Soil Dynamics and Earthquake Engineering 108 (2018) 1–12

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Efficient random field modeling of soil deposits properties

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ARTICLE INFO

Keywords:
Soil deposit
New autocorrelation model
Karhunen-Loeve expansion
Random field simulation

ABSTRACT

The autocorrelation function (ACF) of the soil profile in some sites in Shandong province, China is studied using cone penetration test (CPT) data. This is done in the context of a random field modeling of the soil deposits. It is found that the different types of soil profile have different stochastic parameters, and there is no obvious trend along the depth of the soil profile. Thus, the soil profile is examined within each layer. Numerical values for three existing analytical (ACF) models are derived by the least squares fitting approach for the different types of soil. Further, comparisons of the autocorrelation function between the tip resistance and sleeve friction were examined. Based on the autocorrelation data analysis, a new autocorrelation model, named linear-exponential-cosine (LNCS), is considered with differentiability at the origin of the spatial lag axis, and alternating sign along this axis. For all of the four ACF models, a related integral equation is numerically solved for determining the associated Karhunen-Loeve (K-L) representation. In this regard, it is noted that the new model is not only more physics-consistent, but also yields quite good computational efficiency. In the end, the random field of the soil profile is modeled using a two-dimensional K-L expansion with the new model, assuming separability in two dimensions.

1. Introduction

Uncertainty quantification (UQ) of soil related problems is important as simulation, optimization, and decision making analyses involve capturing the stochastic nature of the soil [1–3]. Due to the fact that soils are spatially variable, the mean, variance, and covariance structure of a specific soil site are needed for any realistic stochastic modeling [4–6]. In this context, and in attempting to establish the correlation structure of various soil profiles, the standard approximation procedure is to analyze the pertinent data and to deduce relevant trends and statistical features. However, in actuality, the soil deposits are often formed by many layers, and not all of the soil parameters have a discernible trend along the depth; the fact is that often no identical trends exists between the different layers. For instance, if the trend of the observed data of all layers is accepted, the correlation length of the data will be exaggerated. Thus, the variations will be averaged during the random field simulation, as it can be seen in Fig. 1, pertaining to a typical cone penetration test (CPT) data from a particular soil site. Therefore, the UQ modeling will be more reliable if it is performed separately for the different layers, and the spatial variations can be properly accounted for. Further and hopefully, the inferred specific soil type autocorrelation may be used for other site of the same type of soil.

In this context, and based on the data collected at alluvial districts in Shandong province, China, the spatial variations of cone penetration test (CPT) data are examined herein for four types of soil. The autocorrelation function models are obtained by the least squares approximation approach to the data, and analysis for the various types of soil. Further, to assess whether the same soil profiles have similar correlation structure, some comparisons are made between the two CPT parameters, tip resistance and sleeve friction. Furthermore, a new model which is both differentiable at zero spatial lag and with alternating sign is proposed based on the analysis of the autocorrelation of the recorded data. The convergence of the model is compared with the ones of the currently used models. Finally, the corresponding random field of the soil profile are simulated using the Karhunen-Loéve (K-L) expansion method [7] with the newly proposed model.

2. CPT site data analysis

CPT data have been used by many researches as a powerful tool to analyze the spatial correlation structure [8–10]. A CPT data provides the cone tip resistance and the sleeve friction with an equal sampling interval distance. In this paper, the CPT data were gathered in the Shandong province, China, and comprise measurements of cone tip

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https://doi.org/10.1016/j.soildyn.2018.01.036
Received 30 November 2017; Accepted 13 January 2018

