DISCUSSION ON "EFFECTS OF LIME ADDITION ON GEOTECHNICAL PROPERTIES OF SEDIMENTARY SOIL IN CURITIBA, BRAZIL" [J ROCK MECH GEOTECH ENG 10 (2018) 188-194]

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Discussion and Discovery

Discussion on "Effects of lime addition on geotechnical properties of sedimentary soil in Curitiba, Brazil" [J Rock Mech Geotech Eng 10 (2018) 188–194]

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ABSTRACT

The present discussion aims at complementing the original work published by Baldovino et al. (2018) by outlining a novel point of view. In light of the inherent limitations associated with the empirical model suggested in the original article, the dimensional analysis technique was introduced to the soil-lime strength problem, thereby leading to the development of simple and physically meaningful dimensional models capable of predicting the unconfined compressive and splitting tensile strengths of compacted soil-lime mixtures as a function of the mixture's index properties, i.e. lime content, initial placement (or compaction) condition, initial specific surface area and curing time. The predictive capacity of the proposed dimensional models was examined and validated by statistical techniques. The proposed dimensional models contain a limited number of fitting parameters, which can be calibrated by minimal experimental effort and hence implemented for predictive purposes.

1. Introduction

Recently, Baldovino et al. (2018) examined the effects of lime content and curing time on the unconfined compressive strength (UCS or q_u) and the splitting tensile strength (STS or q_s) of a sedimentary soil located at the Curitiba region of Brazil. The work under discussion takes a sound step towards amending the inferior engineering characteristics of clay soils, and as such, is gratefully acknowledged. In the present discussion/comment, some shortcomings associated with the aforementioned study will first be outlined in detail. A novel point of view will then be introduced by the discussers to complement the original work.

A notable portion of the original article was dedicated to the development of an empirical model claimed capable of adequately quantifying the UCS and STS of clay-lime blends. For a given curing time, the authors proposed the following two-parameter power function for q_u or q_s (see Figs. 8 and 9 in the original article):

$$q_u \text{ or } q_s = A\left(\frac{\eta}{L_v}\right)^B \quad (1)$$

where η is the porosity, L_v is the volumetric lime content, and A and B are the empirical coefficients (or fitting parameters).

A suitable empirical model can be characterized as one that maintains a perfect balance between simplicity (ease of application) and accuracy (acceptable goodness of fit and low forecast error). As such, any introduced model should involve a minimal number of conventional (and simply measurable) physical parameters, linked by a minimal number of empirical coefficients (or fitting parameters), capable of arriving at a reliable prediction of the problem at hand (Soltani and Mirzababaei, 2018). The empirical model proposed in the original article (or Eq. (1)), however, fails to satisfy the aforementioned criteria, which can be attributed to the following factors:

(1) As outlined in Figs. 8 and 9 of the original article, the coefficient of determination (a measure of the model's accuracy) can be as low as $R^2 = 0.78$ for some mix designs, which basically implies that only 78% of the variations in experimental observations would be captured and further

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explained by the suggested empirical model. Taking into account that the variations of both q_u and q_s against lime content and/or curing time are strongly monotonic (see Figs. 4–7 in the original article), high R^2 values (greater than 0.95) should be simply accomplishable. Moreover, the suggested empirical model, at least in its current form, fails to capture lime content-curing time interactions, as evident with the absence of a L_cT_c term (or other similar terms) in Eq. (1) (L_c is the lime content by weight of soil solids, and T_c is the curing time).

(2) The fitting parameters A and B are functions of curing time (see Figs. 8 and 9 in the original article), and as such, should be calibrated for a wide range of curing times. For any desired curing time, one would require a minimum of two q_u (and two q_s) measurements to arrive at A and B. Therefore, calibrating Eq. (1) with respect to the four curing times investigated in the original article, i.e. T_c = 15 d, 30 d, 60 d and 90 d, would require a minimum of $4 \times 2 = 8$ q_u (and $4 \times 2 = 8$ q_s) measurements. Quite clearly, the proposed empirical model suffers from long-lasting and sophisticated calibration procedures, and as such, would not be trivial to implement in practice.

