

Overview

Load and resistance factor design (LRFD) of mechanically stabilized earth (MSE) walls considers multiple ultimate limit states, associated with both external and internal stability. The companion Powerpoint presentation reflects updated values for coefficients of variation of the parameters entering the ultimate limit state equations reflecting a complete literature review. The values also reflect the fact that soil reinforcements in MSE walls are highly redundant, so the target reliability indices for internal stability were revised from the original report.

Improvements

The following are the changes made during the implementation project.

1. Revision of uncertainties of parameters in the ultimate limit state equations

The uncertainty levels of the parameters in the ultimate limit state equations were revised after further consideration of data that have become available in the literature. The following table summarizes the revised parameter uncertainties.

Table 1. Revised uncertainties of component variables of the ultimate limit state equations

Variables	Bias factor	Coefficient of variation	Distribution type
γ_{rt}	1.0	0.10	Normal
γ_{rf}	1.0	0.05	"
ϕ_{rt}	1.0	0.025	"
δ_{rf} and δ_{fn}	1.0	0.022	"
$\delta_{inter,c}$	1.0	0.075	"
K_r	1.0	0.344	"
f_y	1.09	0.05	"
$q_{0,rt}$	1.2	0.205	Lognormal

In Table 1:

γ_{rt} and γ_{rf} : are the unit weights of retained and reinforced soils;

ϕ_{rt} : is the critical-state friction angles of the soils in the retained soil zones;

δ_{rf} and δ_{fn} : are the interface friction angles of the soils in the reinforced and foundation soil zone;

$\delta_{inter,c}$: is the critical-state interface friction angle against pullout of steel-strip reinforcement;

K_r : is the lateral earth pressure coefficient;

f_y : is the yield strength of steel-strip reinforcement;

$q_{0,rt}$: is the live uniform surcharge load acting on the top of the retained soil.

2. Revision of target reliability indices for internal stability checks

Target reliability indices for internal stability checks were revised. The AASHTO LRFD Bridge Design Specifications (2007) recommend using a target reliability index β_T of 3.5 for the main structural elements of a bridge or components of it whose failure will likely lead to a global bridge failure (meaning an ultimate limit state). The target reliability index β_T of a redundant system should be less than that of a non-redundant system. For example, for pile design, the AASHTO LRFD Bridge Design Specifications (2007) prescribe $\beta_T = 3.0$ for a single pile or pile group with fewer than 5 piles and $\beta_T = 2.33$ for a larger pile group (Paikowsky 2004; Allen 2005; AASHTO 2007). However, the AASHTO LRFD Bridge Design Specifications (2007) have no recommendation of β_T for MSE wall internal stability.

Reinforcements in an MSE wall can similarly be considered redundant. The degree of redundancy of the reinforcement system of an MSE wall depends on the specific limit state, horizontal and vertical spacings of the reinforcements, and MSE wall geometry. Three values

of β_T (2.0, 2.33, and 3.0) were considered to accommodate different scenarios and views on redundancy and its impact on design conservativeness.

3. New proposals: Method of Determination of Maximum Tension Location

In the designs against pullout of reinforcement of MSE walls, it is assumed that there is no contribution towards resistance against pullout along the reinforcement length L_a embedded in the active wedge. Therefore, establishment of the value of L_a is important, and uncertainty in L_a could influence the potential reliability of reinforcement pullout calculations.

Juran (1977) found from laboratory studies that the slip surface in an MSE wall resembled a logarithmic spiral. Corte (1977), with some early finite element analysis of the problem, also found that the locus of the maximum tensile forces is approximated by a logarithmic spiral. The design specifications of AASHTO (2007) and FHWA (2001) approximate the failure zone as bilinear. In these two publications, L_a , the distance of the potential slip surface from the facing of the MSE wall, is expressed as:

$$L_a(z) = \begin{cases} 0.3H & 0 \leq z \leq H/2 \\ 0.6(H-z) & H/2 \leq z \leq H \end{cases} \quad (1)$$

where z is the depth from the top of the MSE wall.

