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Research Paper

Site variability analysis using cone penetration test data

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ABSTRACT

This paper presents a comprehensive methodology for quantification of site variability in a way that can be used in geotechnical practice. Site variability is separated into horizontal and vertical variability. To quantify vertical variability in a CPT sounding, a vertical variability index is proposed based on the complexity of the soil profile, the overall coefficient of variation for the depth range of interest, and intra-layer variability measures. To quantify horizontal site variability, a horizontal variability index is proposed based on the similarity of soundings performed at the same site. The method is illustrated using CPT data from five sites.

1. Introduction

Site investigation is an essential component of every construction project. A thorough site investigation aims to identify the stratigraphy, locate ground water level and estimate the range of physical and mechanical properties of the *in situ* soil layers. Due to the spatial variability of natural soil deposits, uncertainty in estimates of soil properties for a site is inevitable. Although this uncertainty cannot be eliminated, it can be quantified. If reasonably quantified, this uncertainty can be accounted for in reliability analysis or can be used to select resistance factors for use in Load and Resistance Factor Design (LRFD) [1–5].

Properties at different locations on a site are correlated but the correlation becomes increasingly weak with increasing distance between the points considered [6–8]. The spatial variability of cone penetration test (CPT) variables (e.g., cone resistance q_c or sleeve resistance f_s) has been studied using different measures of variability, such as the coefficient of variation (*COV*) and the scale of fluctuation (*SF*) (distance within which data points are significantly correlated) [9–11]. During the site investigation phase, if the variability of the CPT parameters is high, additional CPTs can be performed to better characterize soil properties; on the other hand, if variability is low, it may be possible to reduce the number of CPT soundings from what had been originally planned. Such decisions should of course be made with caution, accounting for the natural variation of the soil profile and geology of the area.

Paikowsky [10] suggests that site variability can be approximately categorized by the *COV* of strength parameters of the soil layers in the profile representative of the site. With this approach, first the bearing layers of the representative soil profile of the site are identified. For each of the bearing layers in the soil profile, the average strength parameter is obtained (e.g., the standard penetration test (SPT) blow count N_{SPT}). The *COV* of the average strength parameters of a representative soil profile is then calculated, and this forms the basis of the variability assessment. Based on the calculated *COV*, the entire site is characterized as low ($COV < 25\%$), medium ($25\% \le COV < 40\%$) or high ($COV \ge 40\%$) variability. Difficulties with the application of such a general approach based on the SPT include the very limited amount of data available for statistical treatment (values are only available at certain tested depths along the profile and, at each tested depth, only a single value is obtained). In comparison to SPT data, CPT data is considerably more reliable and provides a richer dataset of measurements along depth for a profile. These two features of a CPT dataset make it more amenable to statistical variability assessment methods in comparison to an SPT dataset [12].

Rigorous theoretical treatment of spatial variability has been an important topic of recent research [1–3,12–31] but remains difficult to apply for a variety of reasons, including difficulties with determination of key variables, such as the scale of fluctuation. The major focus of the research in geospatial statistics has been to model a site as a random field and then precisely infer the random field parameters (coefficient of variance, scale of fluctuation) at the site. To find values for random field parameters, researchers have used moment estimation techniques [32,33], maximum likelihood estimation techniques [7,34,35] and Bayesian techniques [28,36]. While the current research community is very active in the pursuit of more accurate descriptions of sites as random fields, research is needed for more immediate implementation of methods of site variability characterization based on current practice in CPT interpretation. This is important, for example, in LRFD-based

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codes that attempt to set resistance factors as a function of site variability. In this paper, knowledge of spatial statistics is applied to develop a methodology to quantify site variability via variability indices computed using CPT data. For the development of such a methodology, it was necessary to have a robust and logical algorithm capable of generating a soil profile from the CPT data recorded at the site. The modified soil behavior type (SBT) charts and algorithms proposed by [11,37] are used for this purpose. The methodology was developed in such a way as to be useful to practitioners wishing to gauge uncertainty in a systematic and reproducible manner that may also be used in the future in LRFD code development, with values of resistance factors, partial factors or factors of safety selected based on site variability measures. To demonstrate the use of the methodology, CPT data for five sites in the United States, taken from the United States Geological Survey (USGS) CPT database [38], are analyzed using the proposed method.