The dimensional analysis technique, proposed by Buckingham (1914), has shown great promise in facilitating the development of physically meaningful models capable of adequately simulating the mechanical performance of multi-phase stabilized soil mixtures by means of the mixture's index properties (e.g. Williamson and Cortes, 2014; Zhao et al., 2016; Soltani and Mirzababaei, 2018; Soltani et al., 2018a). To arrive at an alternative for Eq. (1), the present discussion aims at the development of practical dimensional models capable of quantifying the UCS and STS of soil-lime blends. The suggested dimensional models in this discussion intend to aid the geotechnical engineer to arrive at preliminary (and reliable) soil-lime design choices without the hurdles of conducting time-consuming laboratory tests.

2. Dimensional analysis of soil-lime blends

2.1. Model development

As evident with the experimental results discussed in the original article, as well as those reported in relevant literature sources (e.g. Santamarina et al., 2002; Williamson and Cortes, 2014; Soltani et al., 2017), the governing variables with respect to the soil-lime UCS problem can be categorized as: (i) initial mass of the soil solids M_S; (ii) initial mass of lime M_L; (iii) initial mass of water M_W; (iv) initial dry density of the mixture composite ρ_{do}; (v) initial specific surface area of the mixture $S_{a\text{-mix}}$; (vi) curing time T_c; and (vii) net minor principal stress σ_3^*. Therefore, the soil-lime UCS problem can be represented as (all variables in SI units):

$$\sigma_1^* = F_A\left(M_S, M_L, M_W, \rho_{do}, S_{a-mix}, T_c, \sigma_3^*\right) \tag{2}$$

where σ_1^* is the net major principal stress, and F_A is an unknown multi-variable functional expression.

For unconfined compression testing conditions, the net major and minor principal stresses, i.e. σ_1^* and σ_3^*, can be defined as

$$\sigma_1^* = \sigma_1 + P_o = q_u \tag{3}$$

$$\sigma_3^* = \sigma_3 + P_o = P_o \tag{4}$$

where σ_1 is the major principal stress, P_o is the atmospheric pressure (=101.325 kPa), and σ_3 is the minor principal stress (taken as zero for unconfined compression testing conditions).

Accounting for the recent simplifications suggested in Eqs. (3) and (4), one can rewrite Eq. (2) as

$$q_u = F_A(M_S, M_L, M_W, \rho_{do}, S_{a-mix}, T_c, P_o) \tag{5}$$

Any physical problem, such as the soil-lime UCS problem given in Eq. (5), involving N_1 number of physical parameters with N_2 number of basic physical dimensions/units, can be simplified to a new problem involving K=N_1−N_2 number of dimensionless π variables capable of adequately describing the original problem at hand (Buckingham, 1914). The system of N_1 = 7 physical parameters (ρ_{do} is related to M_S and M_L) and N_2 = 3 basic physical dimensions (i.e. mass, length and time) given in Eq. (5) can hence be simplified to a new system involving K = 4 dimensionless π variables given as

$$\pi_o = \frac{\sigma_1^*}{\sigma_3^*} = \frac{q_u}{P_o} \tag{6}$$

$$\pi_1 = \frac{M_L}{M_S} = L_c \tag{7}$$

$$\pi_2 = \frac{M_W}{M_S} = w_o(1 + L_c) \tag{8}$$

$$\pi_3 = T_c S_{a-mix}\sqrt{\rho_{do}\sigma_3^*} = T_c S_{a-mix}\sqrt{\rho_{do}P_o} \tag{9}$$

where π_o is the dependent/output π variable (or the stress ratio), π_1 to π_3 are the input π variables, and w_o is the initial water content of the mixture composite.