In a reliability analysis context, to calculate the total length of the reinforcement length L ($= L_a + L_e$), the uncertainty of the reinforcement length L_a embedded in the active wedge should be assessed. The locus of T_{\max} for all reinforcements has been used in the literature as a proxy for the slip surface. Schlosser et al. (1978) showed measurements of the location of the maximum tensile force T_{\max} for completed MSE walls (Figure 1). Most of the T_{\max} measurements of Schlosser et al. (1978) are found to lie within the active zone defined by Eq. (1), except two measurements made near the bottom of an MSE wall.

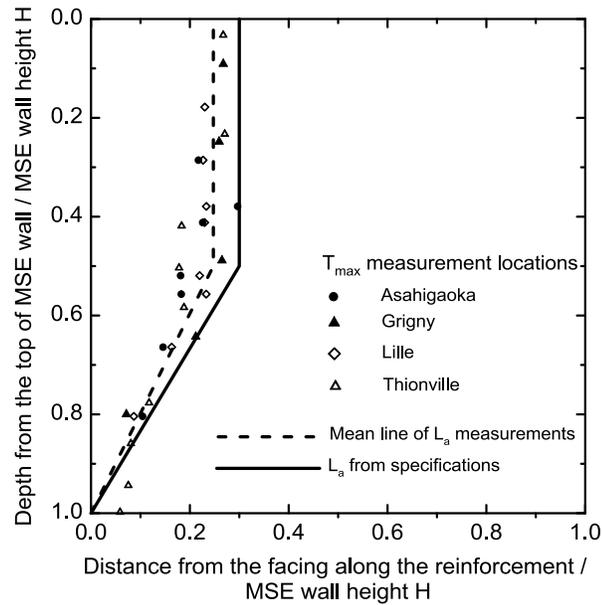
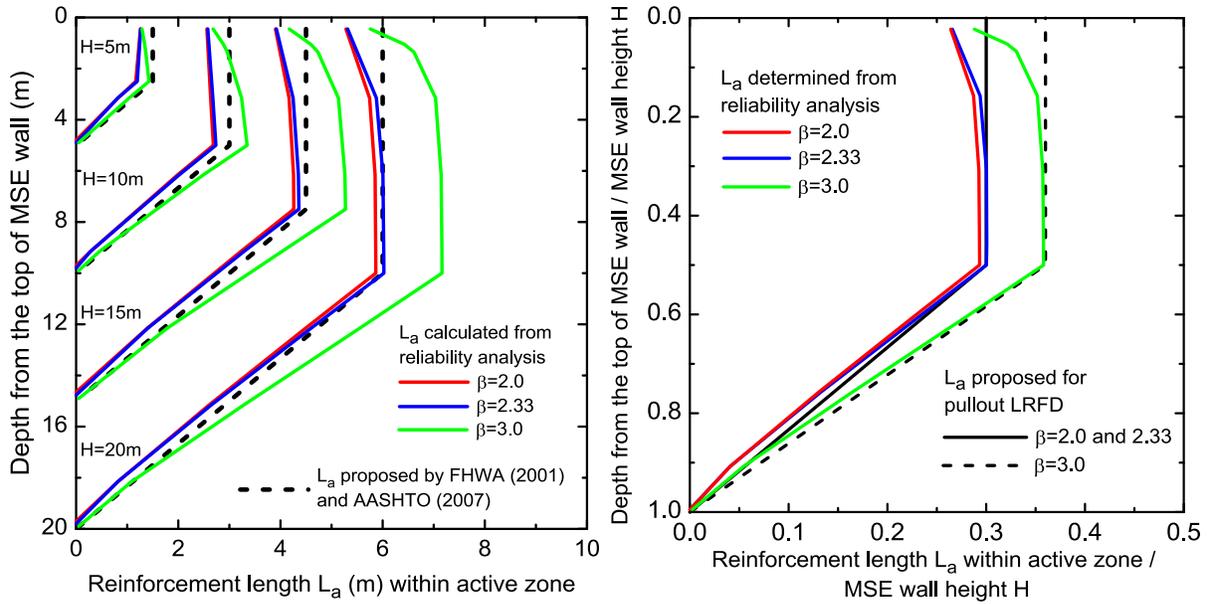


Figure 1. Maximum tensile force T_{\max} measurement locations, mean line of L_a measurements, and L_a proposed in the specifications for $\beta_T = 2.33$ (modified after Schlosser and Elias 1978).

