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Establishment of generic transformations for geotechnical design parameters

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ABSTRACT

Geotechnical design parameters are typically estimated based on the transformations from site investigation results. In general, one expects the transformation uncertainty to change depending on the number and type of sites in the database. This study tries to address the following two issues pertaining to the transformation uncertainty: (a) how transformation uncertainties change with the number and type of sites in the database and (b) whether transformation uncertainties will eventually fall within a narrow range when a "generic" transformation is developed from a sufficiently large database. This study also attempts to propose a framework to establish such a generic transformation and quantify its uncertainty. This framework is demonstrated by the transformation between piezocone CPTU data and undrained shear strengths (S_u) of clays. It was found that the CPTU–S_u transformation and its uncertainty is site or region-dependent, and the "local" transformation equation from one site may not be applicable to another site, both in terms of the mean trend (which is well known) as well as the coefficient of variation (c.o.v.). An approach is proposed to develop the generic CPTU–S_u transformation equations that can be applied for downstream reliability analysis or design in the absence of local data. Sensitivity analysis shows that it requires data from at least 15 sites with the accompanying implicit assumption that sufficient geographical coverage typically implies sufficient geologic diversity to reliably build such "generic" transformation equations.

1. Introduction

Geotechnical designs require careful assessment for the mean values and variabilities of design parameters such as soil shear strength and modulus. These design parameters are typically estimated based on transformations from site investigation results. Quantification of transformation uncertainty [1,2] is essential when reliability analysis and reliability-based design are of concern. In the case where local experiences are sufficient, the mean value and coefficient of variation (c.o.v.) of a design parameter can be readily identified. As a real example, empirical data between undrained shear strength (S_u) and SPT $-$ N value from 25 sites in Japan indicate that [3]

$$\log_{10}(S_u/P_a) = 0.72 \times \log_{10}(N) + \log_{10}(0.29) + \varepsilon \quad (1)$$

where P_a is atmosphere pressure, and ε quantifies the transformation uncertainty for this $S_u - N$ transformation: it has zero mean and standard deviation equal to 0.15 [2]. Given the site investigation result for SPT $-$ N value, the mean value and c.o.v. of S_u can be readily identified.

It is reasonable to question whether or not the mean trend and its uncertainty given in (1) can apply to a site outside Japan, given that N may not be only affected by S_u (e.g., stress history, plasticity index, and sensitivity may also affect N). There can be two major concerns: (a) whether the mean trend can be extrapolated to a site outside Japan and (b) whether the standard deviation of 0.15 can be extrapolated to that site. The above concerns are valid because the clay at the site may not have the same stress history, plasticity index, and sensitivity as the Japan clays. For the first question, the mean trend based on Japan data, in principle, should not be extrapolated to a site outside Japan. In fact, such extrapolation may not be necessary because the local mean trend for the site can be reliably estimated based on site investigation data derived from this site. The second question is rather important for reliability-based design (RBD). For this question, however, site investigation data derived from a single site are typically insufficient to characterize the transformation uncertainty. As a result, it is desirable to know whether this 0.15 standard deviation based on Japan experiences is "generic" so that the extrapolation to a site outside Japan is reliable.

The present paper focuses on the transformation uncertainty (second-order statistics) and this must be clearly distinguished from the better known mean trend (first-order statistics). The mean trend is loosely called the "regression equation" in the literature and it is occasionally reported without the data scatter. In principle, one expects the transformation uncertainty to change depending on the number and type of sites in the database. To our knowledge, no one really knows: (a) if transformation

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uncertainties are comparable or to what degree are they incomparable given the unavoidable differences in the underlying local databases and (b) if transformation uncertainties will eventually fall within a narrow range when a generic transformation is developed from a sufficiently large database. As mentioned above, the first question is rather important for RBD, particularly in situations where there are sufficient local data to estimate the mean trend but insufficient to characterize the uncertainty. It is reasonable to assume that a generic correlation trend will produce a large "generic" transformation uncertainty that can be conservatively applied to sites where relevant local data are insufficient. Under this assumption, we would need to have a means for estimating this "generic" transformation uncertainty.

The main objective of this study is to examine the above issues pertaining to local versus generic transformation uncertainties. As a demonstration, the transformation between cone resistance in a piezocone test (CPTU) and S_u is studied. In particular, local CPTU–S_u trends and magnitudes of the local transformation uncertainties will be studied to verify if the above issues are of practical significance. An approach will be proposed to estimate the magnitudes of the generic transformation uncertainties based on a generic CPTU–S_u database. A procedure of verifying whether the obtained transformation equation is indeed generic is proposed and demonstrated. The practical outcomes of this study consist of simplified formulas for estimating the mean values and coefficients of variation (c.o.v.) of S_u based on the CPTU results. These formulas are expected to work well even for cases where local data are not available. This paper does not seek to improve existing CPTU–S_u correlation equations or to propose new ones, but seek to clarify the uncertainties underlying these correlations (usually mean trends) based on available data in the literature. In short, the focus is not on the well known regression line, but the data scatter about this line. A systematic study of the behavior of this data scatter under different regression scenarios ("local" single site or "generic" multiple worldwide sites) is particularly useful for RBD.

