Evaluation of prediction accuracy of ultimate bond strength of soil nails by the effective stress method

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ABSTRACT
This paper presents a statistical evaluation of the accuracy in predicting the ultimate bond strength of soil nails using the effective stress method (ESM). A total of 113 data points from field nail pullout tests taken to failure in Hong Kong were collected from the literature. After removing outliers, the data were used to estimate the accuracy of the current ESM. Based on the available data, the current ESM pullout model is found to be excessively conservative (on average) by a factor of three or more and the spread in prediction accuracy is large. In addition, the accuracy of the current model for prediction of nail bond strength is shown to be dependent on the magnitude of predicted ultimate bond strength. This undesirable dependency is traced to a strong correlation between model accuracy and vertical effective stress computed at the elevation of the soil nail anchor embedment length.

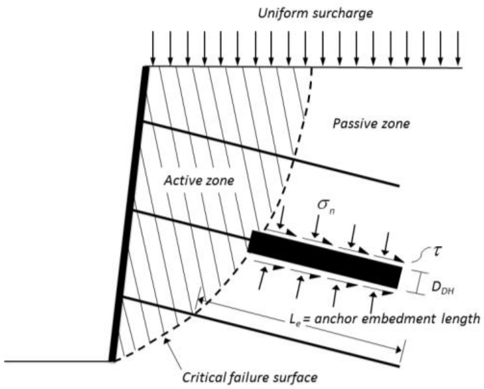
RÉSUMÉ
Cet article présente une évaluation statistique de la précision dans la prédiction de la force de liaison ultime des ancrages dans le sol en utilisant la méthode de contrainte effective (ESM). 113 données provenant d'essais d'arrachement des ancrages à Hong Kong ont été rassemblées à partir de la littérature. Après avoir retiré les valeurs aberrantes, les données ont été utilisées pour estimer la précision de la méthode ESM. Basé sur les données disponibles, le modèle actuel de retrait ESM est jugé trop conservateur (en moyenne) par un facteur de trois ou plus et l'exactitude des précisions est variable. De plus, la précision du modèle actuel pour la prédiction de la résistance d'adhésion de l'ancrage est indiquée comme étant dépendante de la grandeur de la force de liaison finale prévue. Cette dépendance indésirable est attribuable à une forte corrélation entre la précision du modèle et de la contrainte effective verticale calculée au niveau de l'ancrage.

1 INTRODUCTION

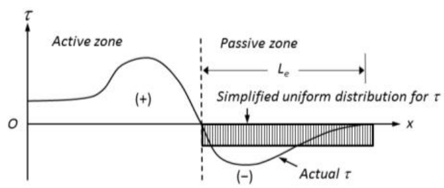
Soil nail walls (SNWs) are now used extensively to reinforce existing slopes and to support deep excavations. For example, in Hong Kong there are more than 50,000 soil nails installed each year on average (Cheung and Lo 2011). The most widely used construction procedure for SNWs is to drill and grout. The construction sequence is as follows: 1) excavate the soil ground to the target depth; 2) drill a hole into the ground; 3) insert a steel bar (nail tendon) to the bottom of the hole; 4) fully grout the annular space between the nail and surrounding soil; and 5) repeat steps 1 to 4 for the next levels. The design of a SNW involves achieving satisfactory margins of safety for external, internal, and facing limit states. Internal limit states include nail-soil pullout capacity and nail tensile strength. The focus of the present study is on the estimation of the ultimate pullout capacity of soil nails and the accuracy of predicted capacities using a well-known method.

The ultimate pullout capacity of a soil nail is dependent largely on the ultimate bond strength between the nail grout and the surrounding soil. There are in general two methods for evaluating the ultimate bond strength of a nail. One is to consider it as a single variable that is selected based on a combination of the soil type, construction method, and engineering experience of the designers, e.g., this method is widely adopted in North America (FHWA 2003) and the UK (Phear et al. 2005). The other approach is to use an equation that has a theoretical geomechanics basis and includes the nail geometry, confining stress level and soil cohesion and frictional strength components of the surrounding soil. Such an approach is the effective stress method (ESM) adopted in Hong Kong [e.g., GEO (2007), Geoguide 7 (GHKSAR 2008)].

