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Influence of Model Accuracy on Load and Resistance Factor Calibration of Multi-anchor Walls

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ABSTRACT: Multi-anchor walls (MAWs) are now a well-established earth retaining wall technology in Japan. This paper examines the accuracy of MAW design models on load and resistance factor design calibration. Measured anchor loads and anchor plate capacities from full-scale tests reported in the literature are compared to predicted values using the analytical models recommended in Japan by PWRC. Modified load and resistance models are proposed that preserve the general form of the PWRC equations but introduce correction factors to improve accuracy. The correction factors are empirically-based and are selected by back-fitting to measured loads to achieve a load bias mean equal to one and a low coefficient of variation (COV) of bias values. In developing the pullout capacity model, a large number of small-scale anchor capacity tests carried out in pullout boxes were also used to guide the selection of back-fitted parameters. This research work represents the first attempt at rigorous reliability-based load and resistance factor calibration for MAW systems.

Keywords: reinforced soil walls, multi-anchor walls, load and resistance factor design, limit states design, load and resistance factors, reliability analysis

1 INTRODUCTION

Reinforced soil wall techniques are now well established and offer economical solutions to geotechnical soil retaining wall problems. Reinforced soil walls can be broadly classified into metallic, geosynthetic and multi-anchor categories. Since ISO 2394 was introduced, there has been increased interest in the development of rigorous reliability-based design approaches for reinforced soil wall systems in Japan, Europe and the USA.

Multi-anchor walls (MAWs) are constructed with steel plate anchors bolted to round bar sections that are attached at the opposite end to the wall facing. Fig. 1 shows details of the key components in the Japanese MAW system. The reinforced concrete panels are 1.5 m wide, 1 m high and 180 mm thick. Pinned connections at the back of the facing panels are used to attach the anchor rods on 0.75 m centers in the running length of the wall face. Each rod is attached to a plate using a threaded end, washer and nut. The standard steel anchor plates are 300 mm by 300 mm.

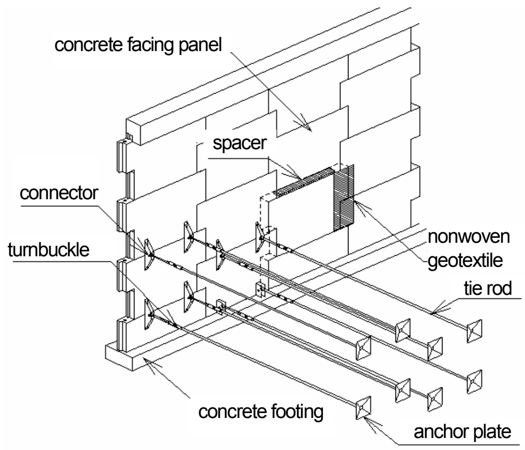

Figure 1. Multi-anchor walls

The current approach for external and internal stability design of reinforced soil wall systems in Japan is based on a classical factor of safety approach (PWRC 2002). Recently, the Public Works Research Center (PWRC) has expressed interest to move towards a more rigorous reliability-based design approach.

An important step to develop a reliability-based design method is calibration of load and resistance factors. A methodology to undertake calibration that explicitly includes underlying model error and variability in model input parameters has been described in the work by Allen et al. (2005) and Bathurst et al. (2008a, 2011). This approach requires measured resistance and load values from a database of laboratory and full-scale tests reported in the literature, predicted values using design models for resistance and load side of limit state equations and, statistical analysis of the bias values computed from the ratio of measured to predicted values. The bias value statistics are used to calibrate load and resistance factors to be used in current PWRC models and new modified design models. The new models preserve the general form of the PWRC equations but introduce correction factors to improve accuracy. The relative accuracy of the models investigated in this paper can be quantified by comparing the magnitudes of the mean and coefficient of variation (COV) of the bias values. This research work represents the first attempt at rigorous reliability-based load and resistance factor calibration for MAW systems.

