Proc. of the 9th International Symposium on Geotechnical Safety and Risk (ISGSR)
Edited by Zhongqiang Liu, Jian Dai and Kate Robinson
Published by Research Publishing, Singapore.
doi: 10.3850/GRF-25280825_isgsr-254-P145-cd

RECENT LRFD CALIBRATION FOR INTERNAL STABILITY LIMIT STATES FOR MSE WALL STRUCTURES

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The next edition of the Canadian Highway Bridge Design Code (CHBDC) to appear in 2025 includes guidance on load and resistance factor design (LRFD) for internal stability limit states for mechanically stabilized earth (MSE) walls constructed with extensible (i.e., geogrid and PET strap) and relatively inextensible (i.e., steel strip and steel grid) reinforcement layers. The simplified, stiffness and coherent gravity methods appear in the main code and in the commentary to calculate the tensile loads in the reinforcement layers under operational conditions. This paper describes how the resistance factors for tensile rupture, pullout and soil failure (stiffness method) were computed for each of the load methods and reinforcement-type combinations. For steel reinforcement cases, potential loss of section due to corrosion is included in the calculations for resistance factors. Calibration incorporates the concept of "level of understanding" that appears in the CHBDC to reward designers with greater resistance factors for projects with greater quality and amount of input data, and greater confidence and experience in the design approach adopted for the project. The computations include the load and resistance bias statistics for each limit state, where bias is the ratio of measured value to predicted model value using an analytical equation for load or resistance, or a code-specified value. Updated resistance factors were also computed for possible inclusion in the next revision of the AASHTO LRFD Bridge Design Specifications in the US. Resistance factor calculation outcomes for polyester (PET) strap MSE walls are provided to demonstrate the general approach using a convenient closed-form solution.

Keywords: mechanically stabilized earth (MSE) walls, internal stability limit states, LRFD calibration, Canadian Highway Bridge Design Code, AASHTO LRFD Bridge Design Specifications.

1. Introduction

Load and resistance factor design (LRFD) is specified in US and Canadian foundation engineering practice (AASHTO 2020; Canadian Highway Bridge Design Code (CHBDC) CSA 2025). This approach extends to the design of mechanically stabilized earth (MSE) walls. For simple soil-structure interaction problems with a single load term,the following limit state design equation must be satisfied:

$$\text{Æ}R_n - {}^{3}{}_{Q}Q_n \geq 0 \quad (1)$$

Here, φ = resistance factor for nominal resistance R_n, and γ_Q = load factor applied to the nominal load Q_n. LRFD calibration involves finding suitable values of the resistance factor and the load factor such that when the above limit state is just satisfied, an acceptable margin of safety in probabilistic terms is assured. Example internal stability limit states are illustrated in Fig. 1 for the case of geosynthetic MSE walls constructed with relatively extensible (polymeric) reinforcing layers. For steel (inextensible) MSE walls, the partition between the active and passive zones is bi-linear. In the US and Canadian codes, the soil self-weight load factor is prescriptive (i.e., γ_Q = 1.35 and 1.25, respectively).

The following equivalent performance function is used to find φ corresponding to the condition that Eq. 1 is just satisfied to a target reliability index (β)(Bathurst et al. 2017, 2019, 2021, 2025):

$$g = \frac{{}^{3}{}_{Q}\,\text{»}_R}{\text{Æ}\text{»}_Q} - 1 \qquad (2)$$

Parameters λ_R and λ_Q are resistance and load method bias values, respectively, and are used to transform nominal values to measured (observed) resistance (R_m) and measured (observed) load (Q_m) values. Hence, resistance method bias is $\lambda_R = R_m/R_n$ and load method bias is $\lambda_Q = Q_m/Q_n$. The ratio $\gamma_Q/\text{Æ}$can be interpreted as the minimum target nominal factor of safety that is familiar from allowable stress design (ASD) (i.e., $F_n = R_n/Q_n =$

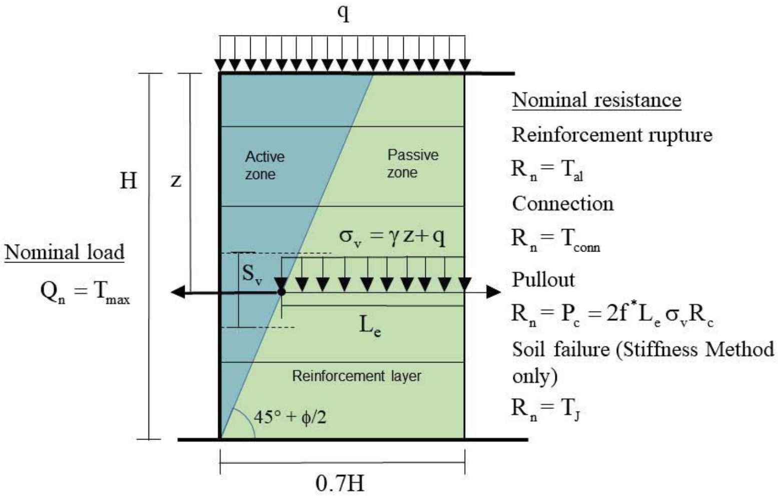

Fig. 1. Example limit states for geosynthetic MSE walls.