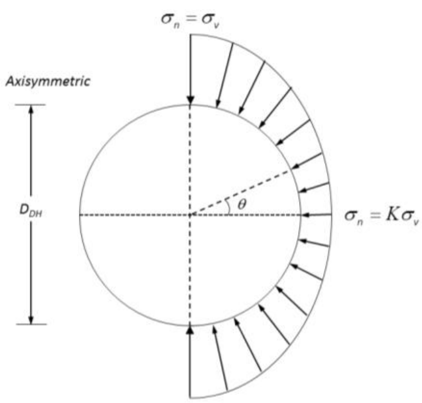
The focus of this paper is a statistical study of the accuracy of the estimation of pullout capacity (or bond strength) of soil nails using the effective stress method (ESM). The statistical approach is based on resistance model calibration using bias values and the procedures described by Huang and Bathurst (2009) and Yu and Bathurst (2015). In these prior studies the soil reinforcement elements were polymeric and steel grids, respectively. The same approach is now used for the first time to estimate the accuracy of the ESM for the ultimate pullout limit state for soil nails used in Hong Kong. This is a necessary first step for the future development of more accurate models for SNW internal pullout capacity design that can be implemented within a probabilistic design and analysis framework.



(a)



(b)



(c)

Fig. 1. Nail pullout limit state: (a) soil nail wall; (b) shear stress along a soil nail; (c) cross-sectional view showing normal stress acting on grouted soil nail

A necessary requirement to carry out the analysis reported in this paper is a large database of field pullout tests. These data are now available for soil nails used in Hong Kong and are described in detail later in the paper.

2 EFFECTIVE STRESS METHOD (ESM) FOR SOIL NAIL WALLS

The soil nail pullout limit state can be referenced to Fig. (1a). A planar or curved failure surface through the soil is assumed and is used to define active and passive zones. The grouted soil nails support the active zone by developing shear resistance along the anchor embedment length, axial tensile force and shear through the nail. The interface shear stress along the nail anchor length τ, varies as a function of x and θ as shown in Figs. 1(b and c). In the passive zone, τ increases longitudinally from the head of the nail to a peak value and then decreases to about zero at the end of the embedded nail as shown in Fig. 1(b). The ultimate pullout capacity, *P*, can be calculated by integrating τ in both longitudinal and radial directions as follows:

$$P = \int_0^{2\pi}\int_{L-Le}^{L} \frac{D_{DH}}{2}\tau(x,\theta)\,dxd\theta$$
$$= \int_0^{\pi}\int_{L-Le}^{L} D_{DH}\tau(x,\theta)\,dxd\theta \qquad (1)$$

where, *L* is the nail length, L_e is the anchorage length, and D_{DH} is the drill hole diameter (Fig. (1a). In order to reduce Eq. (1) to a practical expression, simplifying assumptions are unavoidable. Hence, τ is assumed to be uniform along the perimeter of the nail grout anchorage length. An empirical correction factor (η) has been proposed by Lum (2007) to account for this simplification and for possible extensibility of the nail. Hence, Eq. (1) for the ultimate pullout capacity can be expressed as:

$$P = \eta\pi D_{DH} L_e \tau = \pi D_{DH} L_e q_u \qquad (2)$$

where $q_u = \eta\tau$ is defined as the ultimate bond strength between the soil and nail grout. The current ESM used in Hong Kong to calculate q_u (Watkins and Powell 1992, GEO 2007) can be traced to the work of Cartier and Gigan (1983) and is expressed as:

$$q_u = c + \frac{2}{\pi}\sigma_v \tan\phi \qquad (3)$$

Where, c is soil cohesion, ϕ is soil friction angle and σ_v is vertical stress at the middle of the grouted length L_e. These parameters are effective stress parameters. Primes have been removed for visual clarity.