2 GENERAL APPROACH

The general approach used here to perform load and resistance factor calibration for the pullout ultimate limit state for MAW anchors follows that reported by Allen et al. (2005) and Bathurst et al. (2008a, 2011). They used a database of steel grid soil reinforced walls to demonstrate calculation steps for simple limit states.

The pullout limit state functions in this paper have the general form:

$$g = R_m - Q_m \geq 0 \tag{1}$$

where R_m = measured resistance (pullout capacity) and Q_m = measured (axial) load under operational conditions.

Bias is defined as the ratio of measured to predicted (calculated) value. In limit states design terminology the calculated value is often called the nominal value. Hence, a measured value can be expressed as the product of bias and nominal value; specifically:

$$R_m = X_R R_n \tag{2}$$

$$Q_m = X_Q Q_n \tag{3}$$

where X_R = resistance bias, X_Q = load bias, R_n = nominal resistance, and Q_n = nominal load. In limit states design the limit state function is expressed in terms of the nominal values of the resistance and load terms which are computed using deterministic equations; hence for design the limit state function can be expressed as:

$$g = X_R R_n - X_Q Q_n \geq 0 \tag{4}$$

The failure of a reinforcing anchor occurs when $g < 0$ and therefore the probability of failure must be related to actual (i.e. measured) load and resistance values. Bias statistics allow predicted values to be adjusted to measured values so that probability of failure is computed for the considered limit state conditions. If the equations for load and resistance give values that are equal to measured values then, $X_R = X_Q = 1$. This is unlikely in engineering practice since there are always errors in equation accuracy due to the combined effect of model error and other sources of variation in input parameter values (e.g. random variation in input parameter values, spatial variation in input values, quality of data and, consistency in interpretation of data when data are gathered from multiple sources). In this paper, the source of model accuracy is all of these contributions to error in load and resistance predictions.

In limit state design practice for the case of one resistance term and one load term, the limit states design equation can be expressed as:

$$\varphi R_n - \gamma_Q Q_n \geq 0 \tag{5}$$

Here, γ_Q = load factor and φ = resistance factor. Re-arrangement of Eq. (4) leads to:

$$g = (\gamma_Q/\varphi)\, X_R - X_Q \geq 0 \tag{6}$$

If load and resistance bias values are log-normally distributed and the limit state function is linear, the reliability index β can be calculated as:

$$\beta = \frac{\ln\left[(\gamma_Q/\varphi)(\mu_R/\mu_Q)\sqrt{\left(1+COV_Q^2\right)/\left(1+COV_R^2\right)}\right]}{\sqrt{\ln\left[\left(1+COV_Q^2\right)\left(1+COV_R^2\right)\right]}} \tag{7}$$

where μ_R and COV_R = mean and coefficient of variation of resistance bias values, and μ_Q and COV_Q = mean and coefficient of variation of load bias values. For a given load factor and set of bias mean and COV values, a resistance factor value can be found to satisfy a target reliability index value using Eq. (7).

3 DATABASE OF PHYSICAL TEST RESULTS

Anchor loads recorded from eight full-scale MAW wall sections were collected by the writers (Table 1). All of the walls performed well with facing deformations falling within serviceability criteria recommended by PWRC (2002). Details of these walls can be found in the paper by Miyata et al. (2009).

Anchor capacity data were taken from 28 full-scale in-situ anchor load tests (Table 2). Additional data from reduced-scale laboratory anchor load tests (Table 3) were also used to assist in the formulation of a new anchor pullout capacity design equation.

Table 1. Summary of multi-anchor wall case studies for load models.

