International Journal of Civil Engineering

Geotechnique

Technical Note

Reliability measures for consolidation settlement by means of CPT data

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Received: March 2013, Revised: May 2013, Accepted: July 2013

Abstract

In this technical note, a methodology is introduced for reliability calculation of consolidation settlement based on cone penetration test (CPT) data. The present study considers inherent soil variability which influences consolidation settlements results. To proceed reliability analysis, the measured data of a sample corrected cone tip resistance (q_t) is detrended using a quadratic trend and the residuals are assumed to be lognormally distributed random field. Realizations of q_t is generated by using spatial variability of residuals including standard deviation and the scale of fluctuation. The quadratic trend and the generated residuals are then combined to correlate shear and bulk modulus as input consolidation properties for coupled analysis and subsequently consolidation settlement was calculated by using finite difference method adopted in Monte Carlo simulations. The results of reliability analysis are presented describing the range of possible settlements by considering characteristics of uncertainties involved at the particular site. Number of realizations rendering settlements smaller than the allowable settlement must be such that guarantee proper performance or acceptable reliability index.

Keywords: *Reliability, Settlement, Consolidation, CPT, Monte Carlo Simulation Bests.*

1. Introduction

The importance of variability analysis is increasingly recognized in geotechnical engineering as reliability based design (RBD) methods are assuming a prominent role for the calibration of new design codes. However, in geotechnical practice, there has been rather slow progress in employing RBD, compared to other engineering disciplines. A primary reason for this slow progress is difficulty in estimating the variability of the design properties of geo-material, which is essential for any RBD procedure. A fundamental problem is the lack of data. There is a tradition of basing conclusions in laboratory testing programs on small numbers of tests. It is quite common to encounter laboratory programs consisting of three or four consolidation tests. Therefore there are seldom enough data to support broad conclusions about the statistics of soil properties.

Several studies have been published on the variability of the properties of soils (e.g., Phoon and Kulhawy 1995). Sometimes the values in these publications are simply adopted into reliability calculations without further efforts to establish the variability for the particular project at hand.

Despite the excellent work that has been done on this issue, it is not a closed matter, and more work needs to be done. In particular there needs to be more work on how much effort is required to improve the estimates for a particular site. However calculating the actual variability of soil properties is one of the unresolved problems in geotechnical risk and reliability (Christian and Baecher 2011).

Among in situ testing methods, cone penetration (CPT) measurements are ideal for assessing soil variability because a large volume of near continuous data can be collected in a cost-effective way, the test has good repeatability, the equipment is highly standardized, and the procedure is well-defined and almost operator-independent. Moreover, CPT has strong theoretical basis for interpretation and numerous semi-empirical correlations have been developed to estimate geotechnical parameters from the CPT for a wide range of soils (e.g, Robertson 2009). A number of researches on the application of CPT measurement in reliability analysis for different geotechnical problems have recently been published (e.g., Uzielli 2004 ; Haldar and Babu 2008; Doherty and Gavin 2010 ; Kenarsari et al. 2011 and 2013).

In this technical note, a methodology is introduced for reliability calculation of consolidation settlement based on reliability analysis of CPT data. This general approach can be an effective technique to predict consolidation settlement using probabilistic analyses considering uncertainties involved at a specific site. However, the main shortcoming of current research is that it lacks sufficient

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convincing field measurement data to verify the calculations and predictions on such cases. Field instrumentation was not installed to measure consolidation settlement. However, a deterministic analysis performed to compare reliability results with available conventional method.

2. CPT Data and Statistics

2 In present study, a typical CPT sounding from the Adapazari area, Turkey was selected for stochastic analyses. The CPT was performed by Zemin Teknolojisi, A. S. (ZETAS) and the instrumentation was performed by A. P. van den Berg, Netherlands based company. The specifications of the equipment consist of a 60° cone with a cross-sectional area of 10 cm^2. The friction sleeve, located above the tip, has an area of 150 cm^2. The piezocone has the filter located behind the cone and the cone area ratio is 0.75. For more details, the reader is directed to the internet report (Bray et al. 2001).