We have assessed the uncertainty of the locus of the maximum tensile force using the data in Figure 1 excluding the two measurements of T_{\max} near the bottom of the MSE wall. Required L_a and L_e decrease as reinforcement depth increases but there is an attempt at design time to have total reinforcement lengths be the same to facilitate construction (Salgado 2008; FHWA 2001), so reinforcements lengths near the bottom of the wall have reinforcements longer than required. Consequently, excluding the two T_{\max} measurements near the bottom for the purposes of the present analysis is appropriate. From the regression and statistical analysis, the bias factor and COV of L_a are 0.825 and 0.160, respectively.

The reinforcement length L_a within the active zone is a function of MSE wall height H . For a given MSE wall height H , target reliability index β_T and reinforcement level, reliability analysis was conducted to calculate the most probable L_a by changing the total reinforcement

length until the calculated reliability index was equal to β_T . For different β_T values (2.0, 2.33, and 3.0) and different MSE wall heights H (5, 10, 15, and 20m), the worst-case L_a (the longest most probable L_a value) for each reinforcement level was calculated by varying the mean values of parameters (γ_{rf} , q_0 , and δ_{cv}) within their possible ranges. The resulting worst-case L_a with respect to depth from the top of an MSE wall for $\beta_T = 2.0, 2.33,$ and 3.0 is plotted in Figure 2(a). As shown in Figure 2(a), as the height of the MSE wall increases, the L_a determined from reliability analysis approaches the L_a proposed in the AASHTO specifications [Eq. (1)] for $\beta_T = 2.0$ and 2.33 and exceeds it for $\beta_T = 3.0$. For each β_T , when the vertical and horizontal locations corresponding to T_{max} are normalized by MSE wall height H , the L_a determined from reliability analysis for $H = 20\text{m}$ is the largest for the heights considered. For $\beta_T = 2.0, 2.33,$ and 3.0 , the worst-case L_a lines determined are plotted in Figure 2(b). As shown in Figure 2(b), the worst-case L_a values for $\beta_T = 2.0$ and 2.33 are shorter than the L_a proposed in the specifications, and the worst-case L_a values for $\beta_T = 3.0$ are shorter than 1.2 times the L_a proposed in the specifications. Therefore, in conservative designs, L_a can still be calculated using Eq. (1) for $\beta_T = 2.0$ and 2.33 ; for $\beta_T = 3.0$, L_a could be taken as 20% longer than specified in Eq. (1).



(a)

(b)

Figure 2. Length of reinforcement crossing the active zone: (a) worst-case L_a calculated from reliability analysis by varying the parameter values within their possible ranges for different MSE wall heights and (b) proposed L_a for target reliability index $\beta_T = 2.0, 2.33, \text{ and } 3.0$.

Revised Resistance Factors

Resistance factors were revised from those originally proposed because the uncertainties of parameters in the ultimate limit states and the target reliability indices for MSE wall internal stability were changed.

1. External Stability

For sliding and overturning, the revised resistance factors are plotted in Figure 3. The specific resistance factor values are summarized in Table 2.