Although the UCS of an unsaturated geomaterial, such as the soil-lime composite, is known to be related to its matric suction, one may argue that an accurate measurement of suction, for fine-grained soils in particular, is a rather difficult and time-consuming task (Agus et al., 2010; Malaya and Sreedeep, 2011). A typical unconfined compression test (the problem at hand), however, is deemed as a routine test commonly performed in most laboratories with much less effort. To maintain model simplicity/practicality, it was therefore decided to disregard introducing suction as a governing variable. Interestingly, this simplification also complies with most of the existing literature, where various forms of empirical and dimensional models have been developed (and validated) for different geomaterials without considering suction as an input variable (e.g. Buzzi et al., 2011; Williamson and Cortes, 2014; Consoli et al., 2016; Zhao et al., 2016; Soltani et al., 2018a). As outlined in Section 2.1.8 of the original article, samples for the unconfined compression (and splitting tension) tests were prepared at the corresponding Proctor optimum condition of each mixture, thus implying that $w_o = w_{opt}$ and $\rho_{do} = \rho_{dmax}$ (w_{opt} is the optimum water content, and ρ_{dmax} is the maximum dry density). Moreover, the effect of lime content on both the optimum water content and the maximum dry density was reported to be marginal, and as such, average values of $w_o = w_{opt} = 31\%$ and $\rho_{do} = \rho_{dmax} = 1410$ kg/m^3 can be considered for all mix designs (see Section 2.1.7 of the original article). The specific surface area for the virgin soil (containing no lime) can be estimated by the following empirical relationship (Locat et al., 1984):

$$I_P = 0.7(S_{a-soil} - 5) \tag{10}$$

where $S_{a\text{-soil}}$ is the specific surface area of the virgin soil (m^2/g), and I_P is the plasticity index of the virgin soil (%).

As reported in Table 2 of the original article, the virgin soil possesses a plasticity index of $I_P = 21.3\%$, which in turn results in $S_{a\text{-soil}} = 35.43 \times 10^3$ m^2/kg. For those mix designs involving lime ($L_c > 0$), the weighted averaging technique, as commonly adopted in the literature (e.g. Williamson and Cortes, 2014; Zhao et al., 2016; Soltani and Mirzababaei, 2018), can be employed to arrive at an estimate of the mixture's initial specific surface area $S_{a\text{-mix}}$:

$$S_{a-mix} = (1 - L_c)S_{a-soil} + L_c S_{a-lime} \tag{11}$$

where $S_{a\text{-lime}}$ is the specific surface area of lime.

The only unknown in Eq. (11) is $S_{a\text{-lime}}$, which for lime of hydrated dolomitic origin ranges between 15,000 m^2/kg and 20,000 m^2/kg and hence on average can be taken as $S_{a\text{-lime}} = 17{,}500$ m^2/kg (Boynton, 1980; Lesueur et al., 2013).

The original soil-lime UCS problem given in Eq. (5) can now be expressed as

$$\pi_o = \frac{q_u}{P_o} = F_B(\pi_1, \pi_2, \pi_3) \tag{12}$$

where F_B is a multi-variable functional expression, which can be defined as (e.g. Buzzi, 2010; Buzzi et al., 2011; Simon et al., 2017; Berrah et al., 2018):

$$\pi_o = F_B(\pi_1, \pi_2, \cdots, \pi_N) = \prod_{N=1}^{K-1} \pi_N^{\beta_{N-1}} \tag{13}$$

where π_N is the input π variable, $K-1$ is the number of input π variables, β_{N-1} is the fitting/model parameter (dimensionless), and N is the index of multiplication.

The input π variables, while retaining their dimensionless nature, can be manipulated to avoid mathematical singularities and/or scaling effects associated with SI unit conversions (Simon et al., 2017). The latter facilitates convergence in fitting of the experimental data (Soltani and Mirzababaei, 2018). Common manipulations, as commonly practiced in the literature (e.g. Buzzi et al., 2011; Williamson and Cortes, 2014; Soltani et al., 2018a), include $\pi+C$, πC and π^C (C is a constant real number). The input π variable $\pi_1 = L_c$ can take values of zero for mix designs involving no lime, and as such, π_1 was changed to $1-\pi_1$ to avoid mathematical singularities. Moreover, π_3 was changed to $10^{-16}\pi_3$ to eliminate scaling effects encountered as a consequence of SI unit conversions. Taking into account the aforementioned considerations, Eq. (12) (with F_B given in Eq. (13)) can be rewritten as

$$\pi_o = (1 - \pi_1)^{\beta_o} (\pi_2)^{\beta_1} \left(\frac{\pi_3}{10^{16}}\right)^{\beta_2} \tag{14}$$

where β_o, β_1 and β_2 are the fitting/model parameters (dimensionless).