γ_Q/Æ). The bias values and nominal values in Eq. 2 are assumed to be random variables. With the exception of the tensile strength bias value $\lambda_R$for steel grid and steel strip reinforcement, all variables are usefully approximated by lognormal distributions. Steel reinforcing elements are described by truncated lognormal strength bias distributions which vary depending on the magnitude of anticipated loss of steel section due to corrosion (e.g., Bathurst et al. 2021). For a trial value ofφ, Monte Carlo simulation can be used to compute the probability $P(g< 0)$. A trial value of $\varphi$to a resolution of ±0.05 that gives $P(g< 0) = 0.01$ (or $\beta = 2.33$) is selected.The relatively low margin of safety in probabilistic terms may appear to be very low. However, this value is reasonable given that internally, MSE walls are highly strength-redundant systems. For example, if one layer does not satisfy an internal stability limit state, neighboring reinforcement layers can compensate.

Assuming that all variables in Eq.2 are lognormally distributed,then (Bathurst et al. 2017):

$$\text{Æ}= {}^{3}{}_{Q}\frac{(\mu_{\text{»}R}/\mu_{\text{»}Q})\sqrt{(1+COV_{Qn}^{2})(1+COV_{\text{»}Q}^{2})/(1+COV_{Rn}^{2})(1+COV_{\text{»}R}^{2})}}{exp\left\{{}^{2}\sqrt{ln\left[\frac{(1+COV_{Qn}^{2})(1+COV_{\text{»}Q}^{2})(1+COV_{Rn}^{2})(1+COV_{\text{»}R}^{2})(1+\text{Á}_{R}COV_{Rn}COV_{\text{»}R})^{2}(1+\text{Á}_{Q}COV_{Qn}COV_{\text{»}Q})^{2}}{(1+\text{Á}_{n}COV_{Rn}COV_{Qn})^{2}}\right]}\right\}} \tag{3}$$

Here, $\mu_{Rn}$and COV_{Rn}, μ_{Qn} and COV_{Qn}, $\mu_{\lambda R}$ and$COV_{\lambda R}$, and $\mu_{\lambda Q}$ and$COV_{\lambda Q}$ are mean and COV values for R_n, Q_n, λ_R and λ_Q, respectively. Parameters ρ_R and ρ_Q are *bias dependencies* which are the Pearson correlation coefficients between R_n and λ_R and between Q_n and λ_Q, respectively. When ρ_R and ρ_Q are non-zero, the *on average* accuracies ($\mu_{\lambda R}$ and $\mu_{\lambda Q}$) of the underlying load and resistance models that appear in the design equation will vary with the magnitude of the nominal values (R_n and Q_n). Parameter ρ_n is the cross-correlation coefficient (*nominal correlation*) between R_n and Q_n and is non-zero when equations for R_n and Q_n share one or more input parameters that are random variables. If model error is ignored (i.e., bias values are removed) and nominal correlation is not present, then Eq. 3is greatly simplified and has been reported by others (e.g., Barker et al. 1991).Similarly, if all uncertainty resides in the model accuracy and there are no bias dependencies, then Eq. 3 simplifies to an expression that also appears in the literature (e.g., Allen et al. 2005). The possibility of no model bias is unlikely in soil-structure interaction models in geotechnical engineering including MSE walls. The novelty of Eq. 3 is that it explicitly includes both sources of uncertainty (i.e., project-independent model accuracy and uncertainty in the selection of nominal values at time of designwhich are projectspecific),and possible dependencies between model accuracy and nominal values, and between nominal values.

2. Bias values

Bias values have been collected by the authors and co-workers from measured loads in instrumented MSE walls under operational conditions, and from laboratory tensile strength and pullout box testing. For example, pullout model bias values were computed by dividing each measured ultimate pullout capacity from a pullout box by the predicted value using a particular pullout capacity model and the same conditions. From these data, the mean ($\mu_{\lambda R}$) and $COV_{\lambda R}$ for that particular pullout model can be computed and used in Eq. 3. Conventional linear regression between resistance bias and predicted nominal values is used to calculate the bias dependency, if any.

A compendium of bias statistics for load and resistance models used for internal stability design of MSE walls can be found in Bathurst and Miyata (2024).

