Reliability of Estimated Anchor Pullout Resistance

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Abstract

In anchor pullout design, conservative soil and rock shear strength parameters are usually adopted. Presumptive values of soil/grout and rock/grout bond strength are available in different design manuals. In this study, in-situ pullout test data for anchors in soil and rock type worldwide were collected from published sources and information provided by specialty wall contractors. The measured pullout test data were compared to estimated pullout resistance using the Post-Tensioning Institute (PTI) presumptive bond strength values. Statistical analysis was performed to determine the probability of success and the corresponding reliability indices using the minimum, average and maximum PTI ground/anchor bond strength values for cohesive soils, cohesionless soils and different rock types. A minimum safety factor of 2 recommended by the PTI to the ground/grout bond strength was found not conservative where the maximum presumptive bond strength values were used in clays and sands, and the average and the maximum presumptive bond strength values were used in rocks. Based on the results of this study, an average minimum factor of safety was recommended for ground/grout bond strength.

Introduction

Anchor pullout resistance is determined using soil and rock bond strength parameters based on site specific in-situ and/or laboratory test results. For preliminary design purpose, the designer may adopt presumptive soil and rock bond strength values from available design manuals to determine anchor bond length. However, the designer should account for the uncertainty of soil and rock strength values. Lacasse and Nadim (1996) reported that cohesive soil shear strength had coefficient of variation (COV) ranged between 5% and 30%. Kulhawy and Trautmann (1996) indicated that standard penetration test (SPT) results had COV ranged between 15% and 45%. Note that SPT is a common test to estimate cohesionless soil shear strength. Based on published rock shear strength values (Hoek and Bray 1981), the COV of rock unconfined strength ranged between 30% and 70%. That means, for example, the average rock/grout bond strength adopted in a design could be 70% less than the actual field value.

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Each anchor should be tested to verify the anchor capacity and establish the tendon design preload, which is a way for the designer to evaluate the validity of assumed and/or measured bond strength parameters. PTI (1996) recommended adopting a factor of safety of 2 to the ground/grout interface. Published values of presumptive bond strength (P_p) are typically presented in a range indicating inherent variability within a single soil or rock type. The final design should be based on site specific bond strength values, which are function of several variables including, but not limited to, drilling procedure, hole cleaning, soil permeability and density, soil compressibility, soil strength, rock fractures and features and rock strength. In this study, the ultimate in-situ measured pullout resistance of anchors used to stabilize slopes of clay and sand soils and rocks are compared to the corresponding ultimate P_p values recommended by the PTI (1996).

Database

In-situ pullout test worldwide data for anchors in different soil and rock types were collected from published sources and through personal communications. An ultimate pullout stress was applied to physically pullout or cause failure of an anchor, which was indicated by excessive deformation of the anchor. Measured clay/grout bond strength data were summarized from Barley and McBarron (1997), Bruce (1998), Ostermayer (1975) and Woodland et al. (1997). Measured sand/grout bond strength data were summarized from Barley and McBarron (1997), Jones (1997), Liao et al. (1997) and Ostermayer (1975). In clay and sand soils, the grout was installed under its own weight by gravity or under pressure. Measured rock/grout bond strength data were summarized from Barley (1988a and b), Haberfield and Baycan (1997), Weerasinghe and Littlejohn (1997a and b). Ultimate pullout test results in clays and sands were compared to the minimum, average and maximum corresponding P_p values adopted according to PTI (1996), as depicted in Figures 1 and 2, respectively. Similar comparison between the ultimate pullout test results (P_m) in rocks and the recommended P_p values PTI (1996) is shown on Figure 3.

Reliability and Factor of Safety

The histogram of the ratio of anchor measured pullout resistance (P_m) and presumptive pullout resistance (P_p) recommended by PTI, (P_m / P_p = bias (λ)) in clays, sands and rocks are shown in Figures 4, 5 and 6, respectively. Note that each Figure includes the histogram of λ using minimum, average and maximum P_p values. Using the minimum presumptive bond strength resulted in 0%, 1% and 16% of the anchors to have factor of safety < 1, in the case of clay, sand and rock, respectively. However, using the maximum presumptive bond strength resulted in 8%, 31% and 39% of the anchors to have factor of safety < 1, in the case of clay, sand and rock, respectively. Table 1 summarizes the statistical properties of λ for a certain material including its average (μ (λ)), coefficient of variation (COV (λ)) and probability of failure (PF (λ)), which is simply defined as follows:

