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Penetration test measures for mechanical characterization of sandy deposits at Scanzano Jonico: geostatistical methods for variability interpretation

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ABSTRACT: Field tests, as static cone penetration tests (CPT), are widely used in granular soil characterization because they draw continuous profiles of tip resistance q_c and sleeve friction f_s. Such measurement profiles are affected by two main sources of uncertainties: (1) measurement errors and (2) natural variability of soils. Thus, in order to interpret the inherent variability from CPT measures measurement errors shall be quantified and isolated. Studies and experiences learned from literature can help to have an idea of the extent of measurement errors whereas exploratory spatial data analysis techniques are needed to practically reduce this sources of uncertainty before undertaking variability analyses on soils. The case studied concerns CPTs performed on sandy deposit along Ionian coast in the southern part of Italy in Basilicata Region at Scanzano Jonico site. There the outcropping granular deposit is about 20m depth and it is made up of graded sands from the top to the bottom. Lithological boundaries are sought by means of the analysis of variance technique, that is intraclass correlation coefficient RI method. Therefore the variability structures related to q_c and f_s profiles referring to the two sandy soil types recognised, are investigated.

1 INTRODUCTION

Cone penetration test (CPT) is commonly performed for geotechnical soil characterisation because it is simple, relatively fast and economical and supplies continuous readings with depth showing changes in soil strata, layer boundaries, lenses or inclusions. Moreover it provides numerous data for performing geostatistical studies for recognising lithological variation, mean trends of soil resistance from measurement profiles and the spatial correlation of those measures.

Especially with respect to sandy soil characterization, several correlations are provided between q_c measurements and geomechanical parameters as D_R (Baldi et al., 1986), ϕ' (Robertson and Campanella, 1983; Kulhawy and Mayne, 1990), overconsolidation ratio OCR (Mayne, 2001) and lateral stress coefficient K_0 (Mayne, 2005). Direct application of q_c and f_s profiles to estimate side and tip resistance of piles, can also be found in literature (Bustamante and Gianeselli, 1982; Briaud, 1988; Robertson et al, 1988).

Accordingly, q_c and f_s profiles are useful in design activity. For this reason, in the present paper, few techniques are employed to recognise and study the uncertainties and the natural variability affecting q_c and f_s measurements from CPTs. Such quantities will be employed, in the companion paper, to design pile bearing capacity according to reliability approach.

2 UNCERTAINTY AND VARIABILITY AFFECTING CPTs

Uncertainties and variability coming from geotechnical experimental campaigns attain to two phenomena, which are different in nature:
1) Epistemic uncertainties,
2) Soil inherent variability.

The first one comprises all the sources of errors and uncertainties which cannot be attributed to natural variability of soil. They are effectively summarized (Uzielli, 2004) in the case of CPT measurements as:

- systematic testing error (equipment and operator/procedural effects),
- random testing error.

With respect to systematic errors, equipment errors may be caused by poor selection of installation procedures and by limitations in the instrument design. All standards for CPT testing specify the degree of accuracy and precision required in the measured values. The International Reference Test Procedure IRTP (2001), states that the precision of the measurement shall not be worse than 5% of the measured value and 1% of the maximum value of the measured resistance in the layer under consideration.

As procedural errors are concerned, Orchant et al. (1988) showed that the magnitude of this type of uncertainty depends on the standardization level of the test procedure. Tests with well-defined specifications, such as the CPT, show less total measurement variability than tests with less stringent standard.

Random testing error represents the zero-mean scatter of test results, which is not directly assignable to specific operator/procedural or equipment parameters and is not caused by spatial variability. Orchant et al. (1988) reviewed and summarized the results of several studies focusing on the quantification of random testing error for cone penetration testing. Such data indicate that random test effects may contribute significantly to the total measurement error.