3 DATABASE OF SOIL NAIL PULLOUT TESTS

3.1 General

There are two large databases of field in-situ soil nail pullout test results that are available in the literature (Lazarte 2011, Cheung and Shum 2012). A few full-scale or field tests are also reported by Lum (2007), Li et al. (2008) and Hong et al. (2013). In addition, there are a large number of laboratory nail pullout tests that have been reported in the literature and these tests have improved understanding of pullout behaviour (e.g. Pedley 1990, Tei 1993, Milligan and Tei 1998, Pradhan et al. 2006, Yin and Zhou 2009).

The database developed by Lazarte (2011) is not used in this study because 1) the measured values of bond strength are not for nails at ultimate limit state (i.e., pullout failure was not reached), and 2) the method to predict the nail bond strength was based on recommendations found in FHWA (2003) specifications and engineering judgement of the operators. Laboratory test results from the above noted publications are also not used because 1) the data are sparse with pullout capacities vary widely, 2) soils and test methods varied widely between data sets, and 3) soil nails placed in reconstituted soils in a laboratory setting can be expected to have different quantitative performance from nominal identical field tests.

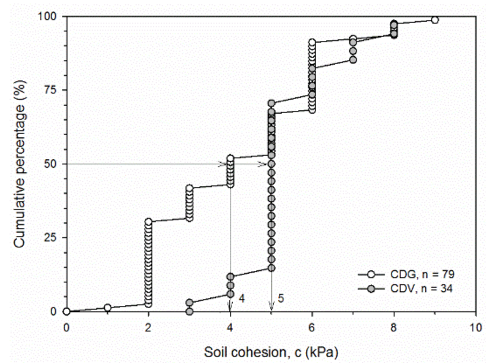
Based on the comments above the database of field soil nail pullout tests from Hong Kong compiled by Cheung and Shum (2012) is used in the current investigation. The data were also used in the development of the pullout resistance design guidelines that appear in Geoguide 7 (GHKSAR 2008).

Most of the pullout tests were conducted in completely or completely to highly decomposed granite and volcanic soils (designated as CDG or C/HDG, and CDV or C/HDV, respectively). The CDG soil in Hong Kong is usually described as silty sand with fine gravel. According to Zhang et al. (2009) CDG soils are classified as SC-SM using the Unified Soil Classification System (USCS). CDV soils can be classified as firm, moist, orange-brown coloured, slightly sandy silt-clay with high plasticity (Ng and Pang 2000). Based on the index properties of a CDV soil provided by Ng and Pang (2000), the CDV soils are classified as MH. A few pullout tests were conducted in other types of materials such as fill and colluvium. These tests are not used in this study.

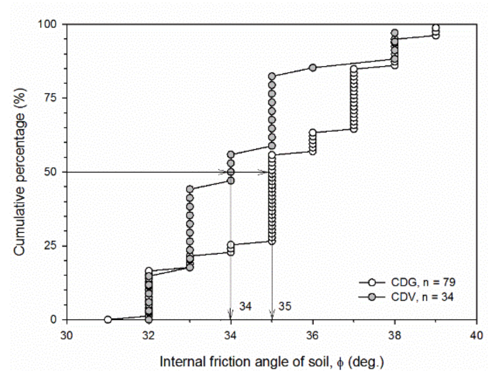
Values of D_{DH} and L_e are also available for each pullout test in the database compiled by Cheung and Shum (2012). All D_{DH} values are 100 or 150 mm, with only a few exceptions. Similarly, L_e was 2.0 m for most cases although there were a few tests with anchor embedment lengths of 3.0 m and as short as 1.9 m. However, because values D_{DH} and L_e in the available database are clustered at a few discrete values, they are treated as deterministic in the analysis of (error) bias values described later and hence are not identified as sources of model accuracy error.