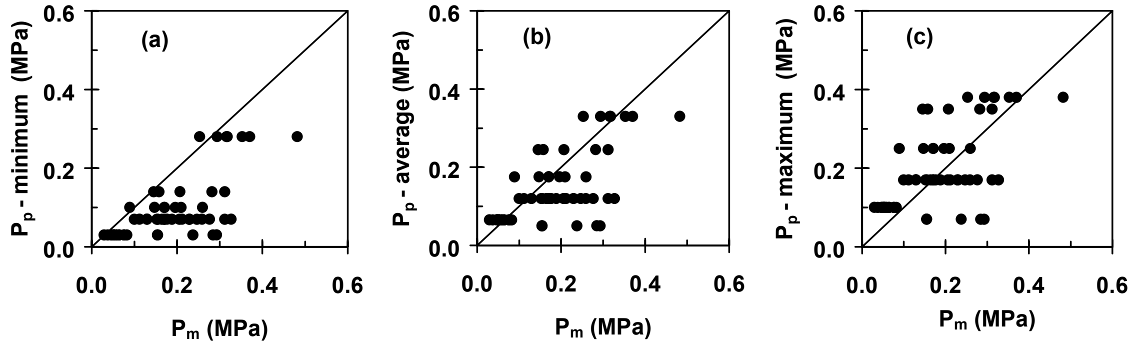

Figure 1. Comparison between anchor measured pullout resistance (P_m) in clay and presumptive pullout resistance (P_p) recommended by PTI: (a) minimum, (b) average and (c) maximum.

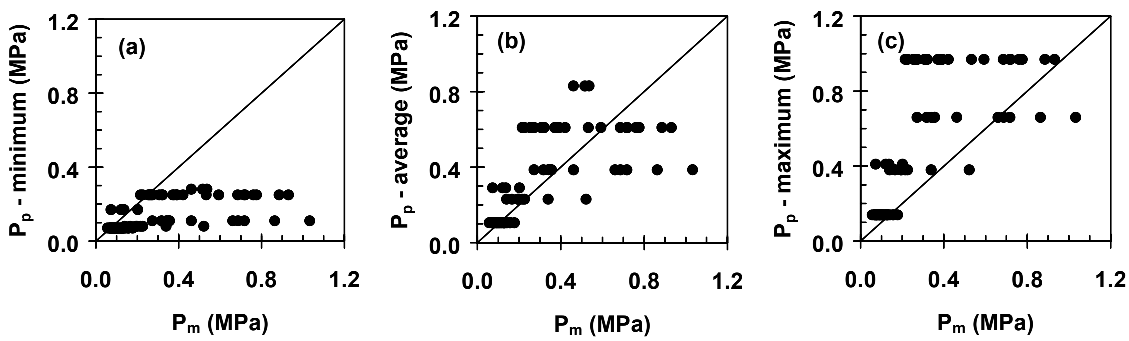

Figure 2. Comparison between anchor measured pullout resistance (P_m) in sand and presumptive pullout resistance (P_p) recommended by PTI: (a) minimum, (b) average and (c) maximum.

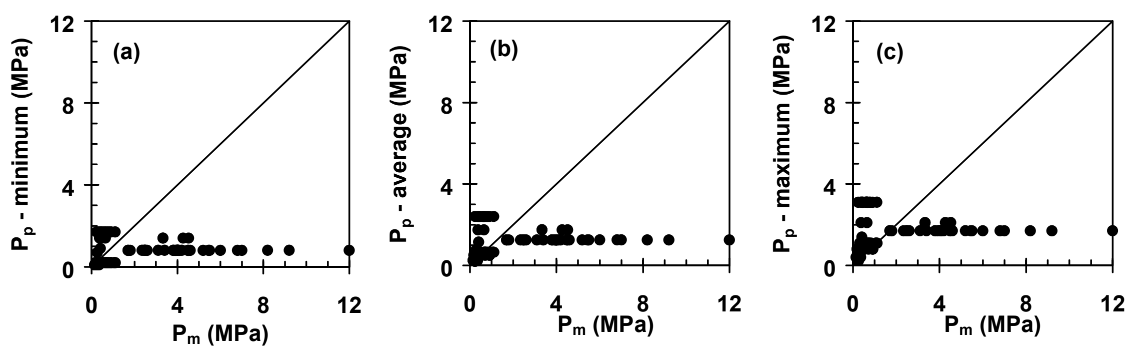

Figure 3. Comparison between anchor measured pullout resistance (P_m) in rock and presumptive pullout resistance (P_p) recommended by PTI: (a) minimum, (b) average and (c) maximum.