Kulhawy and Trautmann (1996) estimated coefficients of variation for mechanical cone testing (MCPT), electric cone testing (ECPT) and piezocone testing (CPTU). Table 1 reports such coefficients of variation related only to the mechanical cone testing which is the device used in this paper. In the table, CoVeqp is the coefficient of variation due to the equipment error; CoVprc is the coefficient of variation of operator and procedural error and CoVrnd is the coefficient of variation of random testing error. In the last column the total coefficient of variation CoVtep relating to epistemic errors is also reported.

Table 1 Estimated coefficients of variation for mechanical cone testing MCPT
(After Kulhawy and Trautmann, 1996)

test	CoV_{eqp}		CoV_{prc}		CoV_{rnd}		CoV_{tep}	
	q_c	f_s	q_c	f_s	q_c	f_s	q_c	f_s
MCPT	0.05	0.05	0.10	0.15	0.10	0.15	0.15	0.22

Moreover, CPT measurements are affected also by soil inherent variability owing to formation processes and environment continuous work to alter them. The inherent variability interpret the remainder of the zero-mean scatter in q_c and f_s measurement profiles. It is this part of variability which can be efficiently studied by means of random field theory which are discussed below.

Furthermore, whenever resistance values RD of soils shall be derived from experimental measurements as CPTs, another source of uncertainty shall be considered, that is transformation model uncertainty, called transformation uncertainty. It is due to the dispersion around the mean trend from empirical relationship and/or to the simplification which mathematical descriptions introduce when interpreting physical behaviour of natural materials. Model uncertainty in empirical correlations can be easily evaluated by means of variability propagation techniques as the point estimate methods or First Order Second Moment methods.

The study below focuses on the calculation of variability structure of CPT measurements.

3 INTERPRETATION OF SPATIAL FLUCTUATION IN CPT MEASUREMENT

Before undertaking variability analyses on vertical profiles of q_c and f_s, it is convenient to understand the physical nature of the observed measures. As Tukey (1977) stated, geostatistical models are built upon available information thus systematic errors can strongly influence results of geostatistical analyses. In order to reduce every sources of systematic errors, exploratory spatial data analysis (ESDA) can be employed. ESDA consists on different exploratory tools which allow the researcher deepen the knowledge of the nature of soil investigated by means of calculating the statistical properties of spatial measurements as outliers, trend function and spatial correlation relating to homogeneous soil units.

Such techniques are used in the foregoing study aiming at characterizing the spatial inherent variability of q_c and f_s profiles. Accordingly, the study has been developed into two stages: the first one, using ESDA techniques, systematic errors are partially eliminated; in the second stage, only inherent variability is investigated by means of 1D random field theory (Vanmarcke, 1983).

Two techniques from ESDA group are applied below:

- the Box-Plot technique;
- the moving window statistics.

The first tool is theoretically introduced by Velleman and Hoaglin (1981). It analyses the nature of measurement values in order to recognise "outliers", that is measures which cannot be considered as part of a data set on statistical basis. The Box-plot technique is described in detail in Cherubini et al. (2006) and here is just applied to the case studied.

The moving window statistics is here used to smooth local peaks and troughs which are not related to a real increasing or decreasing in soil resistance. This method substitutes the measurement yi at a specific depth with the mean value mi among the measure y_i, the preceding measure yi-1 and the following measure yi+1 in depth, according to the weighed mean:

$$m_i = \frac{0.5y_{i-1} + y_i + 0.5y_{i+1}}{2} \tag{1}$$

Such techniques shall be applied to homogeneous soil units, which means the presence of different soil types shall be investigated. Here the Intraclass Correlation Coefficient RI (Wickeremesinghe and Campanella, 1991) has been adopted for searching lithological boundaries on the variance bases. Results from the application of ESDA techniques are presented in the paragraph 4.4.