Fig. 2 shows cumulative percentage plots for the measured parameters in Eq. 2 which have been taken directly from the database compiled by Cheung and Shum (2012). Measured values of q_u shown in Fig. 2d were back-calculated from soil nail geometry and measured P values using Eq. 2.

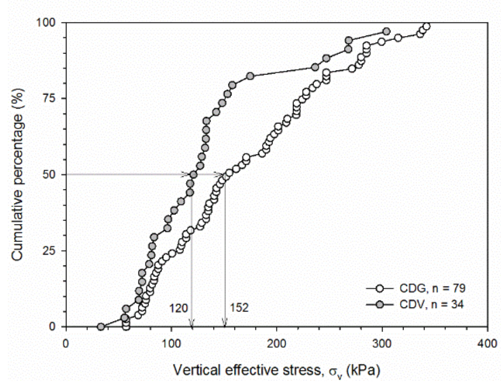
The shear strength parameters c and ϕ for the soils in the database vary from 0 to 9 kPa and 31 to 39 degrees, respectively. The medium values are 4 and 5 kPa for c, and 34 and 35 degrees for ϕ, for CDG and CDV soils respectively. The minimum, medium and maximum values of vertical effective stress at the middle of the soil nail anchor are 57, 152 and 342 kPa for tests in CDG soil and 33, 120 and 304 kPa for tests in CDV soil, respectively. The cumulative distributions for the back-calculated ultimate bond strength are similar for both soil types. For CDG soil, q_u ranges from 65 to 684 kPa with the majority within 488 kPa and the medium value at 237 kPa. For the tests in CDV soil, q_u ranges from 66 to 462 kPa with the medium value at 206 kPa.