Designation	Wall height, H (m)	Soil unit weight, γ (kN/m^3)	Peak friction angle, ϕ_{tx} (deg.)	Cohesion, c (kPa)	Fines content, F (%)	Rod length, L (m)	Reference
MAW-1	6.0	16.0	36	0	6	4.0	PWRC (1995)
MAW-2	6.0	15.4	30	2	19		
MAW-3	6.0	15.3	11	4	42		
MAW-4	4.0	15.0	38	2	8	4.0	
MAW-5	4.0	15.7				2.5	
MAW-6a	3.0	15.0	33	0	7	3.5	Aoyama et al. (2000), Futaki et al. (2000)
MAW-6b	4.0						
MAW-7	6.0	18.0	35	0	0.2	12.8	Kitamura et al. (2000)

Table 2. Summary of MAW full-scale in-situ anchor load tests for pullout (resistance) models.

No.	Soil unit weight, γ (kN/m^3)	Peak friction angle, ϕ_{tx} (deg.)	Cohesion, c (kPa)	Fines content, F (%)	Rod length, L (m)	Plate size, B (m)	Confining stress, σ_v (kPa)	Reference
1	16.0	36	0	6	4.0	0.3	32 – 80	PWRC (1995), Kondo et al. (1995), Nakamura et al. (1995)
2	15.4	30	2	19	4.0	0.3	31 – 77	
3	15.2	11	4	42	4.0	0.3	45 – 61	
4	15.0	34	0	8	4.0	0.3	15 – 45	PWRC (2002)
5	14.4	25	6	68	4.0	0.3	29 – 43	
6	18.9	5	16	52	2.0 – 5.0	0.4	19 – 57	Fukuoka et al. (1984b)
7	17.9	11	18	68	2.0, 4.0	0.3	36	
8	19.8	30	0	10	2.0, 4.0	0.3	40	

Table 3. Summary of MAW reduced-scale laboratory anchor load tests used to develop new pullout capacity model.

No.	Soil unit weight, γ (kN/m^3)	Peak friction angle, ϕ_{tx} (deg.)	Cohesion, c (kPa)	Fines content, F (%)	Rod length, L (m)	Plate size, B (m)	Confining stress σ_v (kPa)	Reference
1	13.8	38	0	n.a.	n.a.	0.051	0.4 – 3.2	Neely et al. (1973)
2	15.8	34	0	0	0.64	0.051	0.9 – 2.7	Das (1975)
3	14.8	31	0	0	0.61	0.032	0.4 – 3.2	Das et al. (1977)
	15.8	34	0	0				
	16.9	41	0	0				
4	14.0	35	0	3	0.3	0.021 – 0.035	2.4 – 12.0	Fukuoka et al. (1984a)
	13.1	22	12	87			9.8 – 39.2	
5	15.8	34	0	0	0.64	0.025 – 0.051	0.6 – 2.2	Hoshiya et al. (1984)
6	15.1	35	0	0	0.9 – 2.5	0.075 – 0.125	50 – 150	Takeoka et al. (2009), Watanabe et al. (2009)

4 CURRENT DESIGN MODELS

4.1 *Formulations*

In the current PWRC (2002) approach, the maximum anchor load (T_{max}) is computed in units of force as:

$$T_{max} = \left[K_a \sigma_v - 2c\sqrt{K_a}\right] S_v S_h \quad (8)$$

where K_a = coefficient of active earth pressure, σ_v = γz = maximum vertical (confining) stress acting at the elevation of the reinforcement (here γ is soil unit weight and z is the depth of anchor below the backfill surface), S_v = anchor vertical spacing, S_h = horizontal anchor spacing (S_h = 0.75 m for MAW anchors), and c = soil cohesion. K_a in Eq. (8) is computed as:

$$K_a = \frac{\cos^2\phi}{\cos\delta\left\{1+\sqrt{\dfrac{\sin(\phi+\delta)\sin\phi}{\cos\delta}}\right\}^2} \quad (9)$$

where $\delta = 2\phi/3$ is the interface friction angle between the soil and back of the panel facing.