To exclude lithological heterogeneity a clay - silty clay layer with 7.36 meter thickness was identified from the CPT profile for variability analysis by adopting the classification charts proposed by Robertson (1990). Figure 1 provides the soil profile acquired from normalized soil behavior chart according to the CPT profile. The data set consists of 368 measurements of corrected cone tip resistance, q_t, digitized at a 0.02 m interval.

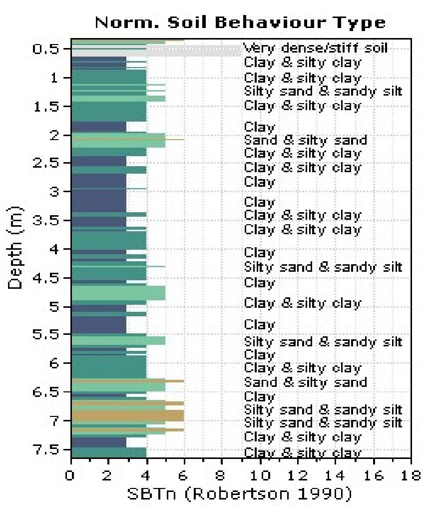

Fig. 1 Normalized soil behavior type based on CPT profile

To guarantee stationary, a quadratic trend was sought to remove from original data set. The original measured data, quadratic trend and the residual component are illustrated in figure 2. Pishgah and Jamshidi (2011 a and b) have shown that the deterministic component of the inherent variability plays a prominent role in consolidation behaviour of natural alluvial deposits. The stochastic properties of the residual component can be quantified thorough calculation of the standard deviation and the correlation length.

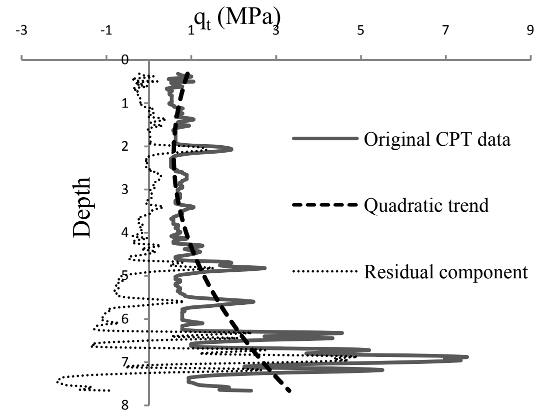

Fig. 2 Detrending of CPT data

Standard deviation is translated into a more recognized parameter, coefficient of variation (COV) which is defined as the ratio of the standard deviation to the deterministic mean value. Correlation length or the scale of fluctuation which is defined as the distance over which the data points have meaningful correlation. The procedure proposed by Jones et al. (2002) was employed to calculate the scale of fluctuation of the CPT residual profile. Figure 3 shows how the lag distance varies with the window size used in moving average scheme. The plot peaks at 0.16 m; therefore the scale of fluctuation is taken to be 0.16 m.

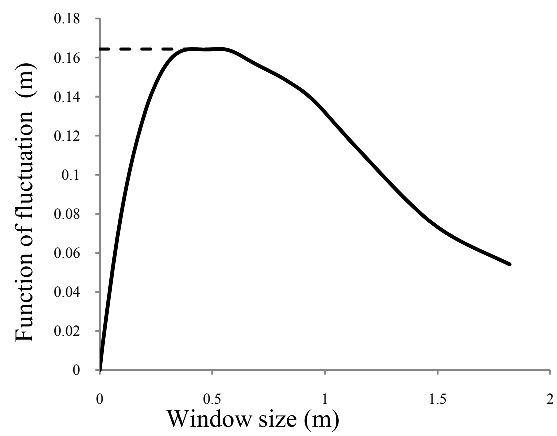

Fig. 3 Calculation of the correlation length

3. Consolidation Problem

Soils are naturally, inherently variable because of the way they are formed and the continuous processes of the environment which work to alter them. Taking the coefficient of consolidation as a constant is a major shortcoming of conventional theory. It is well known that consolidation properties must be treated independently and cannot embodied into a single coefficient of consolidation. Therefore it is very important to use a coupled approach for proper modeling of consolidation behavior of heterogeneous soils (Huang et al. 2010).

