Characterization of geotechnical spatial variability in river embankments from spatially adjacent SCPT

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ABSTRACT: characterization of the spatial variability of geotechnical properties of river embankment soils is important for the enhanced modelling and assessment of embankment stability. In practice, available data is usually limited. This study presents the results of a quantitative statistical analysis of the spatial variability of cone tip resistance from the results of 16 closely spaced SCPT carried out near a recent breach in a levee on the Panaro river in northern Italy. Two geotechnical homogeneous soil units are preliminary identified in the levee to ensure the meaningfulness of the analysis in terms of soil type. For each unit, the horizontal and vertical spatial variability and spatial correlation structures of cone tip resistance are investigated by a two-step procedure involving the calculation of empirical semivariograms and the subsequent fitting of semivariogram models. Horizontal and vertical scales of fluctuation are estimated based on fitted semivariogram model parameters.

1 INTRODUCTION

Levee and dike collapses cause considerable financial and social losses in many countries, especially in highly developed areas. Therefore, risk assessment of river embankment stability is receiving increasing attention worldwide. The quantitative estimation of the vulnerability of embankments, which is necessary for the risk assessment process, can be pursued in the form of fragility curves from the outputs of slope stability analyses. A key parameter in slope stability analyses is soil strength, which varies spatially within soil volume due to factors such as compositional heterogeneity, level of compaction, degree of saturation, cementations, and presence of ancient breech-repairing materials.

A levee failure occurred along the Panaro River in Northern Italy on 6th December 2020. The failure was caused by a combination of concurrent causes including soil heterogeneity, relict animal burrows, presence of ancient brick elements in the embankment body, as well as of rhizomes of Arundo Donax.

To corroborate the interpretation of such collapse, an extensive geotechnical and geophysical campaign was conducted, including a series of 16 closely spaced SCPT. CPT measurements have extensively proved to be well-suited for assessing inherent 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 independent of operator skill. The investigations revealed that the levee embankment is made of sand-silt mixtures in different proportions. While friction angle varies within a limited range (30-33 degrees), cohesion, which depends primarily on compaction level, soil suction and cementation, varies significantly even within a limited area.

This paper describes the procedures and results of a quantitative investigation into the vertical and horizontal spatial variability of cone tip resistance performed on the unsaturated silty sand of the river levee embankment. Section 2 describes the results of the geotechnical site investigation campaign along with a preliminary descriptive statistical analysis. CPT results are pre-processed to identify homogeneous soil units (Sec. 3) in which spatial soil variability is modelled through the application of geostatistical techniques (Sec. 4). Results of the geostatistical modelling process are assessed and discussed in Sec. 5

2 DESCRIPTION OF GEOTECHNICAL CAMPAIGN

The geotechnical campaign conducted in the area of the breach consisted in 12 CPTU, 2 SCPTU, 2 DMT, 2 boreholes, 7 ERT. A total of 11 undisturbed samples were collected for laboratory testing. To investigate in greater depth the spatial variability of soil strength, a short stretch of levee embankment, located approximately 150m west of the breach, was investigated through 16 seismic CPT soundings at a constant horizontal spacing of 2.5 m.

Cone tip resistance q_c and sleeve friction f_s were measured at vertical intervals of 1cm and the shear wave velocity V_s was measured at vertical intervals of 25cm with the true interval method. These tests reached a maximum depth of 5.5m. Figure 1a-b plots the complete set of results of the SCPT campaign. A smoothing procedure based on a moving average with a 40cm-wide window is applied to each SCPT vertical to remove small-scale noise.

Although the tests are very closely spaced and the boreholes show that the material is classifiable consistently as a mixture of sand and silt, simple visual inspection of Figure 1a-b reveals significant horizontal inter-sounding variations in the measured properties at the same depth, and intra-sounding, depth-wise variability in the vertical direction. While vertical variability can be expected due to in-situ stress effects and to stratigraphic layering, horizontal variability is more significant than could be foreseen given the close spacing of the soundings and the limited extension of the area. To quantify this variability, descriptive second-moment sample statistics were calculated depth-wise for q_c, f_s, and V_s; more specifically: mean (μ), standard deviation (σ), and coefficient of variation ($COV=\sigma/\mu$), given by the ratio of the standard deviation to the mean. Figure 1c-e plots the depth-wise mean and COV of q_c, f_s, and Vs. The grey shaded area represents the values within one sample standard deviation from the sample mean.