In the current PWRC (2002) approach, the ultimate anchor plate capacity (resistance) (R_p) is computed in units of force as:

$$R_p = \left[cN_c + K_a\sigma_v(N_q - 1)\right]B^2 \quad (10)$$

where, N_c and N_q = non-dimensional capacity factors expressed as functions of soil peak friction angle (ϕ), c = cohesion, K_a = active earth pressure coefficient, σ_v = vertical (confining) stress at the anchor rod elevation and, B = height (width) of the square anchor plate. The non-dimensional capacity factors (solid lines) shown in Fig. 2 are calculated from a plasticity model proposed by Miura et al. (1994).

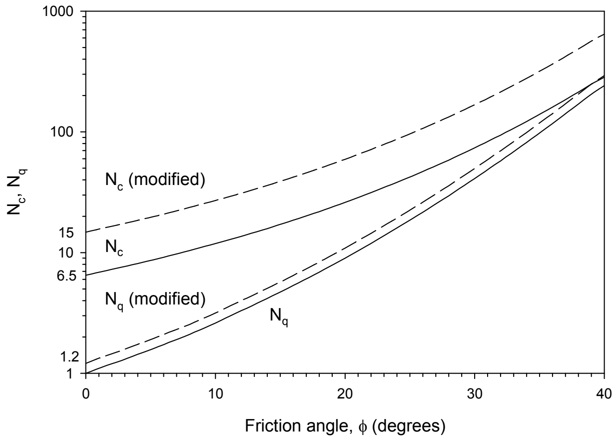

Figure 2. Non-dimensional anchor capacity factors.
Note: solid curves are for current model (Miura et al. 1994) and dashed curves are for modified model.

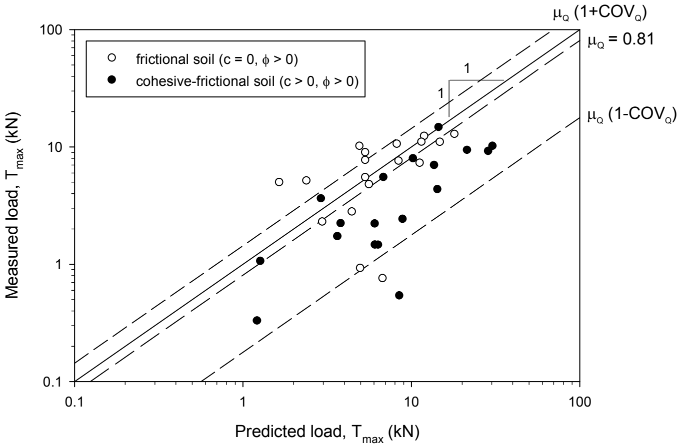

Figure 3. Measured versus predicted maximum anchor loads using current design model.

4.2 *Accuracy of current design models*

Measured versus predicted loads using the current load model are plotted in Fig. 3. The data are plotted using logarithmic axes to improve visibility for small load values. Values of μ_Q and COV_Q for all data and data subsets are shown in Table 4. These numbers show that for granular soil backfill wall cases the prediction of maximum anchor loads is reasonably accurate on average. However, for cohesive-frictional soil wall cases the bias statistics are much poorer. On average, measured anchorage loads are about 50% of the predicted values. However, the low mean bias value and large bias COV value demonstrate that the current load model is very inaccurate and if these values are used in load and resistance factor calibration they result in unrealistic load and resistance factors. A more accurate load model is desirable to improve calibration outcomes.

Measured versus predicted anchor capacities using the current design model are plotted in Fig. 4. Again, the data are plotted using logarithmic axes to improve visibility for small load values. The quantities μ_R and COV_R are the mean and coefficient of variation (COV) of anchor capacity bias values for all data points in each data set. Bias statistics are summarized in Table 5. These bias statistics show that the accuracy of the current anchor capacity model also depends on soil type. This dependency is smaller than that for the load model. However, improvement of the pullout capacity (resistance) model can be expected to lead to better bias statistics and therefore load and resistance factors that are closer to one.