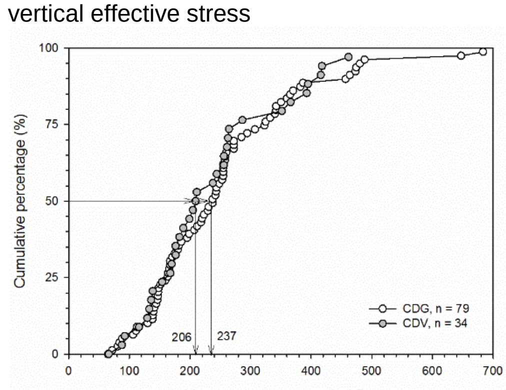
(a) cohesion



(b) soil friction angle

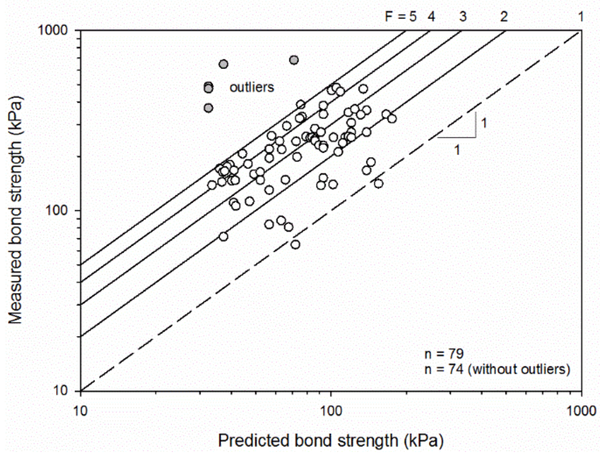


(c) vertical effective stress

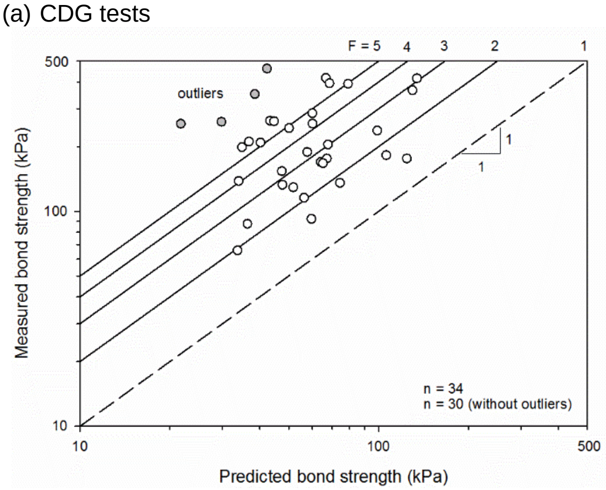


(d) measured ultimate bond strength, q_u

Fig. 2. Cumulative distribution plots for measured parameters and measured ultimate bond strength from in-situ nail pullout tests



(a) CDG tests



(b) CDV tests

Fig. 3. Measured versus predicted bond strength

3.2 Initial screening of pullout test results

Fig. 3 shows measured versus predicted pullout bond strength of all pullout tests carried out in CDG and CDV soils. Predicted values of q_u were calculated using Eq. 3. The plots show that there is visual scatter in both data sets. However, the current ESM method for design is conservative (i.e. safe) since almost all measured values are greater than the predicted values. In Fig. 3a, 82% of measured values are greater than a factor of F = 2 times the predicted values. In Fig. 3b, 85% of measured values are greater than F = 2 times the predicted values. A value of F = 2 corresponds to the minimum factor of safety that is typically used in allowable stress design for the ultimate soil nail pullout capacity (FHWA 2003, GHKSAR 2008). A set of data points (grey symbols) is identified in both plots of Fig. 3.

These tests can be understood to be outliers (at least visually) because they are excessively conservative (safe) from the point of view of design (i.e. they fall above the line with F = 5). These data points were also identified quantitatively as outliers using the Mann-Whitney rank sum test (at a level of significance of 5%) on the median of bias values where bias is defined as the ratio of measured to predicted bond strength. Hence, these data are treated as outliers hereafter. The reason for the outliers could not be explained based on available information in the source document. For example, they were not associated with any particular set of field tests, range of soil parameters, soil type, nail geometry or installation depth.

4 STATISTICAL EVALUATION OF CURRENT ESM

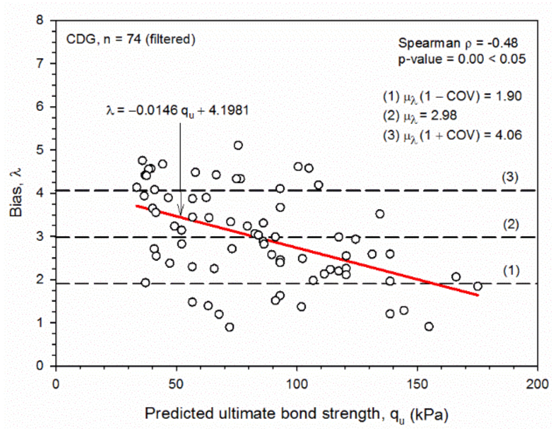
4.1 General

Statistical analysis of the accuracy of the current ultimate bond strength equation using the effective stress method (ESM) (Eq. 3) and potential sources of inaccuracy were carried out by examining bias values taken from the filtered database of n = 74 and 30 data points for the CDG and CDV soils, respectively. The bias value for each data point (λ) is the ratio of measured bond strength to predicted value. The measured value is back-calculated from a pullout test taken to failure as described earlier. The corresponding predicted value is computed using Eq. 3.