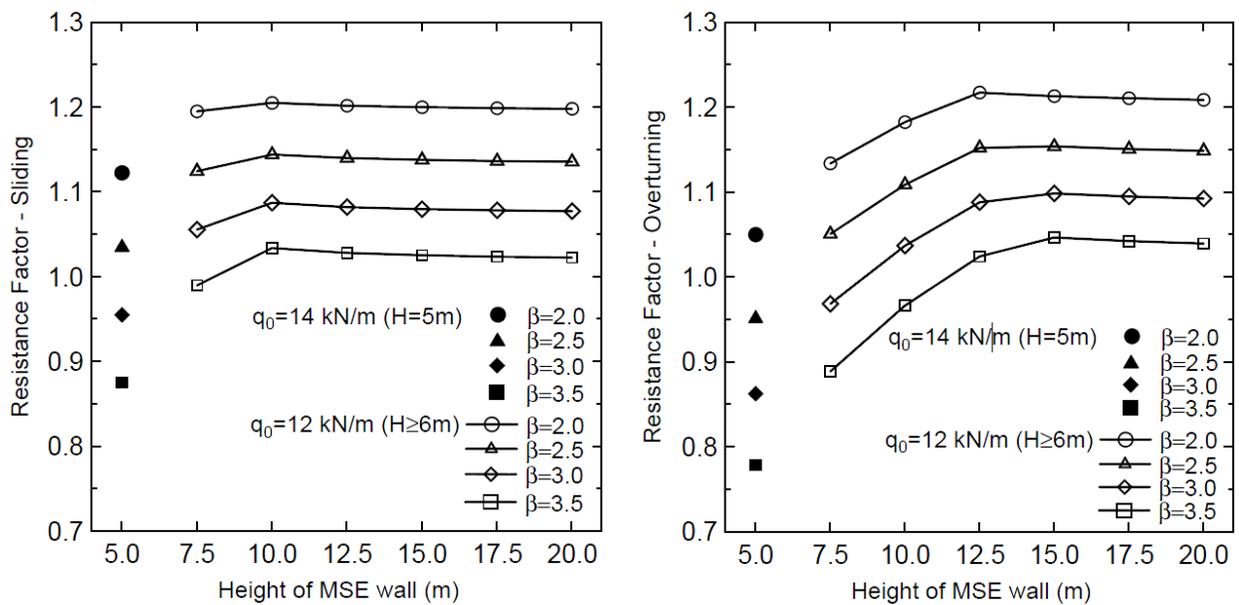


Figure 3. Resistance factors for sliding and overturning ultimate limit state versus MSE wall height.

Table 2. Resistance and load factors of sliding and overturning of MSE walls (Load factor for dead and live loads = 1.5 and 1.75)

MSE wall height H (m)	Sliding limit state				Overturning limit state			
	$\beta_T=2.0$	$\beta_T=2.5$	$\beta_T=3.0$	$\beta_T=3.5$	$\beta_T=2.0$	$\beta_T=2.5$	$\beta_T=3.0$	$\beta_T=3.5$
5	1.12	1.03	0.95	0.87	1.05	0.95	0.86	0.77
7.5	1.19	1.12	1.05	0.99	1.13	1.05	0.96	0.88
10	1.20	1.14	1.08	1.03	1.18	1.10	1.03	0.96
12.5	1.20	1.14	1.08	1.02	1.21	1.15	1.08	1.02
15	1.20	1.13	1.08	1.02	1.21	1.15	1.09	1.04
17.5	1.19	1.13	1.07	1.02	1.21	1.15	1.09	1.04
20	1.19	1.13	1.07	1.02	1.20	1.14	1.09	1.03

2. Internal Stability

The resistance factors for pullout ultimate limit state changed with reinforcement depth z measured from the top of the MSE wall are plotted in Figure 4. The resistance factors for structural ultimate limit state do not change significantly with reinforcement depth or its spacing.

