the roadway and does not require accessing the toe of the failed area. This technique is generally not expected to completely arrest movement seen in the road but rather slow it down to manageable levels.

Deep patch repairs consist of reinforcing the top of a failing embankment with several layers of soil reinforcement. This work is typically done with a small construction crew consisting of a laborer, hydraulic excavator, and a dump truck. The design is based on determining the extent of the roadway failure based on visual observations of cracking and then and then using analytical or empirical methods for determining the reinforcement requirements. An empirical design procedure is presented in Highway Deep Patch Road Embankment Repair Application Guide which was produced by the U.S. Department of Agriculture (USDA) Forest Service in partnership with FHWA Federal Lands Highway Division. An analytical approach is summarized as follows:

1. Characterize the existing soil properties, new fill properties if applicable, and establish the desired slope stability factor of safety after the deep patch mitigation technique is implemented.

2. Generate a cross section of the failed embankment at a location that represents the most severe movement.

3. Locate the cracks furthest from the edge of the embankment slope break (hinge point) on the cross section. Similar to the concept of MSE wall internal active and restive mechanisms the active portion of the embankment movement will be considered to be taking place on the outside of the embankment crack limits and the resisting portion on the inside of the crack limits.

4. Determine the distance from the crack limits to the embankment slope hinge.

5. Determining the total reinforcement tension required per unit width as described in Chapter 9 or using reinforced soil slope software.

6. Based on the site limitations and geometry determine the reinforcement spacing and corresponding number of reinforcement layers (Typically 2-5 layers). Divide $T_s$ by the

number of layers to obtain the required reinforcement tensile strength per layer and per unit width (Treq'd).

7. Determine the minimum required pullout length (Le) by using a factor of safety of 1.5 and setting Treq'd = Tmax. Determine the minimum reinforcement length by adding Le to the distance from the crack to the slope face for each layer.

8. Select a reinforcement in which the long-term allowable strength per unit width (Chapter 3) is greater then Treq'd.