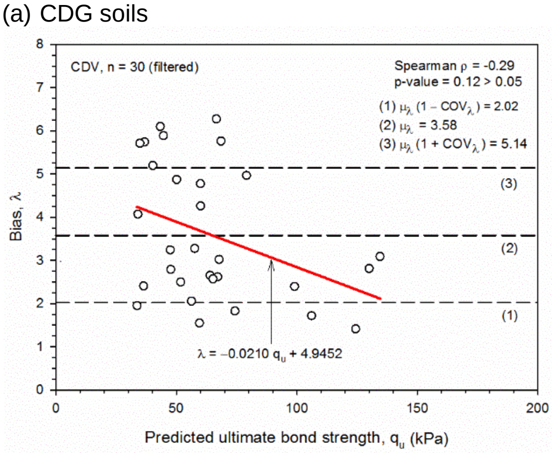
Based on the filtered database the mean and coefficient of variation (COV) of bias values for CDG tests are $\mu_\lambda = 2.98$ and $COV_\lambda = 0.36$ and for the CDV tests $\mu_\lambda = 3.58$ and $COV_\lambda = 0.44$. This means that the current ESM under-estimates measured ultimate pullout capacity *on average* by a factor of about 3 and 3.6 for the CDG and CDV soils, respectively. These values are consistent with the conservative estimates of predicted capacity and spread in the data points that are visually apparent in Fig. 3.

Fig. 4 shows the same bias data plotted against magnitude of predicted bond strength. The means of bias values correspond to curve (2) in the two plots and curves (1) and (3) are ±1 standard deviation on bias values. Superimposed on these two data sets are regressed first order polynomials fitted to the data. The visual impression from the fitted lines is that bias values are dependent on magnitude of predicted anchor strength. This visual trend was examined quantitatively at level of significance of 5% using two statistical tests. The first test was the Spearman rank correlation test which is a common tool to quantitatively assesses how strongly two data sets are related to each other in a monotonic relationship regardless whether or not the relationship is linear. The magnitude of Spearman's rank correlation coefficient (ρ) is a quantitative indicator of the strength of this trend and the sign of the value is the direction of the trend (dependent variable increasing or decreasing with independent variable).

The Spearman rank correlation coefficient for the filtered data (n = 74) in Fig. 4a gives $\rho = -0.48$ (less than zero) and the p-value is 0.00 (less than 0.05). This means that the null hypothesis that the two populations are independent is rejected. The rejection was confirmed by carrying out a zero slope test on the regressed line. This test showed that a zero slope cannot be accepted at a level of significance of 5%. This is an undesirable outcome for the current ESM used in soil nail design



(a) CDG soils



(b) CDV soils

Fig. 4. Bias versus predicted ultimate bond strength

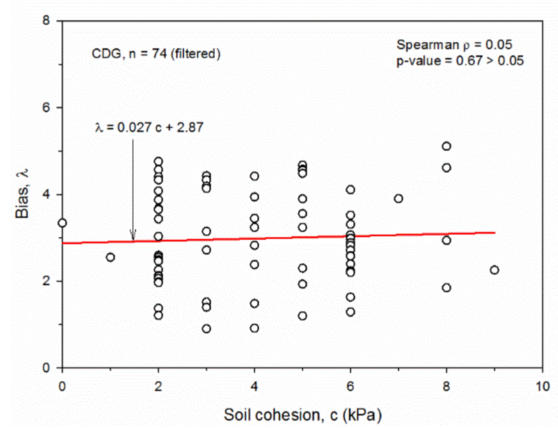
because the magnitude of conservatism is a function of the predicted nail capacity.

The Spearman rank correlation coefficient for the filtered CDV data (n = 30) (Fig. 4b) gives $\rho = -0.29$ (less than zero) and p-value of 0.12 (higher than 0.05). Hence, this test indicates that the two datasets are uncorrelated at a level of significance of 5%. However, the zero slope test gives the opposite outcome. Because the null hypothesis that the two populations are independent cannot be accepted at a level of significance of 5% for one of the tests, the bias values for CDV soils are judged to be dependent on predicted pullout capacity in this study.