Consolidation is one type of fluid/solid interaction, in which the slow dissipation of pore pressure causes displacements to occur in the soil. This type of behavior involves two mechanical effects. First, changes in pore pressure cause changes in effective stress, which affect the response of the solid. Second, the fluid in a zone reacts to mechanical volume change by a change in pore pressure. For the coupled consolidation analysis in present study, commercially finite difference code, FLAC 5.0 (Itasca 2006) is used that models the flow of fluid (e.g., groundwater) through a soil. The *saturated fast-flow* logic is used for simulating coupled fluid flow/deformation of a porous medium (i.e., consolidation) by simply adding the command "SET fast flow on". This numerical scheme provides faster solutions for consolidation calculations which can be very time-consuming. The FLAC model for one-dimensional consolidation problem is a column of 368 zones representing adjacent CPT readings and 100 kPa pressure is applied at the top of the column to model the surcharge effect.

4. Reliability Analysis

CPT profiles were virtually reproduced using random field theory and the stochastic properties acquired from the original CPT profiles. Cholesky decomposition technique was used to produce correlated random fields of q_t. The generated realizations of q_t were then employed to correlate shear modulus and produce equivalent profiles of the shear modulus. The small strain shear modulus, G_0, for young, uncemented soils can be estimated from equation 1 using the following relationship proposed by Robertson (2009):

$$G_0 = 0.0188\left[10^{(0.55 I_c + 1.68)}\right](q_t - \sigma_{v0}) \tag{1}$$

in which I_c is soil behavior type index and σ_{v0} is vertical total stress.

The above correlation was used to interpret input shear modulus values for numerical modeling. A constant Poisson's ratio of 0.35 was considered for correlation of the bulk modulus, *K*. Ultimate consolidation settlement is assumed to be independent of the hydraulic conductivity of alluvial deposits, *k*. Therefore the variability of the permeability coefficient was neglected. Near 100 percent average degree of consolidation was sought as an index for full consolidation settlement.

2000 Monte Carlo simulations were conducted to investigate the effect of spatial variability of q_t on consolidation settlement results as shown in figure 4. The results show that the consolidation settlement fluctuates between 8 and 11.5 mm. The mean settlement of 9.6 mm is considered as the most likely settlement value. Reliability theory can be employed to evaluate the effects of uncertainties embedded in settlements calculations and the probability that the computed settlement will be larger than allowable settlements can be defined as probability of failure, P_f. For this reason a performance function should first be defined as introduced in equation 2.

$$M = 1 - \frac{S_c}{S_{all}} \tag{2}$$

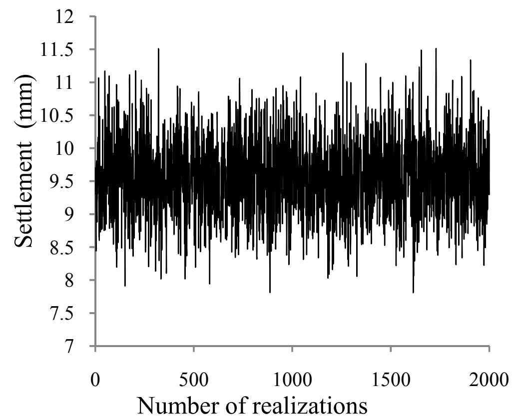

Fig. 4 Settlement results of Monte Carlo simulations

in which S_c is the consolidation settlement calculated from numerical analysis for each realization and S_{all} is the allowable consolidation settlement.

Failure is conceived when the performance function bears negative values. According to the computed settlement values from Monte Carlo simulations, the performance function is calculated and probability when the performance function adopts negative values is easily calculated. A more convenient measure of design risk is the reliability index, β which is defined as $-\Phi^{-1}(\mathrm{P_f})$ in which Φ^{-1} function is the inverse standard normal cumulative function (figure 5). Target reliability index should be more than 3 for proper performance according to *USACE* standard (Phoon, 2004). In figure 6 reliability index is calculated for different allowable settlements and it shows that target reliability index will satisfy when the allowable settlements is around the maximum possible settlement. This sort of analysis demonstrates that relying solely upon a single deterministic settlement calculation (Schmertmann's procedure as introduced shortly herewith) does not guarantee reliability. Instead different realizations of the same procedure should be generated and the same procedure to be repeated by either resorting to the numerical analyses as introduced and adopted before or empirical models to be employed subsequently. Figure 7 provides a flowchart on the introduced calculation process. It clearly demonstrates the procedure step by step.