Substituting Eqs. (6)–(9) in Eq. (14) leads to the following equation for the UCS:

$$q_u = P_o(1 - L_c)^{\beta_o}[w_o(1 + L_c)]^{\beta_1} \left(\frac{T_c S_{a-mix}\sqrt{\rho_{do} P_o}}{10^{16}}\right)^{\beta_2} \tag{15}$$

Assuming that the proposed dimensional analysis also applies for splitting tensile testing conditions, Eq. (15) can be rewritten in terms of the STS as

$$q_s = P_o(1 - L_c)^{\alpha_o}[w_o(1 + L_c)]^{\alpha_1} \left(\frac{T_c S_{a-mix}\sqrt{\rho_{do} P_o}}{10^{16}}\right)^{\alpha_2} \tag{16}$$

where α_o, α_1 and α_2 are the fitting/model parameters (dimensionless).

2.2. Results and discussion

The proposed dimensional models given in Eqs. (15) and (16) were, respectively, fitted to the experimental/actual q_u and q_s data (presented in Figs. 5 and 7 of the original article) by means of the nonlinear least squares optimization technique (Estabragh et al., 2016). It should be noted that only median values of q_u and q_s were considered for each mix design. Statistical fit-measure indices consisting of the coefficient of determination (R^2), the root mean squares error (RMSE) and the normalized root mean squares error (NRMSE) were then obtained for model validation by the following relationships (Soltani et al., 2018b):

$$RMSE = \sqrt{\frac{1}{M}\sum_{m=1}^{M}(\hat{y}_m - y_m)^2} \tag{17}$$

$$NRMSE = \frac{RMSE}{y_{max} - y_{min}} \times 100\% \tag{18}$$

where $\hat{y}$ is the predicted value of the dependent variable ($=q_u$ or q_s); y is the actual value of the dependent variable; M is the number of data points (or soil-lime mix designs) used for model development ($M = 20$, as outlined in Section 2.1.8 of the original article); m is the index of summation; and y_{max} and y_{min} are the maximum and minimum values of the dependent variable data, respectively.

The regression analysis outputs with respect to the proposed dimensional models, i.e. Eq. (15) for q_u and Eq. (16) for q_s, are summarized in Table 1. The R^2 values were greater than 0.97, implying that leastwise 97% of the variations in experimental observations are captured and further explained by the suggested dimensional models. For Eq. (1) (suggested in the original article), however, R^2 was reported as low as 0.78 for some mix designs (see Figs. 8 and 9 in the original article), thereby indicating a greater capacity to simulate the UCS and STS by means of the proposed dimensional models. The NRMSE values were found to be less than 5% for both cases, thereby predicating a maximum offset of only 5% associated with the predictions. The variations of predicted (by Eq. (15) for q_u and Eq. (16) for q_s) versus actual data, along with the corresponding 95% prediction bands, are provided in Fig. 1a and b for q_u and q_s, respectively. All data points firmly lie between the upper and lower 95% prediction bands, thus indicating minor scatter and no major outliers associated with the predictions.

Fig. 2 illustrates the variations of q_s (predicted by Eq. (16)) against q_u (predicted by Eq. (15)) for the tested mix designs. A strong correlation in the form of a two-parameter linear function, i.e. $q_s = 0.268q_u - 55.745$ (with $R^2 = 0.988$), can be achieved between q_s and q_u, which is essentially similar to that reported by the

Table 1
Summary of the regression analysis outputs with respect to the proposed dimensional models.