The depth-wise COV of tip resistance and sleeve friction varies between 0.15 and 0.6, with an average of 0.37 for q_c and 0.49 for f_s. This indicates that the horizontal variability of the deposit is relatively high, according to the “rule of thumb” provided by Harr (1987), by which coefficients of variation below 10% are considered to be “low”, between 15% and 30% “moderate”, and greater than 30%, “high”. The COV of shear wave velocity varies between 0.11 and 0.78 with an average of 0.22; indicating that the overall level of horizontal variability of this parameter is moderate.

From a geotechnical perspective, it is important to parameterize not only the degree of horizontal and vertical scatter in data measurements, but also the spatial correlation structure, i.e., whether the spatial variation of mechanical behavior as described by SCPT occurs abruptly or with continuity. The above descriptive statistical analysis is not suited to fully describe variability as it cannot provide information regarding spatial variability patterns. Moreover, the descriptive analysis does not account for the possible presence of different stratigraphic units which could display distinct geotechnical properties. In the following we focus on the variability of the tip resistance.

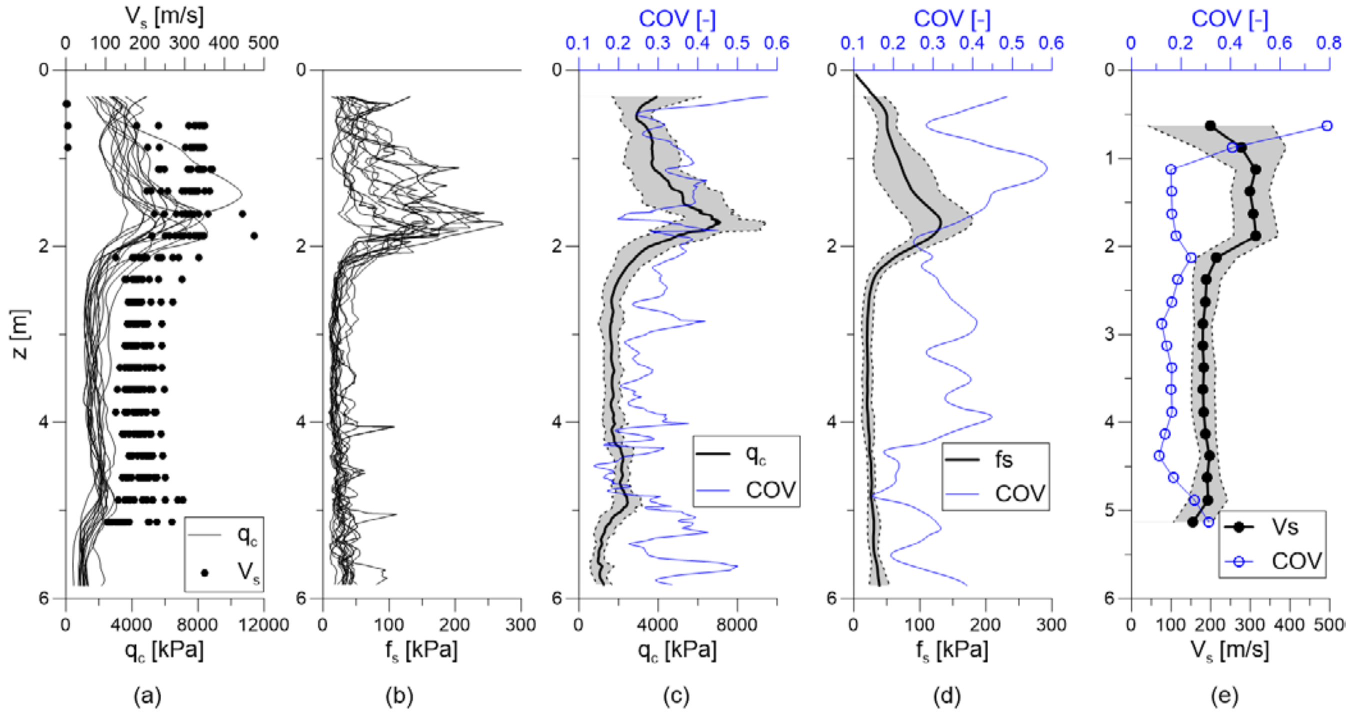

Figure 1 (a) q_c and V_s measured in the 16 SCPT; (b) f_s measured in the 16 SCPT; (c-e) average values and COV in horizontal direction of q_c, f_s and V_s respectively.