5 MODIFICATION OF DESIGN MODELS

5.1 *Modification of load model*

A modified design equation to predict the maximum load in an anchor at end of construction has been proposed by Miyata et al. (2009) which can be written as:

$$T_{max} = \bar{\sigma} D_{tmax} \alpha \Phi_c S_v S_h \quad (11)$$

where $\bar{\sigma}$ = average active earth pressure computed as:

$$\bar{\sigma} = \frac{1}{H}\int_0^H K_a \gamma z \, dz = \frac{1}{2} K_a \gamma H \quad (12)$$

The other terms not defined earlier are D_{tmax} = load distribution factor, H = the height of the wall, and α = empirical factor applied to Φ_c. The latter is called the soil cohesion factor which reduces the anchor load due to the cohesive component of soil strength. The cohesion factor is computed as:

$$\Phi_c = 1 - \lambda \frac{c}{\gamma H} \quad (13)$$

These equations have been inspired by the structure of similar expressions to estimate loads in geosynthetic reinforced soil walls proposed by Miyata and Bathurst (2007) and Bathurst et al. (2008b).

Parameters α and λ have been estimated by back fitting to measured loads in the full-scale walls summarized in Table 1 as explained below. D_{tmax} is the ratio of measured T_{max} normalized with T_{mxmx} = maximum anchor load in the wall and is plotted against depth z normalized with H in Fig. 5. For design, D_{tmax} is taken as the dashed line shown in this figure. This is different from the generally monotonically increasing load distribution for anchor loads using the current PWRC design method (Eq. 8).

Both α and λ are estimated using an optimization technique with the objective function taken as the mean of the load bias value equal to one where load bias = T_{max} (measured) / T_{max} (predicted) = X_Q. This analysis gives α = 1.21 for frictional backfill soils, α = 1.02 for cohesive-frictional soils and λ = 15.2. A practical consequence of Eq. (13) with λ = 15.2 is that walls with $c/\gamma H \geq 0.06$ will not generate any anchor loads. However, the designer must decide if the cohesive soil strength component is available for the life of the structure.

Table 4. Summary of statistics for ratio (bias) of measured to predicted reinforcement loads using current design model.

	All	Granular soil backfill (c=0, ϕ>0)	Cohesive-frictional soil backfill (c>0, ϕ>0)
μ_Q	0.81	1.14	0.50
COV_Q (%)	79	65	62

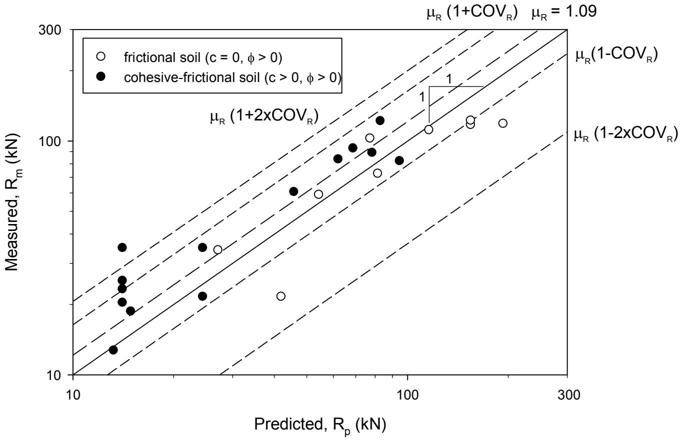

Figure 4. Measured versus predicted anchor pullout capacity using current design model.

Table 5. Summary of statistics for ratio (bias) of measured to predicted anchor pullout capacity using current design model.