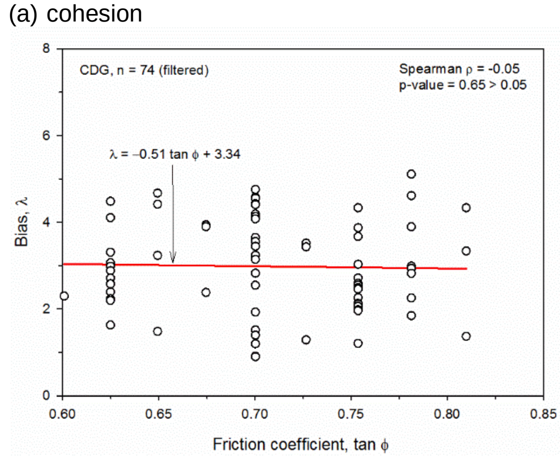
4.2 Source of conservatism

The source of the undesirable dependency noted above was examined by plotting bias values against model input parameters (c, ϕ and σ_v). These plots are shown in Fig. 5. Spearman rank correlation tests and the zero slope tests applied to the data in Fig 5a and 5b confirmed that bias values were independent of c and $\tan\phi$ at a level of significance of 5%.

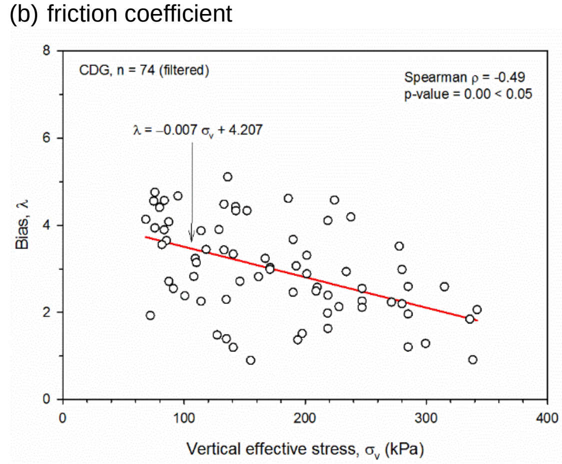
The regressed line in Fig 5c suggests, at least visually, that there is a correlation between bias values and vertical effective stress at the location of the nail anchorage length. This was confirmed quantitatively using the Spearman rank correlation test and the zero slope test. In fact, the Spearman rank correlation coefficient is almost the same as the value shown in Fig. 4a. This is interpreted to mean that the source of dependency noted in Fig. 4a is due to the strong correlation between model accuracy and vertical effective stress.



(a) cohesion



(b) friction coefficient



(c) vertical effective stress

Fig. 5. Bias versus input parameters for ESM for soil nail ultimate pullout capacity (Eq. 3)

5 CONCLUSIONS AND DISCUSSION

This paper reports the details of a database of in situ soil nail pullout tests conducted in Hong Kong. The data are used to investigate the accuracy of the current ESM used in Hong Kong to estimate ultimate bond strength of soil nails installed in CDG and CDV soils. The analyses show that the current ESM underestimates ultimate soil nail bond strength by a factor of three or more *on average*. The COV for bias values was computed as 0.36 and 0.44 for tests in CDG and CDV soils, respectively. These numbers may appear large but COV values for the cohesive and frictional strength components of in-situ (natural) soils due to random variability can also be high [e.g., 0.20-0.55 for cohesion and 0.05-0.15 for friction angle (Phoon and Kulhawy 1999)]. Hence, the spread in bias values may be expected. However, the under-estimation of soil nail capacity is likely due to the conservatism of the underlying deterministic ESM model (Eq. 1 and 2).

A strategy to correct the overall (average) conservatism in the current ESM is to multiply Eq. 3 by an empirical factor (multiplier) which is equal to the inverse of the mean of bias values for each soil type computed in this study. In order to correct the undesirable dependency between model accuracy and magnitude of predicted nail capacity, attention must be focused on removing the correlation between bias and vertical effective stress. This can be corrected by the introduction of a stress-dependent empirical correction function for each soil type. A similar approach was adopted by Huang and Bathurst (2009) and Yan and Bathurst (2015) to remove stress dependency in a pullout capacity model for the steel grids used in mechanically stabilized earth (MSE) wall applications. This work is underway at the time of this paper and will be presented in a future publication.

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