3. Nominal values

As a first approximation, the statistical characteristics for the nominal values R_n and $Q_n$can be computed knowing the statistical values for each non-deterministic parameter in each analytical equation used to compute R_n and Q_n. However, there are other contributions to uncertainty in the estimate of the nominal values at time of design. When calibrating internal limit states for MSE walls for Canadian LRFD practice, the concept of *level of understanding* is used.A typical level of understanding represents expected typical good project knowledge, experience and design practice. If the quality and quantity of project data, experience with the design of MSE wall structures of similar type is greater, and the structure is typical for these systems, then the designer is assumed to have a high level of understanding. If these conditions arereversed, and the designer has less project information and experience, etc, than typical, then the designer is judged to have a low level of understanding.LRFD foundation practice in Canada rewards designers with *larger* resistance factors for high level of understanding and *smaller* resistance factorsfor low level of understanding with respect to the resistance factors for typical level of understanding (Fenton et al. 2016). Bathurst et al. (2017) assigned the best estimate of each nominal value to the mean of nominal values ($\mu_{Rn} and \mu_{Qn}$) in Eq. 3, and values of COV_{Rn} and COV_{Qn} = 0.1, 0.2 and 0.3 to high, typical and low levels of understanding, respectively. For the tensile strength limit state for polymeric reinforcement materials, the nominal strength value R_n is assumed to be deterministic and thus COV_{Rn} = 0. The uncertainty in this value is captured by the COV of the strength bias values where the bias is the measured strength from a single test divided by the mean of tensile strength from multiple tests carried out on specimens taken from the same sample in accordance with ASTM testing protocols.

4. Example results

Table 1 summarizes resistance factor calculation outcomes for polyester (PET) strap MSE walls using Eq. 3. The load model is the stiffness method (Allen and Bathurst 2015, 2018)and the resistance model for the tensile strength has been described in the previous section. The pullout model is based on a single strap configuration and has the form of the equation shown in Fig. 1. The soil failure limit state is unique to the stiffness method and is required to ensure that the reinforced soil zone remains at a serviceability limit state for which the original model was calibrated(Bathurst and Allen 2023). The lower load factors for the soil failure limit are consistent with the assumption of a serviceability limit state while tensile strength and pullout limit states are assumed as ultimate limit states.There are two soil failure bias data cases that can be used when computing the resistance factor. If project-specific product testing is available, a higher resistance factor is computed compared to the case where a less accurate estimate of reinforcement stiffness is available using an approximation; thus, the designer is rewarded when higher quality test data are used. The concept of level of understanding is not found in US LRFD practice and thusCOV_{Qn} = 0 in this table for AASHTO (2020). Computed resistance factors using Eq. 3 are shown in parentheses. Recommended values in both codes are reported to±0.05 accuracy.It can be seen that computed φvalues do not decrease smoothly with increasing COV_{Qn} as would be expected from Eq. 3; this is because there isa negative correlation (dependency) between nominal load and load bias values of ρ_Q = –0.30.

The strategy to select recommended resistance factors is as follows:

1. Resistance factor φ d 1.
2. Resistance factor as close as possible to current specified value unless there is adequate justification based on the available data to not do so.
3. Value rounded to 0.05 consistent with code calibration practice in North America (Allen et al. 2005).
4. For Canadian practice, the φ value at COV_{Qn} = 0.2 (typical level of understanding) was selected first based on the above rules and the calculated values in the previous section. The values at COV_{Qn} = 0.1 (high level of understanding) and COV_{Qn} = 0.3 (low level of understanding) were adjusted upward and downward from this value by 0.05, respectively. This was done to provide the same incremental differences in resistance factors at different levels of understanding that appear in the Canadian LRFD code. Recall that the intent of Canadian LRFD code practice is to encourage designers to improve project level of understanding at time of design by rewarding them with higher resistance factors.
5. Values of resistance factor using load factor γ_Q = 1.35 should be greater than the value computed using load factor γ_Q = 1.25 for typical level of understanding. This ensures that US and Canadian codes will give the same or similar target reliability index value when a limit state is just satisfied (i.e., ratio of the resistance factors in both codes using Eq. 3 is equal to the ratio of load factors).

Table 1. Recommended and computed (in parentheses) resistance factors (φ) for different limit states in AASHTO (2020) and CSA (2025) codes with single PET strap arrangement (data from Bathurst et al. 2025).