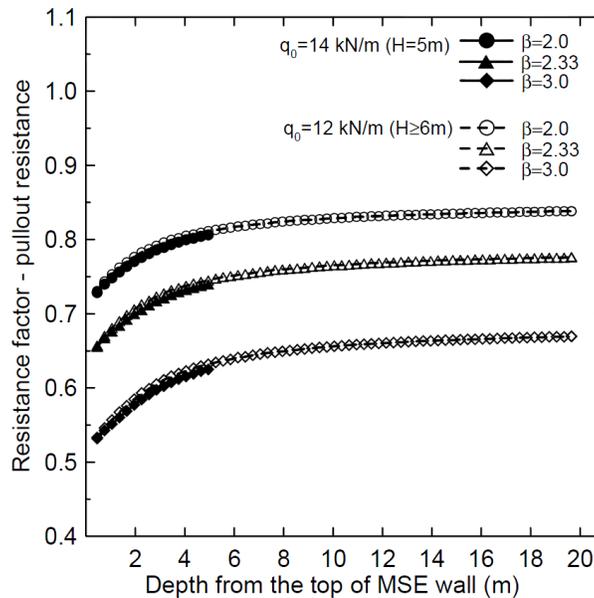


Figure 4. Resistance factors for pullout ultimate limit state versus reinforcement depth z measured from top of MSE wall.

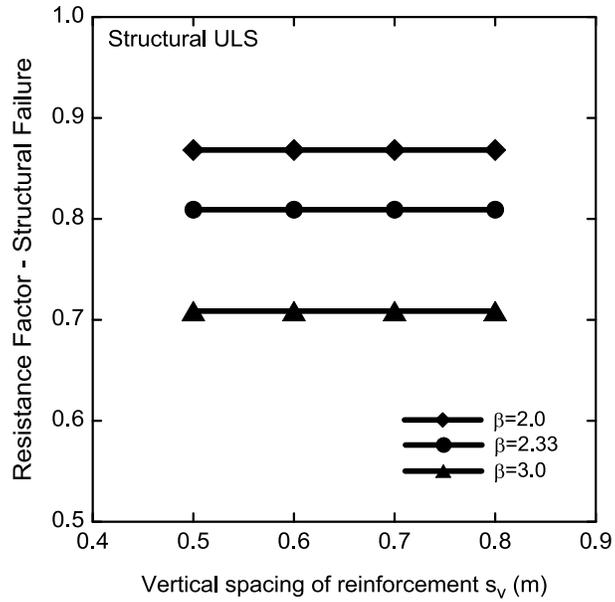


Figure 5. Resistance factors for structural ultimate limit state versus reinforcement depth z measured from top of MSE wall.

Table 3. Resistance and load factors of pullout and structural failure for steel-strip reinforcements

Factors	Ultimate limit state	Method proposed in this paper		
		$\beta_T = 2.0$	$\beta_T = 2.33$	$\beta_T = 3.0$
Resistance factor	Pullout	0.73 – 0.84	0.65 – 0.77	0.53 – 0.67
	Structural failure	0.7	0.8	0.86
Load factor for dead loads	Pullout/Structural failure	1.5		
Load factor for live loads	Pullout/Structural failure	1.75		

Conclusions

LRFD methods for checking external (sliding and overturning) and internal (pullout and structural failure of steel-strip reinforcement) stabilities of MSE walls were revised based on the improved revisions made during the implementation project. The major contributions are (1) revision of uncertainties of parameters in the ultimate limit state equations, (2) reconsideration of target reliability indices for internal stability checks, and (3) recalculations of resistance factors reflecting the changes of (1) and (2). We suggested resistance factors that are compatible with the load factors of the AASHTO LRFD bridge design specifications (2007). These resistance factors are worst-case (lowest) resistance factor values obtained from varying the parameters within their possible or likely ranges for different MSE wall heights and different target reliability indices.

A practical way to think of the reliability index is to consider the probability of attainment of the corresponding limit state to which it refers. For example, in internal stability limit states, a reliability index of 3 would imply roughly one failure in a thousand reinforcement elements. Due to the redundancy of soil reinforcement in an MSE wall, using 3 for the reliability index would clearly be a conservative design. It is important for INDOT engineers to start thinking in those terms as they perform LRFD designs. The understanding and experience that will follow, combined with high-quality research, will eventually lead to an optimal method of design that best balances safety and economy.

References

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