	All	Granular soil backfill (c=0, ϕ>0)	Cohesive-frictional soil backfill (c>0, ϕ>0)
μ_R	1.21	0.96	1.39
COV_R (%)	35	31	30

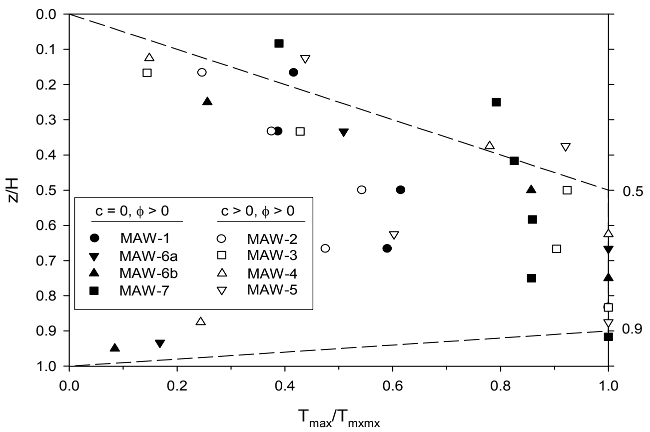

Figure 5. Distribution of D_{tmax} = ratio of maximum anchor load (T_{max}) to maximum anchor load in the wall (T_{mxmx}).

Measured versus predicted loads using the modified load model are plotted in Fig. 6. The visual impression is that there is better agreement between predicted and measured values since the data is more closely grouped around the 1:1 correspondence line compared to Fig. 3 using the current design approach. The summary of bias statistics using the new load model shown in Table 6 confirms that the proposed approach to compute reinforcement loads is better than the current Japanese model (PWRC 2002). The quantitative improvement is greatest for the cohesive-frictional backfill soil cases. In a related earlier work the writers have demonstrated that the new load model is also accurate for MAW systems subjected to transient flooding conditions (Miyata et al. 2009).

5.2 *Modification of anchor pullout capacity model*

A modified design equation to predict anchor plate capacity is proposed to improve the accuracy of the current ultimate anchor pullout capacity equation (Eq. 10) for MAW systems:

$$R_p = S_L \left[cN'_c + K_a S_d \sigma_v (N'_q - 1) \right] S_B B^2 \qquad (14)$$

Here, N'_c and N'_q = new bearing capacity factors modified from the original values (Fig. 2). The modified bearing capacity coefficients are computed using empirically determined constant correction factors m_c and m_q:

$$N'_c = m_c \, N_c \qquad (15)$$

$$N'_q = m_q \, N_q \qquad (16)$$

The other parameters are: S_L = correction factor for the influence of anchor rod length L; parameter S_d = correction factor for influence of anchor depth, and; parameter S_B = scale factor on anchor plate size. This is similar to the approach used to modify the classical bearing capacity equation for a strip footing to account for the effect of other footing shapes, load eccentricity and the like.

Correction factors were based on back-analysis and optimization using in-situ load test measurements for the case studies shown in Table 2. Measurements from the reduced-scale laboratory pullout tests are summarized in Table 3 and plotted against predicted values in Fig. 7. These data were used to examine the accuracy of the form of the correction terms but were not used quantitatively in the back-calculation process. The correction terms with constant coefficient terms ξ, ψ_1, ψ_2 and ζ are expressed as:

$$S_L = \xi \, L \qquad (17)$$

$$S_d = \left(\psi_1 \frac{z}{B} \right)^{\psi_2} \qquad (18)$$

$$S_B = \left(\frac{0.3}{B} \right)^{\zeta} \qquad (19)$$

The new constant coefficients are taken as or calculated as: m_c = 2.27, m_q = 1.21, ξ = 0.25 [unit =1/m], ψ_1 = 1/6, ψ_2 = 1.0 for $1/3 \le z/6B \le 1$ or $\psi_2 = -0.5$ for $z/6B > 1$ and ζ = 0.5.