Limit state	Cohesive-frictional soils $\phi > 0$ c e 0			
	AASHTO	CSA[a]		
	Load factor $\gamma_Q = 1.35$	Load factor $\gamma_Q = 1.25$		
	$COV_{Qn} = 0$	$COV_{Qn} =$		
		0.1	0.2	0.3
		Level of understanding		
		High	Typical	Low
Tensile (ultimate) strength	0.70 (0.63)	0.70 (0.61)	0.65 (0.61)	0.60 (0.59)
Pullout (single strap)	0.85 (0.83)	0.85 (0.85)	0.80 (0.86)	0.75 (0.79)
Soil failure	Load factor $\gamma_Q = 1.2$	Load factor $\gamma_Q = 1.1$[b]		
	$COV_{Qn} = 0$	$COV_{Qn} =$		
		0.1	0.2	0.3
		Level of understanding		
		High	Typical	Low
Based on product testing	0.95 (0.92)	0.95 (0.86)	0.90 (0.87)	0.85 (0.86)
Based on product type	0.90 (0.97)	0.90 (0.82)	0.85 (0.82)	0.80 (0.82)

Notes: [a] PET strap reinforcement and stiffness method appear in next edition of CSA (2025) code. [b]scaled to 1.2×1.25/1.35 ~ 1.1. ϕ capped at 40 degrees. Calculations using Minimum Average Roll Value (MARV) tensile strength. $COV_{Rn} = 0$.

5. Conclusions

This paper provides a cursory overview of the LRFD calibration methodology that has been developed by the authors to select resistance factors for the internal stability limit state equations for future editions of the US and Canadian LRFD codes for internal stability limit states for MSE walls. The case of PET strap MSE walls using the stiffness method to compute reinforcement loads is used here to demonstrate example results, but the approach is general for other reinforcement types (e.g., geogrid, steel strip and steelgrid) and different load and resistance models. Readers are invited to read the related papers that appear in the reference list below.

References

Allen, T.M. and R.J. Bathurst (2015). An improved simplified method for prediction of loads in reinforced soil walls. *ASCE Journal of Geotechnical and Geoenvironmental Engineering 141(11)*, 04015049.

Allen, T.M. and R.J. Bathurst (2018). Application of the Simplified Stiffness Method to design of reinforced soil walls. *ASCE Journal of Geotechnical and Geoenvironmental Engineering 144(5)*, 04018024.

AASHTO (2020). *LRFD Bridge Design Specifications, ninth ed.* American Association of State Highway and Transportation Officials (AASHTO).

Allen, T.M., A.S. Nowak and R.J. Bathurst (2005). *Calibration to Determine Load and Resistance Factors for Geotechnical and Structural Design*. Circular E-C079. Transportation Res Board, National Research Council, Washington, D.C., USA.

Barker, R.M., J.M. Duncan, K.B. Rojiani, P.S.K. Ooi, C.K. Tan and S.G. Kim (1991). Manuals for the design of bridge foundations: Shallow foundations, driven piles, retaining walls and abutments, drilled shafts, estimating tolerable movements, and load factor design specifications and commentary. *National Cooperative Highway Research Program. Report 343*. Transportation Research Board, National Research Council, Washington, D.C., USA.

Bathurst, R.J. and T.M. Allen (2023). LRFD calibration for soil failure limit state using the Stiffness Method. *Canadian Geotechnical Journal 60(7)*, 1006-1014.

Bathurst, R.J., T.M. Allen, P. Lin and N. Bozorgzadeh (2019). LRFD calibration of internal limit states for geogrid MSE walls. *ASCE Journal of Geotechnical and Geoenvironmental Engineering 145(11)*, 04019087.

Bathurst, R.J., N. Bozorgzadeh and T.M. Allen (2021). LRFD calibration of internal limit states for MSE walls using steel strip reinforcement. *ASCE Journal of Geotechnical and Geoenvironmental Engineering 147(12)*, 04021156.

Bathurst, R.J., S. Javankhoshdel and T.M. Allen (2017). LRFD calibration of simple soil-structure limit states considering method bias and design parameter variability. *ASCE Journal of Geotechnical and Geoenvironmental Engineering 143(9)*, 04017053-1-14.

Bathurst, R.J. and Y. Miyata (2024). Mechanically stabilized earth (MSE) walls. Chapter 14. In *Databases for Data-Centric Geotechnics*. Edited by C. Tang and K.K. Phoon. Taylor & Francis Group, LLC, 17 p.

Bathurst, R.J., Y. Miyata and T.M. Allen (2025). LRFD calibration of internal limit states for polymer (PET) strap MSE walls. *ASCE Journal of Geotechnical and Geoenvironmental Engineering 151(1)*, 04024140.

CSA (2025). *Canadian Highway Bridge Design Code. CAN/CSA-S6-25*. Canadian Standards Association (CSA), (in press).

Fenton, G.A., F. Naghibi, D. Dundas, R.J. Bathurst and D.V. Griffiths (2016). Reliability-based geotechnical design in the 2014 Canadian Highway Bridge Design Code. *Canadian Geotechnical Journal 53(2)*, 236-251.