3 IDENTIFICATION OF HOMOGENEOUS SOIL UNITS.

Sample statistics and spatial variability parameters aimed at characterizing specific soil types are only meaningful if conducted on soil volumes which are sufficiently homogeneous for geotechnical purposes. A moving-window procedure proposed by Uzielli et al. (2008) is employed to identify Homogeneous Soil Units (HSUs) statistically. The normalized tip resistance Q_{tn}, normalized friction ratio F_r and soil behaviour type index I_c are computed from field measurements according to Robertson (2009).

$$Q_{tn} = \frac{q_c-\sigma_{v0}}{p_a} * \left(\frac{p_a}{\sigma'_{v0}}\right)^n \tag{1}$$

$$F_r = \frac{f_s}{q_c-\sigma_{v0}} * 100 \tag{2}$$

$$I_{cn} = ((3{,}47 - \log Q_{tn})^2 + (1{,}22 + \log F_r)^2)^{0{,}5} \tag{3}$$

where

$$n = 0{,}381 I_c + \frac{0{,}05\sigma'_{v0}}{p_a} - 0{,}15 \tag{4}$$

The vertical effective stress is estimated considering soil suction (s) by applying the Bishop effective stress principle

$$\sigma'_{v0} = \sigma_{v0} + sS_r \tag{5}$$

S_r is the degree of saturation computed from soil suction assuming the Van Genuchten soil water retention model (Eq. 6) with typical parameters for these soils derived from the laboratory tests, i.e., p_0=5kPa, λ=0.3, $S_{sat} = 1$, $S_{res} = 0.16$.

$$S_r = S_{res} + (S_{sat} - S_{res})\left(1 + \left(\frac{s}{p_0}\right)^{\frac{1}{1-\lambda}}\right)^{-\lambda} \tag{6}$$

A linear suction distribution is assumed above water level, which is 10m-deep in this site.

For each investigated depth, average values of Q_{tn}, F_r and I_{cn} are computed over the horizontal direction and used to identify the homogeneous soil units (HSU), see Figure 2a. The procedure is based on the evaluation of the coefficient of variation (COV) of the data within a 40cm-wide moving window. Each position of the moving window defines two semi-windows of equal height above and below a centre point. The COV shows a peak at the interface between different homogeneous soil units. Q_{tn}, F_r and I_{cn} show an increase of COV between 1.8m and 2.3m as well as between 5.0 and 5.3m, which correspond to the transition zone between different HSU (Fig. 2b). Q_{tn} is used for the identification of HSU because it is the parameter that best captures soil compaction effects. Indeed, it is clear from the borehole that the embankment is built with silty sand but compacted at different densities. The threshold value for COV is set to 0.15.

With this procedure it is possible to identify two HSUs: Unit A (between the depths of 0.30m and 1.80m) and Unit B (between 2.35m and 5.00m).