The accuracy of the original ultimate anchor pullout capacity equation (Eq. 10) can be seen in Fig. 4 for all available data. The improvement in anchor capacity prediction for full-scale anchors is shown in Fig. 8 where measured versus predicted anchor capacities using the new modified anchor capacity model are plotted. The visual impression is that the data for both soil types is more closely distributed about the one-to-one correspondence line compared to the data in Fig. 4 (current model). Computed mean and

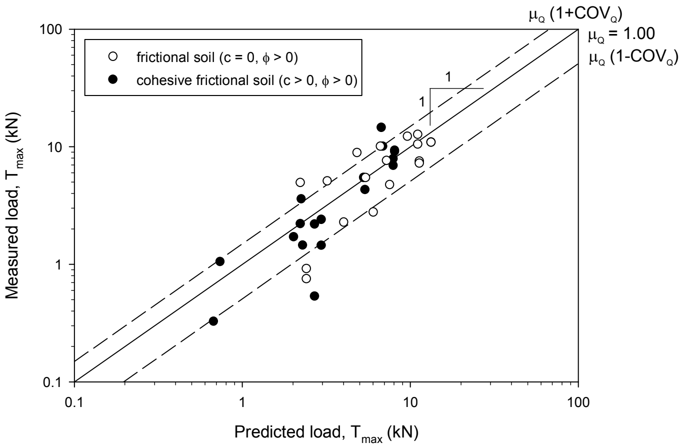

Figure 6. Measured versus predicted maximum anchor loads using modified design load model.

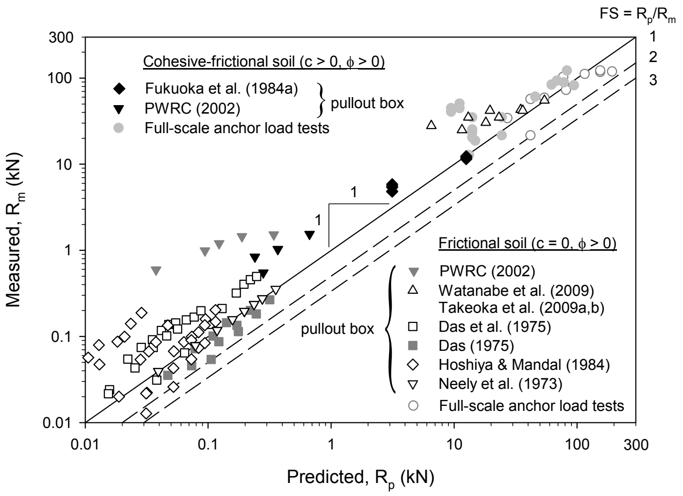

Figure 7. Measured versus predicted maximum anchor capacity using current design model and results of laboratory pullout tests and full-scale anchor pullout tests.

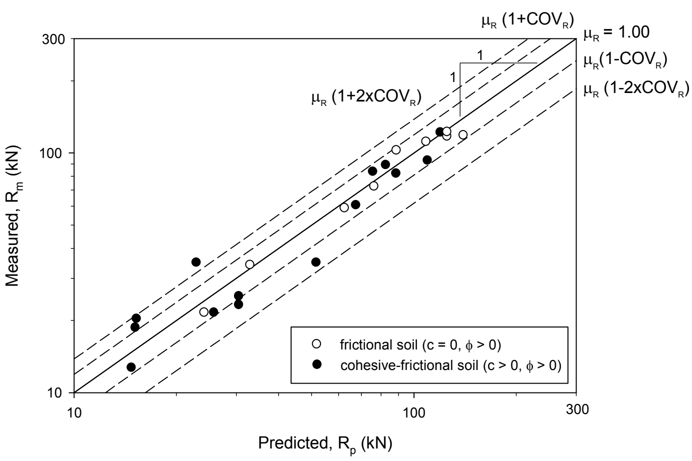

Figure 8. Measured versus predicted maximum anchor capacity using modified design model and full-scale anchor pullout tests.

spread in bias statistics are shown in Table 7. These numbers show that the proposed approach to compute anchor pullout capacity is quantitatively better than the current Japanese (PWRC 2002) for frictional backfill cases. The quantitative prediction accuracy is even greater for c-ϕ backfill soil cases using the new anchor capacity method.

Table 6. Summary of statistics for ratio (bias) of measured to predicted reinforcement loads using modified design model.