Variable	β_o or α_o	β_1 or α_1	β_2 or α_2	R^2	RMSE (kPa)	NRMSE (%)
UCS, q_u (Pa) (Eq. (15))	−12.429	−1.44	0.267	0.979	34.54	3.88
STS, q_s (Pa) (Eq. (16))	−17.614	0.258	0.365	0.977	9.91	4.48

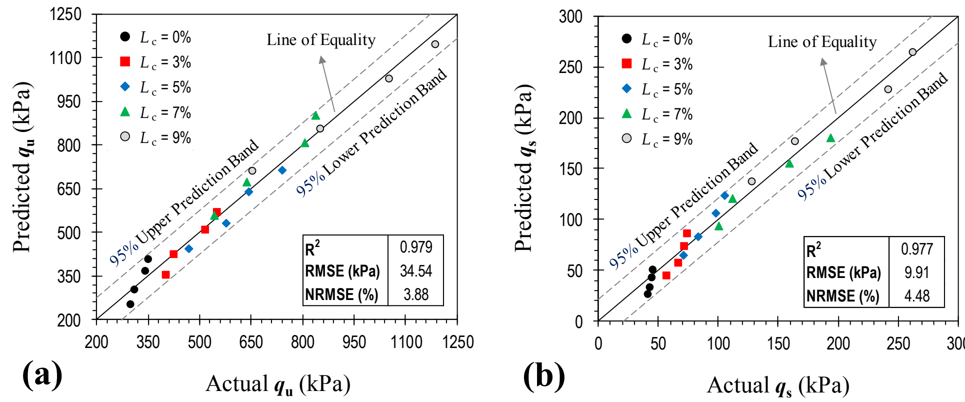

Fig. 1. Predicted versus actual data, along with the corresponding 95% prediction bands, for various soil-lime mix designs: (a) q_u (Eq. (15)); and (b) q_s (Eq. (16)).

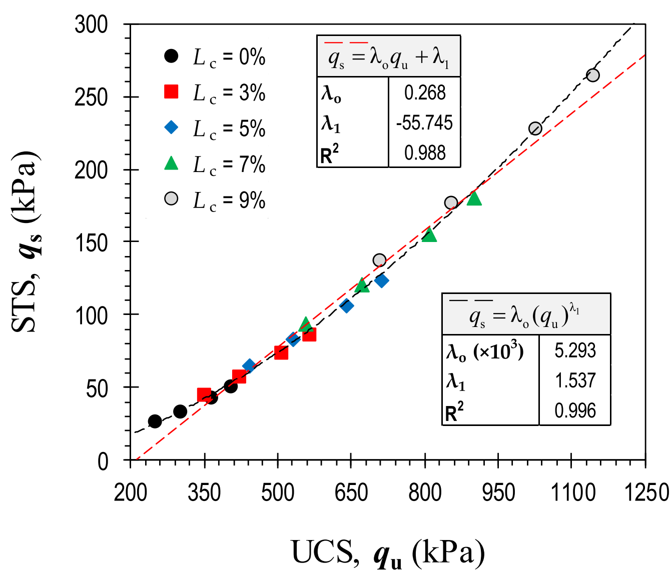

Fig. 2. Variations of q_s (predicted by Eq. (16)) against q_u (predicted by Eq. (15)) for the tested mix designs.

authors with respect to the actual q_s and q_u data (see Fig. 10 in the original article). As demonstrated in Fig. 2, the correlation can be further improved by means of a two-parameter power function defined as (with $R^2 = 0.996$):

$$q_s = \lambda_o (q_u)^{\lambda_1} \tag{19}$$

where λ_o and λ_1 are the fitting parameters (taken as $\lambda_o = 5.293 \times 10^{-3}$ and $\lambda_1 = 1.537$, as outlined in Fig. 2).

By substituting Eq. (15) into Eq. (19), the following semi–dimensional relationship can be derived for q_s:

$$q_s = \lambda_o \left\{ P_o (1 - L_c)^{\beta_o} [w_o (1 + L_c)]^{\beta_1} \left(\frac{T_c S_{a-mix} \sqrt{\rho_{do} P_o}}{10^{16}} \right)^{\beta_2} \right\}^{\lambda_1} \tag{20}$$

The variations of predicted (by Eq. (20)) versus actual q_s data for various soil-lime mix designs are provided in Fig. 3. Similar to the independent dimensional model proposed for q_s, i.e. Eq. (16), all data points firmly lie between the upper and lower 95% prediction bands, thus indicating minor scatter and no major outliers associated with the predictions. The R^2 and NRMSE values with respect to Eq. (20) ($R^2 = 0.973$, and $NRMSE = 4.81\%$) were observed to be on a par with that of Eq. (16) ($R^2 = 0.977$, and $NRMSE = 4.48\%$), thus signifying an excellent capacity for estimating q_s by means of the predicted q_u data.