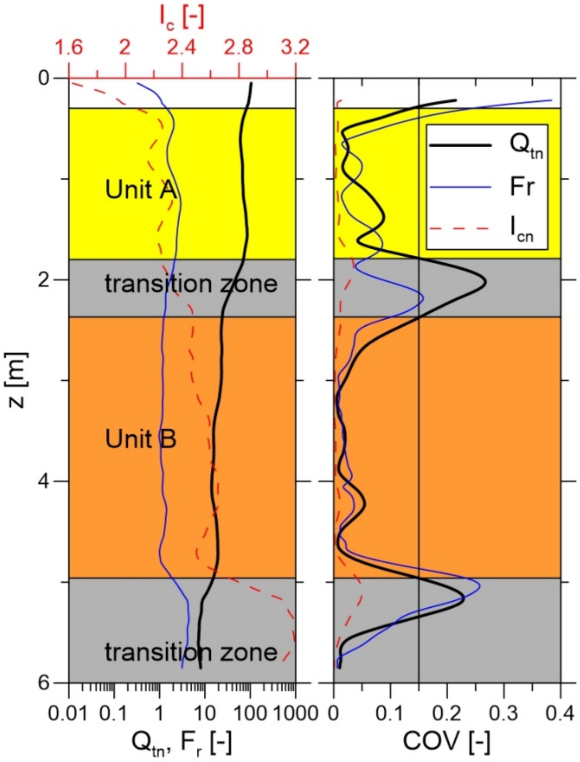

Figure 2 Identification of HSU

4 MODELLING OF SPATIAL VARIABILITY

The spatial correlation structure of tip resistance is investigated using a geostatistical approach by means of semivariograms. Given the well-known anisotropy in geotechnical properties stemming from in-situ stress effects and other site-specific factors, horizontal and vertical variability are addressed separately. The adoption of specific geostatistical techniques and models relies heavily on the hypothesis of data stationarity, which denotes the invariance of a data set's statistics to spatial location. Stationarity can be achieved through a number of data transformation techniques. Here, data decomposition is implemented, by which the "total" spatial variability of a spatially ordered measured geotechnical property [$q(z_1 \ldots z_n)$] in a sufficiently physically homogeneous soil unit is broken down into a trend function [$t(z_1 \ldots z_n)$] and a set of residuals about the trend [$r(z_1 \ldots z_n)$]. In the one-dimensional case, for instance, taking depth (z) as the single spatial coordinate, decomposition is expressed by the following additive relation

$$q(z) = t(z) + r(z) \tag{7}$$

Stationarity of the residuals is verified with the Mann-Kendall test (Kendall, 1938, 1955). This non-parametric statistical test involves the calculation of the test statistic τ. Low values of τ indicate a low significance of spatial correlation (and, thus, a more probable stationarity of data), while τ values close to

+1 or -1 indicate positive or negative correlation respectively.

The spatial correlation structure of residuals is investigated through a sequential process involving: (1) the calculation of empirical semivariograms; (2) the fitting of semivariogram models; and (3) the estimation of the scale of fluctuation from semivariogram model parameters. The scale of fluctuation (δ) describes the distance over which the parameters of a soil are significantly correlated. A low scale of fluctuation attests to less gradual spatial variability. The scale of fluctuation can be calculated from the values of the characteristic parameters of the semivariogram models (a: range; c_0: nugget; c: sill) which are fitted to empirical semivariograms. Table 1 summarizes the semivariogram models used in this study and the model-specific functions used to calculate the scale of fluctuation (Elkateb et al. 2003). In the model equations given in Table 1, h is the lag distance, i.e., the distance between observations.

Table 1 Semivariogram models and analytical expressions for the scale of fluctuation (Onyejekwe et al. 2016).

Model	Equation	δ
Gaussian (GAU)	$c\left(1-\exp\left(-\frac{h}{a}\right)\right)+c_0$	$\sqrt{\pi}a$
Spherical (SPH)	$\begin{cases} c\left(\frac{3h}{2a}-\frac{h^3}{2a^3}\right)+c_0 \text{ for } h \leq a \\ c+c_0 \text{for } h > a \end{cases}$	$0.75a$
Exponential (EXP)	$c\left(1-\exp\left(-\frac{h^2}{a^2}\right)\right)+c_0$	$2a$

4.1 *Horizontal spatial variability*

Horizontal spatial variability is investigated by slicing each homogeneous soil unit into 30cm-thick sub-units and conducting two-dimensional geostatistical modelling on each sub-unit. A total of 15 sub-units were obtained. The central value of the vertical depth interval and the average tip resistance in of each sub-unit are considered as reference values for geostatistical modelling purposes. A linear trend in horizontal direction is determined for each reference depth ($q_{c,trend}(x) = a_1x + a_0$) and the residuals are calculated through data decomposition. Application of the Mann-Kendall test assessed the stationarity of the residuals of linear detrending for all sub-units.

The empirical semivariograms of the residuals for all sub-units are plotted in Figure 3. These are fitted with the Gaussian (GAU), Spherical (SPH) and Exponential (EXP) semivariogram models summarized in Table 1. Though semivariogram model fitting is performed automatically, best-fit models were subsequently scrutinized critically to assess their adequateness. The GAU and SPH model are those providing the best fits overall. An example of the best-fit model for the depth of 3.53m is shown in Figure 4.