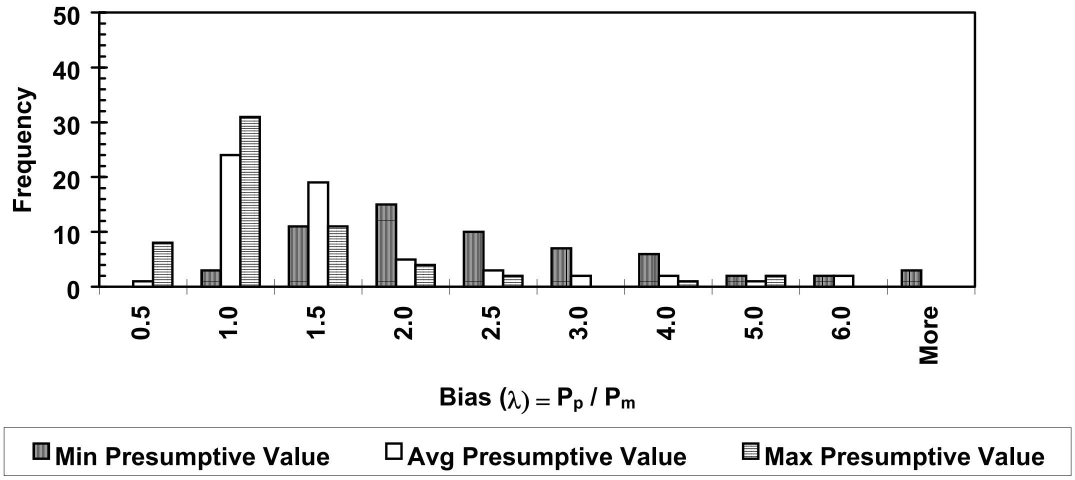

Figure 4. Histogram of bias (λ) of anchor pullout resistance in clay.

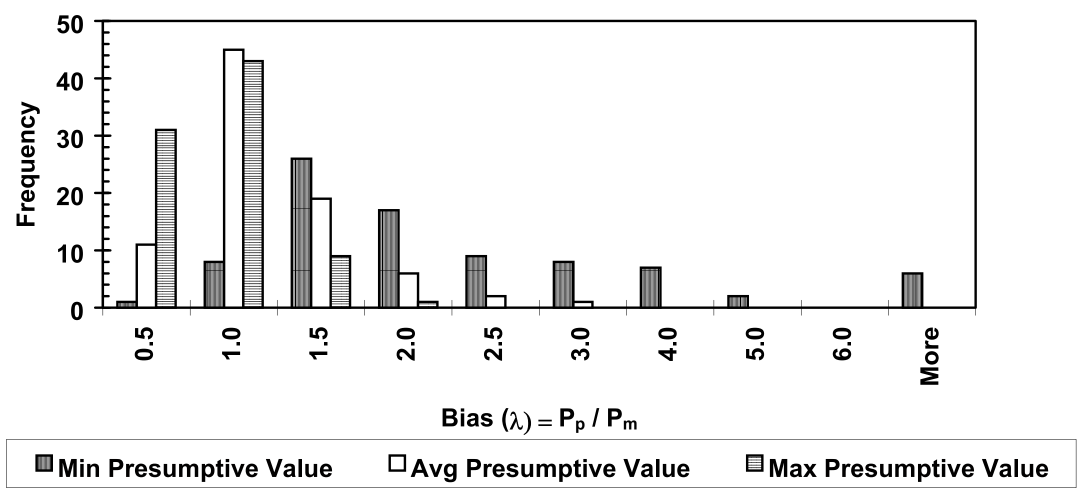

Figure 5. Histogram of bias of anchor pullout resistance in sand.

$$PF(\lambda) = \frac{\text{No. of data with } \lambda < 1}{\text{Total No. of data}} \qquad (1)$$

Table 1 indicates that μ (λ) decreased, and COV (λ) and PF (λ) increased using a higher P_p value. The minimum recommended factor of safety (FS) of anchor bond strength for each material type using the minimum, average and maximum P_p values was determined as explained herein.