3. Summary and conclusions

The dimensional analysis concept was extended to the soil-lime UCS/STS problem, thereby leading to the development of physically meaningful models capable of predicting the UCS and STS of soil-lime mixtures as a function of the mixture's index properties, i.e. lime content, initial placement (or compaction) condition, initial specific surface area and curing time. The shortcomings associated with the empirical model proposed in the original article (or Eq. (1)) were outlined in detail. It was observed that Eq. (1) suffered from long-lasting and sophisticated calibration procedures as well as low accuracy. The empirical model suggested in the original article contained a total of two fitting/model parameters, which were both functions of curing time, and as such, should be calibrated over a wide range of curing times. For the dataset presented in the original article, which considered a total of four curing times,

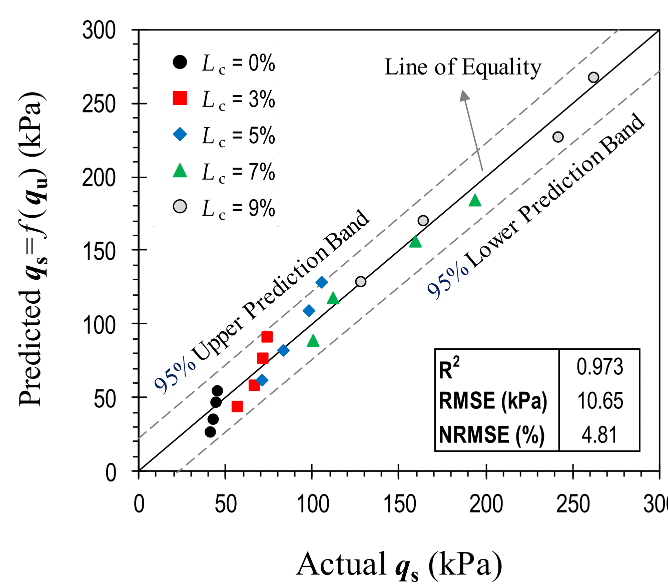

Fig. 3. Predicted (by Eq. (20)) versus actual q_s data, along with the corresponding 95% prediction bands, for various soil-lime mix designs.

the model calibration would have required a total of $4 \times 2 = 8$ q_u and $4 \times 2 = 8$ q_s measurements. However, the proposed dimensional models in this discussion each contain a total of three model parameters, which can be calibrated by minimal experimental effort and hence implemented for predictive purposes. The dimensional model parameters, regardless of curing time, can be adequately estimated by a total of three unconfined compression and three splitting tension tests (i.e. $3 + 3 = 6$ compared to $8 + 8 = 16$ for Eq. (1)). Three testing scenarios consisting of the virgin soil (containing no lime) and an arbitrary soil-lime mixture at two different curing times are recommended for the calibration phase. In general, the choice of lime content and curing time for the adopted soil-lime mixture would be arbitrary. However, from a statistical perspective, a median lime content tested at both short and long curing conditions is expected to yield a more reliable estimate of the model parameters (Mirzababaei et al., 2018; Soltani and Mirzababaei, 2018). Alternatively, the STS can be indirectly estimated by means of the UCS predicted by its relevant dimensional model. Additional tests, carried out on soils of varying plasticity and geological origin, may complement the derivation of empirical relationships for the dimensional model parameters (i.e. β_o, β_1 and β_2 in Eq. (15) and α_o, α_1 and α_2 in Eq. (16)) as a function of the soil's index properties (e.g. consistency limits, grain-size distribution and specific surface area), thereby eliminating any potential difficulties associated with model calibrations.

Conflicts of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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