Figure 5 plots the scale of fluctuation for each reference depth for the selected semivariogram models. GAU and SPH model provide similar values of δ, while higher values are obtained with the EXP model. The horizontal scale of fluctuation (Table 2) ranges between 3.7 and 21.1m. Average values of 6.8m, 7.4m and 11.5m are obtained for the GAU, SHP and EXP models, respectively. These average scale of fluctuations are lower than reported in other studies (e.g. (Cami *et al.*, 2020)), but it must be considered that they highly depend not only on the database but also on the reduced horizontal spacing between soundings, which allows full exploitation of the typically existing nested correlation structure as discussed in Cami *et al.* (2020).

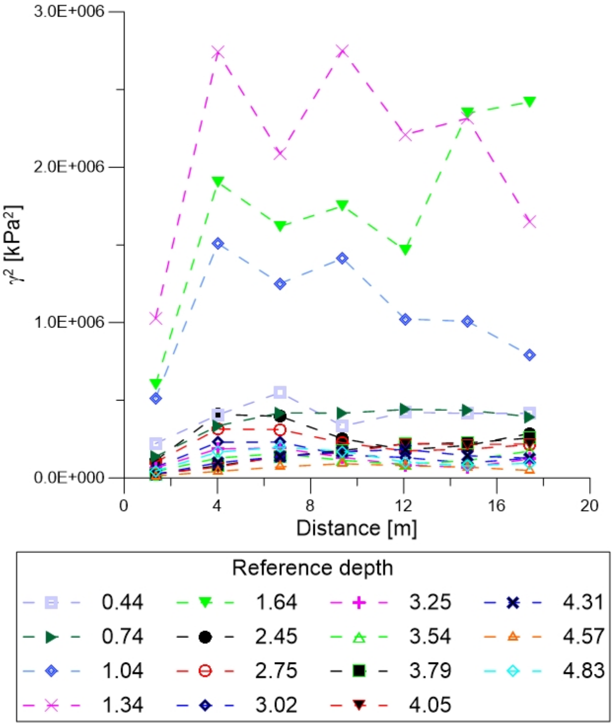

Figure 3 Empirical semivariogram in horizontal direction

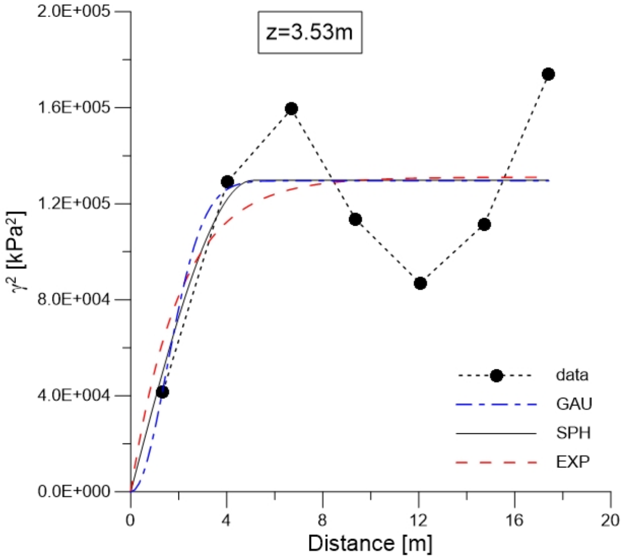

Figure 4 Best fitting semivariogram model for the reference depth of 3.53m.

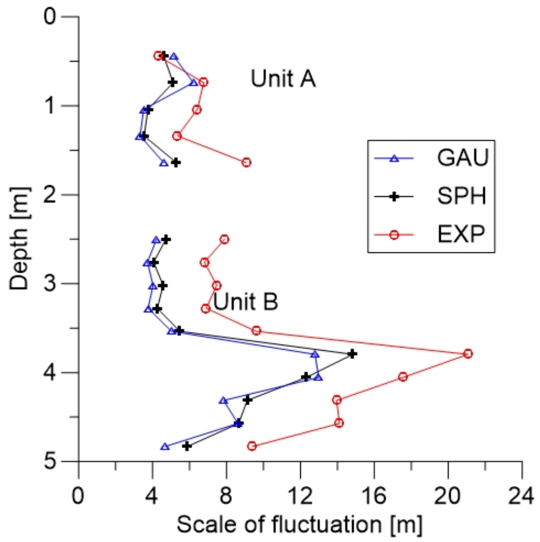

Figure 5 Horizontal scales of fluctuation by reference depth obtained from semivariogram model fitting.