	All	Granular soil backfill ($c=0$, $\phi>0$)	Cohesive-frictional soil backfill ($c>0$, $\phi>0$)
μ_Q	1.00	1.00	1.00
COV_Q (%)	50	53	46

Table 7. Summary of statistics for ratio (bias) of measured to predicted anchor pullout capacity using modified design model.

	All	Granular soil backfill ($c=0$, $\phi>0$)	Cohesive-frictional soil backfill ($c>0$, $\phi>0$)
μ_R	1.00	1.00	1.00
COV_R (%)	19	11	24

6 INFLUENCE OF MODEL ACCURACY ON LOAD AND RESISTANCE FACTORS

For a target reliability index β and prescribed load factor γ_Q a value of resistance factor φ can be computed using the limit state function (Eq. 6) and Monte Carlo simulation or the closed-form solution given by Eq. 7. The results of this calculation using the closed-form solution are shown in Fig. 9 using the bias statistics for current anchor load and anchor capacity equations (Tables 4 and 5) and the corresponding new equations (Tables 6 and 7). The plots show that the resistance factor is closer to one using the new approach which is a better outcome for load and resistance factor calibration and design.

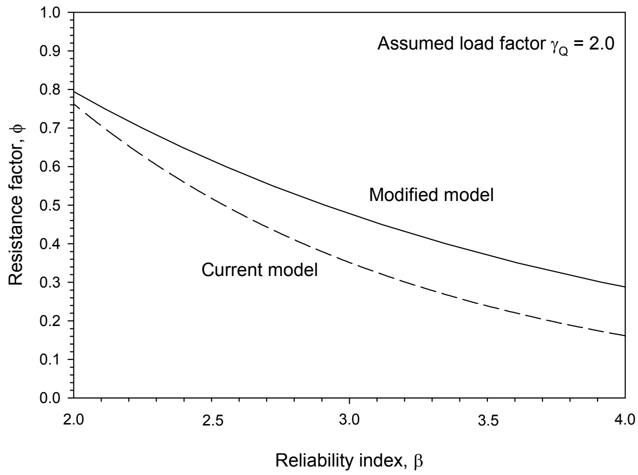

Figure 9. Estimated resistance factor with current or modified model.

7 CONCLUSIONS

This paper examines the accuracy of the MAW design models on load and resistance factor design calibration. Measured anchor loads and anchor plate capacities from full-scale tests reported in the literature are compared to predicted values using the analytical models recommended in Japan by PWRC.

Modified load and resistance models are proposed that preserve the general form of the PWRC equations but introduce correction factors to improve accuracy. The following conclusions can be made:

1) Accuracy of the current PWRC (2002) design model to calculate anchor loads was evaluated by using measurements from a series of eight full-scale wall sections. For purely frictional backfill soil cases, the current model was shown to slightly over-predict loads on average. For cohesive-frictional soil cases, accuracy of the current model was much poorer.
2) A new load model is proposed to improve prediction accuracy. The model with constant coefficients back-fitted to measured loads was shown to improve maximum anchor load predictions on average and to reduce the spread in bias values defined as the ratio of measured to predicted load values.
3) Accuracy of the current PWRC (2002) design model to calculate anchor plate pullout capacity was evaluated by using a total of 28 tests from multiple sources. The current resistance model is demonstrated to predict loads that vary widely from measured values in many cases.
4) A new resistance model is proposed that preserves the general form of the current PWRC (2002) model but includes correction factors to improve accuracy for the pullout ultimate limit state condition. Coefficients in the correction factor expressions were estimated from back-fitting analysis similar to the new load model development. The model gives improved predictions of anchor capacity for both frictional and cohesive frictional soil cases based on the mean and COV of resistance bias values where bias is the ratio of measured to predicted anchor load.
5) The results of load and resistance calibration assuming a simple linear limit state function leads to resistance factors that are closer to one which is a desirable outcome for load and resistance factor calibration and design.

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