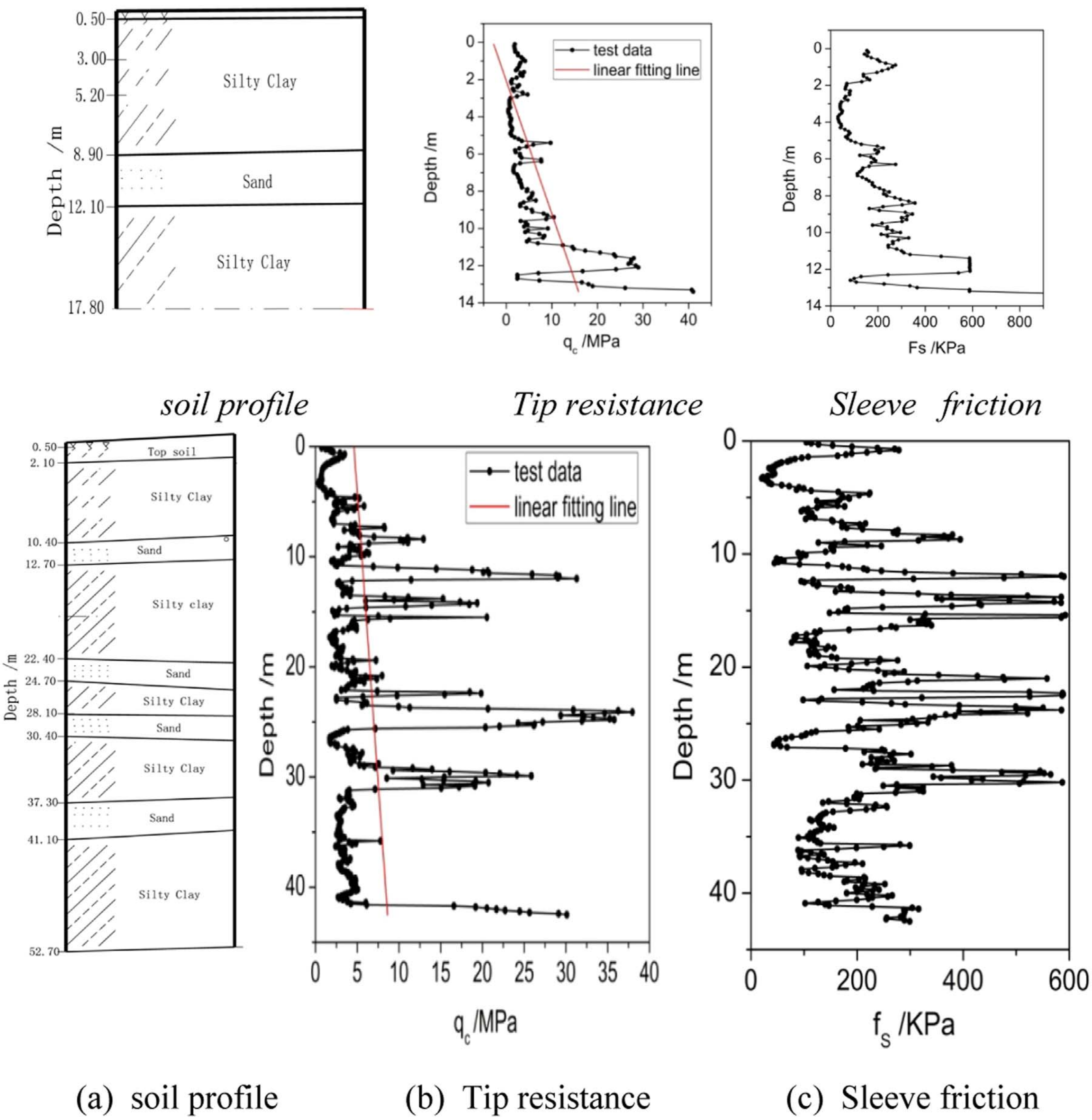

Fig. 1. CPT data of a typical soil profile.

resistance q_c (MPa), and sleeve friction f_s (kPa). The measurements were recorded at vertical intervals of 0.01 m. Six different sites including 157 soundings data are considered, scattered over the district of Shandong province, China.

In the statistical analysis of the actual soil data obtained from field or lab tests, obvious 'trends' (changes in average values) are often encountered, most often as a function of the depth. It is commonly accepted that the trends can be viewed as segments of a large-scale fluctuation and this large-scale fluctuation must appear as part of the statistical characterization if the trend also exist on other site inference [5,6]. The choice of the trend to be removed is a delicate task as it affects the correlation structure and the value of the statistical parameters describing the random filed [11]. Linear trend removal has been used in several variability studies. However, from the field data considered, it is found that in the same soil layer, no apparent linear trend with the depth exists. In this case, it is advantageous to standardize the soil data by substituting each original datum point $q_c(z)$ by the equation

$$q(z) = \frac{[q_c(z) - \bar{q}_c]}{\tilde{q}_c}, \tag{1}$$

where $\bar{q}_c$ is the mean value of the layer soil, and $\tilde{q}_c$ is the standard covariance.

Examining the collected data, it is seen that the sites mainly comprise four types of soil: silty clay, clay, silt and sand. Therefore, these four types of soil are analyzed in the paper. The mean values and the coefficients of variation (COV) for each soil type are listed in Table 1. It can be seen that less variation is exhibited in the clay soil, with the COV value of 34%. The silty clay soil has greater variance, with a COV value of 75%.

Next, it is assumed that the soil is spatially homogeneous, and that a CPT sounding represent an ensemble of realizations of a one-dimensional random field. That is, the random process representing the variation of q_c with depth has the same joint distribution at every vertical

Table 1
Mean values and COV of the soil type.

Soil type	No. of data groups	Mean q_c [MPa]	COV
Silty clay	144	2.95	0.75
Clay	121	1.88	0.34
Silt	136	2.85	0.51
Sand	108	16.16	0.51