Table 2 Horizontal scale of fluctuation calculated from semivariogram model parameters

z[m]	GAU	SPH	EXP
0.4	5.1	4.6	4.3
0.7	6.2	5.1	6.8
1.0	3.5	3.8	6.4
1.3	3.3	3.5	5.4
1.6	4.6	5.3	9.1
2.5	4.2	4.7	7.9
2.8	3.7	4.1	6.8
3.0	4.0	4.6	7.5
3.3	3.8	4.3	6.9
3.5	5.0	5.5	9.6
3.8	12.8	14.8	21.1
4.1	13.0	12.3	17.6
4.3	7.8	9.1	14.0
4.6	8.6	8.7	14.1
4.8	4.7	5.9	9.4
Mean	6.0	6.4	9.8
Min	3.7	4.1	6.8
Max	13.0	14.8	21.1

4.2 *Vertical spatial variability*

Vertical spatial variability is investigated by soil unit and sounding. A cubic trend model ($q_{c,trend}(z) = a_3z^3 + a_2z^2 + a_1z + a_0$) is applied to each instance and the residuals are calculated. The Mann-Kendall test is performed to assess stationarity. The empirical semivariograms for all soil units and SCPT soundings are shown in Figure 6. These are fitted with the semivariogram models summarized in Table 1, yielding the vertical scales of fluctuation given in Table 3 and plotted in Figure 7.

The EXP model predicts the largest values of scale of fluctuation, followed by the SHP and GAU models. In Unit A, δ varies between 0.1m and 0.6m, thus generally lower than in Unit B, where calculated values range between 0.2m and 0.9m. These values are consistent with the results of previous studies, e.g. (Cami *et al.*, 2020).