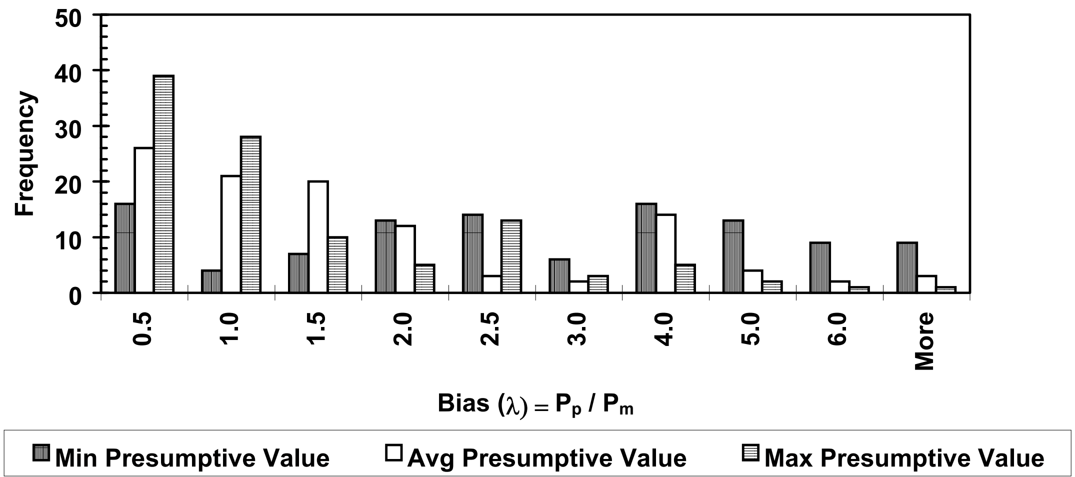

Figure 6. Histogram of bias of anchor pullout resistance in rock.

Table 1. Statistical properties of data bias ($\lambda = P_m / P_p$)

Material	Bias (λ)	No. of Data	μ (λ)	COV (λ)	PF
Clay	P_m / P_p-min	59	2.56	0.71	0.05
	P_m / P_p-avg	59	1.48	0.75	0.42
	P_m / P_p-max	59	1.05	0.75	0.66
Sand	P_m / P_p-min	84	2.2	0.74	0.08
	P_m / P_p-avg	84	0.94	0.49	0.67
	P_m / P_p-max	84	0.63	0.47	0.88
Rock	P_m / P_p-min	107	3.13	0.81	0.19
	P_m / P_p-avg	107	1.70	0.97	0.44
	P_m / P_p-max	107	1.21	1.02	0.63

1. A factor of safety is known as the ratio between resistance (R) and load (Q). Knowing PF, the reliability index (β) was determined for lognormally distributed values of R and Q according to (Withiam et al. 1998):

$$\beta = -\frac{1}{4.3} * \ln\left(\frac{PF}{460}\right) \quad (2)$$

The normal and lognormal probability distribution functions are the most commonly used in geotechnical problems (Lacasse and Nadim 1996). The lognormal is often used to characterize variables that can not be negative such as the ratio of measured to predicted anchor pullout resistance.

2. The resistance factor (ϕ) was determined as follows (Withiam et al. 1998):

$$\phi = \mu(\lambda) * \exp(-0.87 * \beta_T \; COV(\lambda)) \quad (3)$$

3. Then the FS was calculated as follows:

$$FS = \frac{1}{\phi} \quad (4)$$

Table 2 summarizes determined β, ϕ and FS for each material type using the minimum, average and maximum P_p value, and indicates that the minimum recommended FS increases using a higher P_p value. For instance, FS of anchor bond strength in clays using the minimum and maximum P_p values were recommended equal to 1.5 and 2.6, respectively.

Table 2. Minimum recommended factor of safety to ground / grout bond strength

Material	Bias (λ)	β	Φ	FS = 1 / Φ
Clay	P_m / P_p-min	2.12	0.69	1.5
	P_m / P_p-avg	1.63	0.52	2.0
	P_m / P_p-max	1.52	0.39	2.6
Sand	P_m / P_p-min	2.00	0.61	1.7
	P_m / P_p-avg	1.52	0.50	2.0
	P_m / P_p-max	1.46	0.35	2.9
Rock	P_m / P_p-min	1.82	0.88	1.2
	P_m / P_p-avg	1.62	0.43	2.3
	P_m / P_p-max	1.53	0.31	3.3

Conclusions

The measured anchor grout bond strengths in clays, sands and rocks were compared with the corresponding recommended presumptive bond strength values by PTI. This study indicated that applying a minimum factor of safety of 2 (recommended by PTI) to the ground/grout bond strength was conservative where the minimum and average presumptive bond strength (P_p) values were used in clay and sand and the minimum P_p values were used in rock. However, the maximum P_p values in clay and sand and the average and maximum P_p values in rock were high and should be reduced or the factor of safety should be increased. Based on the results of this study, the minimum factor of safety of the soil/grout bond strength was recommended to increase from 2 to 2.6 and 2.9 in clay and sand, respectively, where the maximum P_p was used. Also, where the average and maximum P_p values were used in rock, the minimum factor of safety of the rock/grout bond strength was recommended to increase from 2 to 2.3 and 3.3, respectively.

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