2. Soil profile generation from CPT data

Quantification of soil variability at a site requires identification of soil layers with different characteristics in a soil profile [14,39]. Typically, soil profiles are inferred from CPT data using soil behavior type (SBT) charts. An SBT chart serves as a simple signal transfer function that converts cone resistance-sleeve resistance pairs to "soil behavior" types [11,37]. Many SBT classification charts have been proposed over the years [40–53]. While any SBT chart in the literature could be used as a simple signal transfer function to develop a soil profile from CPT data, in this paper the soil profile generation algorithms proposed by [11,37] were used to generate soil behavior profiles from the CPT data. The algorithms [11,37] use modified versions of the Tumay chart [48] and Robertson chart [50], shown in Fig. 1(a) and (b), to convert CPT data into a soil profile that is amenable to the site variability algorithms introduced in the present paper. These algorithms were used because (1) they generate coherent soil profiles in which layers are classified using intrinsic and state-variable based descriptors and (2) occurrence of soil layers thinner than what can be properly sensed by the CPT probe [54,55] is handled in a logical manner. To properly sense a soil layer, the cone penetrometer must penetrate the layer to a certain extent to develop the shaft resistance f_s and tip resistance q_c corresponding to that layer; this length of penetration is called the development distance. Also, while within a soil layer, the CPT probe will start sensing the next soil layer before even reaching it; the distance from the next layer at which this happens is called sensing distance. Both the sensing and development distances are affected by the density of the soil layers and the dimensions of the probe and are of the order of 2.2–5.4 cone diameters [4–6]. If the layer is too thin in comparison to the probe dimensions, the cone resistance and sleeve friction will be as much affected by the overlying and underlying layers as by the thin layer itself, with the result that they are not representative of the layer. Thin layers cannot therefore be characterized as individual layers using the CPT; accordingly, layers thinner than 150 mm are consolidated into the adjacent thicker layers.

3. Site variability assessment algorithm

Fig. 2 shows the overarching procedure proposed to quantify site variability, which consists of the following steps: (1) soil profile generation, (2) quantification of vertical variability, (3) quantification of horizontal variability and (4) integration of vertical and horizontal variability into a site variability rating system.

Soil profiles can be obtained using SBT charts, as discussed in the previous section. Once a soil profile is established, the vertical variability index *VVI* (which reflects variability in q_c, f_s, layering and other factors for each CPT sounding) and the horizontal variability index *HVI* (which is based on the cross-correlation [11,56] between cone resistance logs, cone resistance trend differences and the spacing between

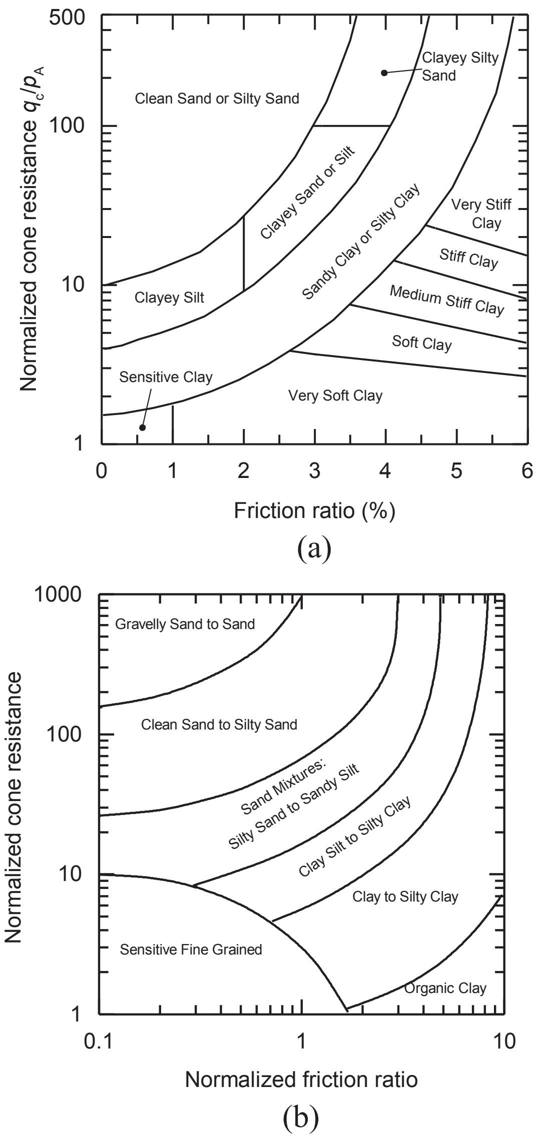

Fig. 1. Modified SBT charts used for soil profile generation: (a) modified Tumay chart [11,37,48]. (b) Modified Robertson chart [11,37,50].

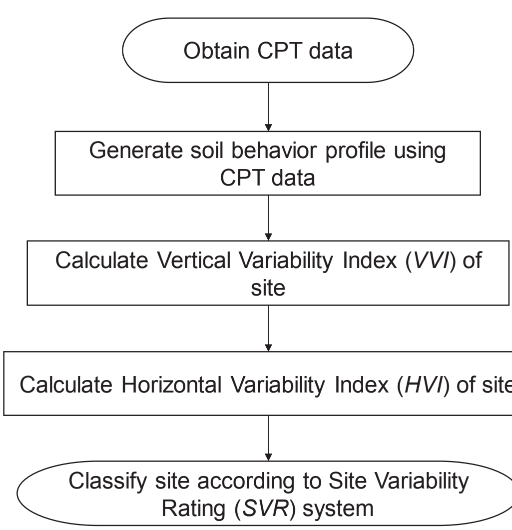

Fig. 2. Site variability assessment procedure based on computation of vertical variability index (*VVI*) and horizontal variability index (*HVI*).