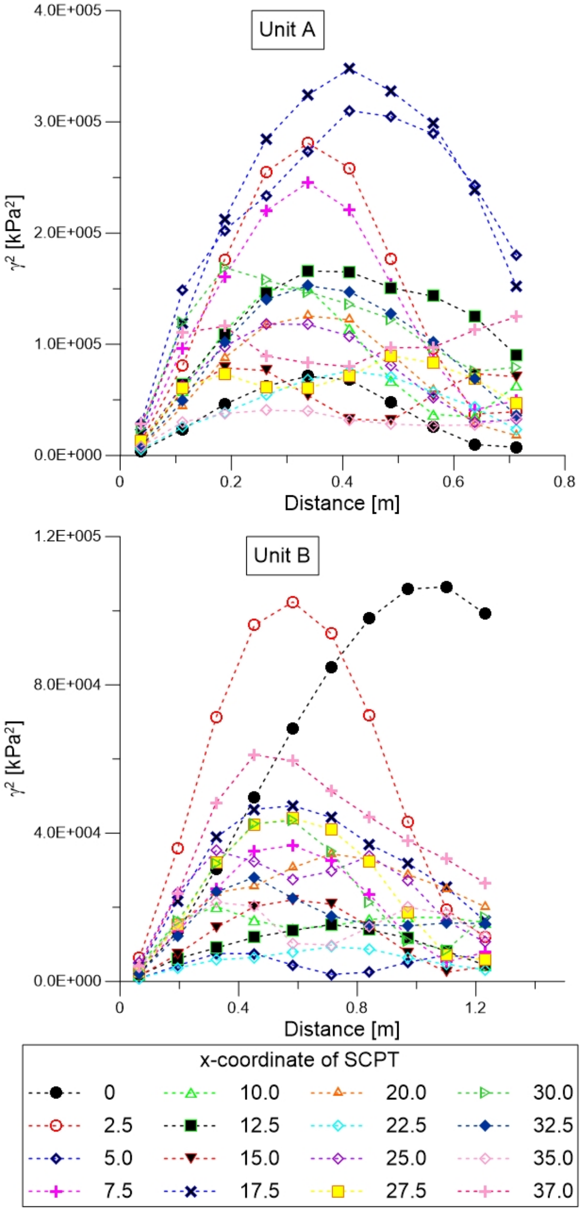

Figure 6 Empirical semivariogram in vertical direction

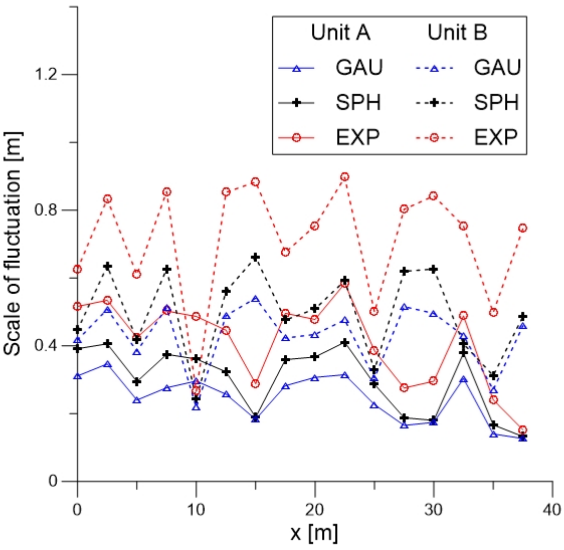

Figure 7 Vertical scales of fluctuation by semivariogram model and soil unit.

Table 3 Vertical scale of fluctuation from variogram models

	Unit A			Unit B		
x[m]	GAU	SPH	EXP	GAU	SPH	EXP
0.0	0.3	0.4	0.5	0.4	0.4	0.6
2.5	0.3	0.4	0.5	0.5	0.6	0.8
5.0	0.2	0.3	0.4	0.4	0.4	0.6
7.5	0.3	0.4	0.5	0.5	0.6	0.9
10.0	0.3	0.4	0.5	0.2	0.2	0.3
12.5	0.3	0.3	0.4	0.5	0.6	0.9
15.0	0.2	0.2	0.3	0.5	0.7	0.9
17.5	0.3	0.4	0.5	0.4	0.5	0.7
20.0	0.3	0.4	0.5	0.4	0.5	0.8
22.5	0.3	0.4	0.6	0.5	0.6	0.9
25.0	0.2	0.3	0.4	0.3	0.3	0.5
27.5	0.2	0.2	0.3	0.5	0.6	0.8
30.0	0.2	0.2	0.3	0.5	0.6	0.8
32.5	0.3	0.4	0.5	0.4	0.4	0.8
35.0	0.1	0.2	0.2	0.3	0.3	0.5
37.5	0.1	0.1	0.2	0.5	0.5	0.7
Mean	0.2	0.3	0.4	0.4	0.5	0.7
Min	0.1	0.1	0.2	0.2	0.2	0.3
Max	0.3	0.4	0.6	0.5	0.7	0.9

5 DISCUSSION AND CONCLUSIONS

The vertical and horizontal spatial variability in cone tip resistance of the unsaturated silty sand forming a levee is investigated through statistical and geostatistical modelling of the results of 16 closely spaced SCPT soundings. Results of the descriptive second-moment statistical analysis attest to a high degree of scatter in measured data, presumably due to the effect of partial soil saturation and other site-specific phenomena.

To supplement the outputs of the statistical analysis and to overcome its limitations with respect to the quantitative characterization of the spatial correlation structure of mechanical resistance to cone penetration, geostatistical modelling of the spatial correlation structure was conducted both in the horizontal and vertical directions for two depth intervals referring to highly homogenous soil units.

The horizontal correlation structure, parameterized by the horizontal scale of fluctuation, proved to be stronger (i.e., with cone resistance varying significantly over smaller horizontal distances) than typically assessed in existing literature. This result could be reconducted to both the high quality of the dataset (the small horizontal spacing between consecutive soundings allows the appreciation of nested correlation structures) and to the specific site effects which result in the surprisingly high degree of inter-sounding variability. Results of vertical spatial correlation modelling are fully in line with previous studies, thus attesting to the general correctness in the modelling approach.

The results obtained in the study confirm the particular site conditions which lead to the significant horizontal inter-sounding variability observed through the geotechnical testing campaign. While the complexity of the physical phenomena which lead to such variability require further and more extensive investigation, the quantitative assessment of the spatial correlation structure and its anisotropy attest to the importance of statistical and geostatistical analyses for geotechnical modelling purposes. The availability of quantitative spatial variability parameters allows the enhanced modelling of the geotechnical systems by providing realistic inputs to, for instance, limit equilibrium and numerical analyses.

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