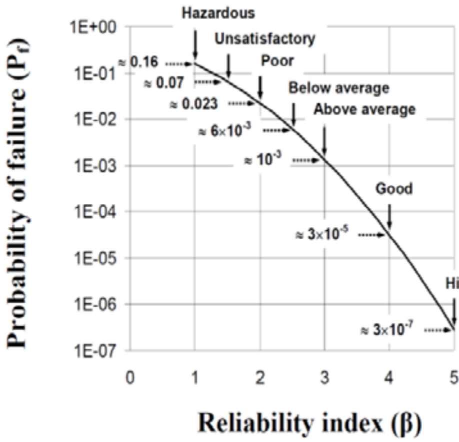

Fig. 5 Probability of failure versus reliability index according to *USACE* standard (Phoon, 2004)

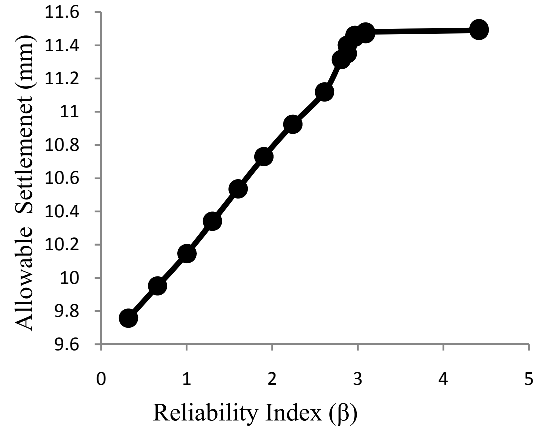

Fig. 6 Evaluation of the reliability index for different allowable settlements

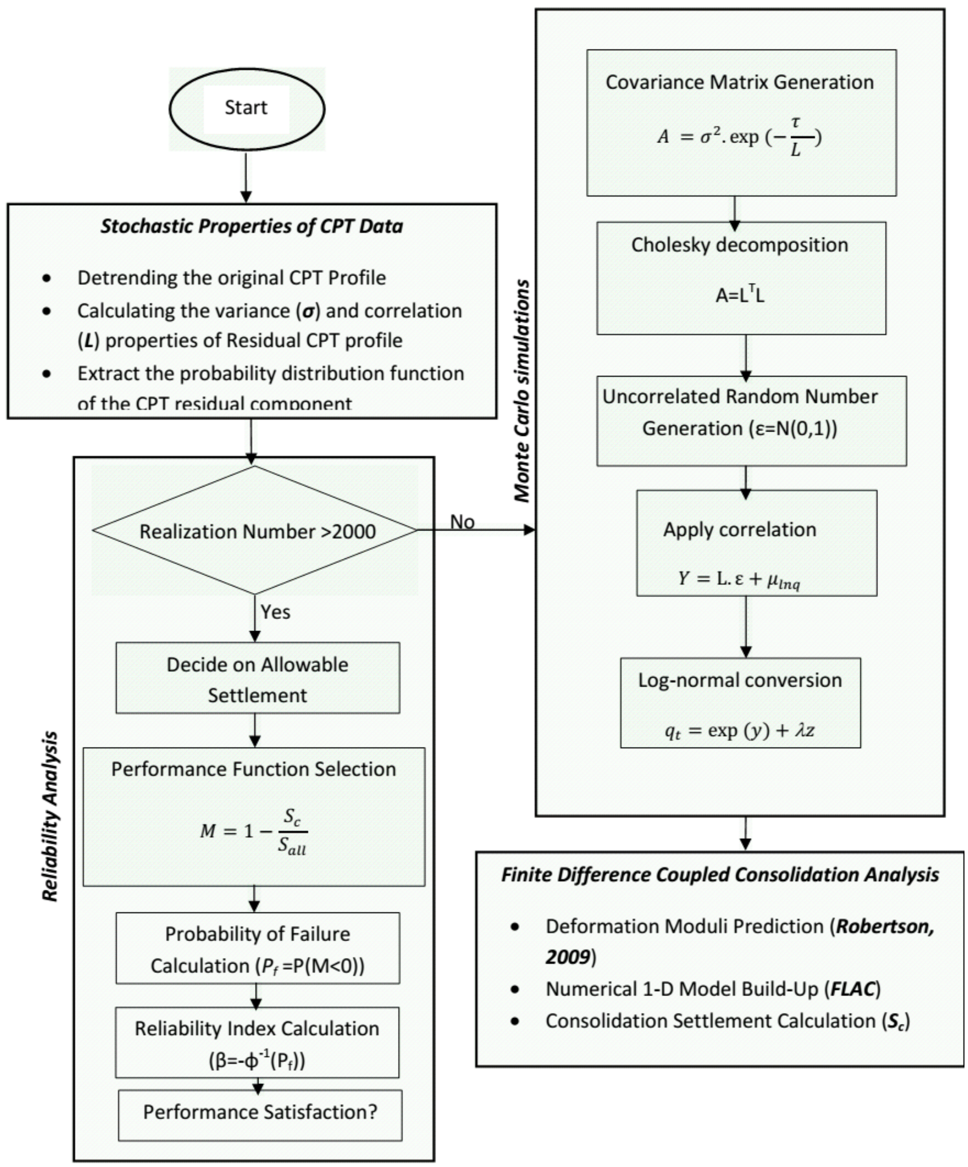

Fig. 7 Flowchart for calculation process of reliability analysis for consolidation settlement

5. Deterministic Analysis

CPT_u data can be used to directly estimate induced settlements due to an external load. To validate reliability results with a deterministic estimate of settlements, the Schmertmann's simple formula introduced in equation 3 (based *1-D* consolidation) is used to estimate vertical settlements:

$$s = q \times \sum h \times \frac{I_z}{M_{CPT}} \quad (3)$$

Where, q, h and I_z are applied footing pressure, layer thickness and stress reduction factor according to Boussinesq respectively. As shown in figure 8, constrained modulus of soil layer, M_{CPT} can be estimated from CPT results using the CPTet-IT software based on the correlation suggested by Robertson (2009). For a constant surface load, $q=100\ kPa$, maximum settlement result accumulated on top of the layer is 9.2 mm. The computed consolidation settlement for deterministic analysis (9.2 mm) is in the range of proposed settlement estimation based on reliability analysis (8 and 11.5mm). As the deterministically predicted settlement is around the mean value in this case it is then considered the most probable settlement value.