2. CPTU–S_u transformations

The CPTU test is increasingly popular nowadays for profiling S_u because it is quick, relatively reliable and potentially able to construct continuous profiles [4–9]. Previous studies [4–6,9–33] typically compiled data points for some local regions (e.g. Hong Kong, Vancouver, London, etc.) to develop the CPTU–S_u transformation equations. A more sophisticated study involving estimating of S_u from multivariate data such as CPTU, SPT, and OCR, was carried out recently [34]. To our knowledge, this study is the first of its kind to construct multivariate correlations (CPTU–SPT–S_u) from existing pairwise correlations (e.g., CPTU–S_u, SPT–S_u) within a rigorous Bayesian framework. However, [34] assumed that the transformation uncertainties associated with pairwise correlations can be readily estimated based on the data scatter. Although this is true, it is reasonable to question if the results can be applied to another site located in a different region, which was not addressed in [34].

There are at least three correlation models for S_u based on CPTU results [5,7]: (a) N_{KT} model; (b) N_{KE} model; and (c) $N_{\Delta u}$ model. These models propose non-dimensional parameters N_{KT}, N_{KE} and $N_{\Delta u}$:

$$N_{KT} = \frac{q_T - \sigma_{v0}}{S_u} \quad N_{KE} = \frac{q_T - u_2}{S_u} \quad N_{\Delta u} = \frac{u_2 - u_0}{S_u} \tag{2}$$

where $q_T = q_c + (1 - a)u_2$ is the corrected total cone resistance; q_c is the uncorrected cone resistance, u_2 is the pore pressure measured right behind the cone, and a is the area ratio of the cone; σ_{v0} is the total vertical stress; u_0 is the hydrostatic pore pressure. Let us employ the following unified notation:

$$N_j = \frac{\theta_j}{S_u} \tag{3}$$

where $N_1 = N_{KT}$, $N_2 = N_{KE}$ and $N_3 = N_{\Delta u}$, while $\theta_1 = q_T - \sigma_{v0}$, $\theta_2 = q_T - u_2$ and $\theta_3 = u_2 - u_0$. These cone "N factors" are found to be empirically correlated to the pore pressure ratio (B_q):

$$B_q = \frac{u_2 - u_0}{q_T - \sigma_{v0}} \tag{4}$$

In Lunne et al. [35] and Karlsrud et al. [36], the CPTU–S_u correlations are studied, and Fig. 1 summarizes the possible ranges of these N factors (the dashed red lines) proposed by these studies. Apart from these studies, Kulhawy et al. [37] examined a large database of CPTU–S_u correlations and summarized that N_{KT} is on average 1/0.0789 = 12.7 with a c.o.v. of 0.35. In the following section, a global CPTU–S_u correlation database compiled from available data in existing literature will be presented, and these ranges and conclusions will be re-examined with greater rigor.

3. CPTU–S_u database

A global database of CPTU tests is compiled. There are in total 38 sites worldwide in the database, nearly 1/3 of the sites were mentioned in [38]. Table 1 summarizes the background information for the 38 sites. Among them, 13 sites in Canada, 8 sites near Norway (including North Sea), 5 sites are located in the United States, 3 sites in Brazil, 3 sites in Britain, 2 sites in Venezuela, 1 site in Hong Kong, and 1 site in Italy. The clays range from normally consolidated to medium over-consolidated clays; the clays of ten sites are sensitive with sensitivity up to 500.

All sites were tested with standard electric cones; four sites do not have the pore pressure information u_1 or u_2. The area ratios a for the test cones ranges from 0.38 to 0.82. The data for each site is typically composed of the following items: (1) q_c profile; (2) u_2 profile; and (3) either the tested S_u values at selected depths (by laboratory UU, UC, CIUC, CAUC tests) or the S_u profile from field vane shear tests (VSTs). The number of data points listed in the table denotes the number of S_u data points for each site, ranging from 2 to 27 data points. The total number of data points is 482. Among the 38 sites, the Atterberg limits for 33 sites are known at selected depths, and OCRs are known for 33 sites at selected depths.

The original data points are pre-processed based on available information to ensure that subsequent analyses would be as consistent as practically possible:

1. All q_c are converted into q_T to correct for the effect of pore pressure generated behind the cone. This requires the knowledge of u_2 and area ratio a. There are 15 sites, where a is not documented. For these cases, an average a value = 0.7 is assumed, because a typically ranges from 0.55 to 0.9 [41] and because 0.7 is also the average a value for our database. There are also four sites, where the pore pressure is not measured. For these cases, the correlation equations suggested by Mayne et al. [42] is adopted to estimate u_2 based on q_c.
2. All measured pore pressures are converted into u_2. There are seven sites where u_1 (pore pressure at cone tip) rather than u_2 is measured. In this case, the correlation equation suggested by Mayne et al. [42] is used to convert u_1 into u_2.
3. The vertical total stress is estimated from the soil profile. In the cases where the soil unit weights and water table depths are not known, reasonable estimates are made. Note that bulk unit weight of soil varies over a relatively narrow range and water table depth affects it marginally due to saturation. Hence, it is possible to obtain reasonable estimates of the vertical total stress even in the absence of bulk unit weights and water table depths.