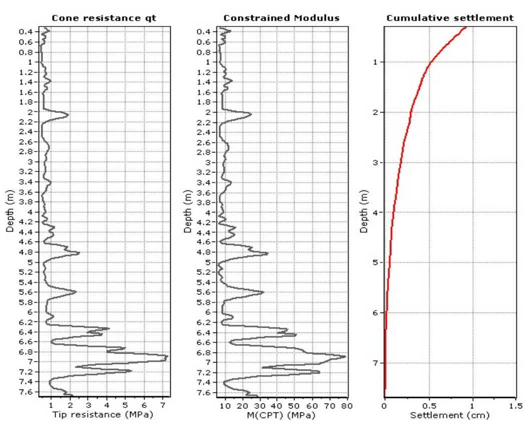

Fig. 8 Consolidation settlement prediction from deterministic analysis

6. Conclusions

CPT data can be used to evaluate uncertainties involved at a specific site by generating corrected cone tip resistance, q_t based on spatial variability parameters of residual components including the standard deviation and the scale of fluctuation. The quadratic trend and the generated residuals were superposed to realize profiles of q_t which are then employed in subsequent Monte Carlo simulation of coupled consolidation problem. Realizations of q_t were utilized for correlation of shear modulus which is finally fed to the finite difference formulation to calculate ultimate consolidation settlement. The results of 2000 Monte-Carlo simulation shows that variation of q_t has significant effect on settlement values. Range of ultimate consolidation settlements was computed and provides a pool of settlement data which are essential for reliability analysis. Reliability concepts can be applied to settlement analyses by comparing the predicted settlements and allowable settlement. The probability of failure occurs when the predicted settlement is larger than allowable settlement. The results of reliability index for different allowable settlements demonstrates that for satisfactory performance it is important that the maximum possible consolidation settlement in this case to be smaller than allowable settlement.

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