Moreover, in order to study the spatial variability of the investigated soils, q_c and f_s measures m are represented as the summation of two components: the deterministic trend t and the random variation ε, called residuals:

$$m = t + \varepsilon \tag{2}$$

Nevertheless, for the same measurement profile, different trend functions can be used which will provide different residuals. As a rule of thumb, trends should be kept as simple as possible, for example linear trends should be preferred to quadratic trends. This can be justified by the fact that the more parameter estimates that a trend function requires, the more the uncertainty there is in the numerical values of those estimates (Baecher and Christian, 2003).

After the trend function is carried out, according to Eq. (3) the spatial correlation structure of residuals, ε, can be investigated by means of 1D random field theory (the depth is the only spatial dimension taken into account). Thus, the condition of stationarity of ε zero mean random field shall be verified, at least in a weak sense, in order to assume that the sample variance is constant along the depth, and the spatial correlation of residuals depend only on the distance of two measures along the depth. This assumption warrantees the autocorrelation function can interpret only the spatial correlation due to the soil inherent variability because of it depends only on the distance between measures and not on their locations (Baecher and Christian, 2003).

To verify the stationarity condition in a weak sense, residuals form q_c and f_s are tested by means of CUSUM analysis (Caulcutt, 1983). This technique compares the cumulative standard deviation of residuals along depth with a target value at two confidence levels: 1% and 5%. In the study discussed below, the confidence level of 1% is taken into account.

Finally, the estimation of the scale of fluctuation δ and the sample autocorrelation function R(τ) of CPT profiles is carried out. Two methods are compared for the evaluation of the scale of fluctuation. The simplified Vanmarcke's method (Vanmarcke, 1977), estimates δ according to the expression:

$$\delta = 0.8 \cdot \overline{d} \tag{3}$$

in which $\overline{d}$ represents the arithmetic mean of the length of all the residual intersections with the depth axis. The other method is related to the estimation of the sample correlation function. To this aim the moment method is used, thus the unbiased R(τ)u and biased R(τ)b estimators of the autocorrelation function can be introduced:

$$R(\tau_{ij})_u = \frac{1}{\sigma^2 \cdot (n_d - j)} (\varepsilon_i)(\varepsilon_j) \tag{4}$$

$$R(\tau_{ij})_b = \frac{1}{\sigma^2 \cdot n_d} (\varepsilon_i)(\varepsilon_j) \tag{5}$$

where σ^2 is the sampling variance, n_d is the number of measures, ε_i and ε_j are two residual values at different spatial locations whose distance is τ_{ij}. While the unbiased expression is commonly suggested by literature, the efficiency of the biased estimator is warranted by experiences in random field modelling in the context of geotechnical engineering (Priestely, 1981, Fenton, 1999). In the foregoing study, the two types of estimators are calculated.

However, the sample autocorrelation function becomes ever closer to the true autocorrelation function for $n_d \to \infty$, thus for finite sample sizes, Weinstock (1963) suggested a criterion to make consistent estimate of autocorrelation function. Assuming L as the sample size, with measure lag τ0 the most distant correlated measures by which the autocorrelation function shall be estimated are those whose distance τ verifies the condition: $\tau/\tau_0 \geq 5\text{-}6$.

After the estimate of the sample autocorrelation function, it must be fitted by one of the following autocorrelation models:

Single exponential	$R(\tau) = \exp(-\lambda\lvert\tau\rvert)$	
Cosine exponential	$R(\tau) = \exp(-\lambda\lvert\tau\rvert)\cos(\lambda\tau)$	
Second-order Markov	$R(\tau) = (1 + \lambda\lvert\tau\rvert)\exp(-\lambda\lvert\tau\rvert)$	(6)
Squared exponential	$R(\tau) = \exp\left[-(\lambda\tau)^2\right]$	

Care should be taken in fitting the upper models to the sample autocorrelation function. Accordingly, the model parameters shall be obtained by least squares regression whose maximum determination coefficient r doesn't exceed (Spry et al., 1988):

$$r = \frac{1.96}{\sqrt{n_d}} \tag{7}$$

where n_d is the number of measures considered. After that, the scale of fluctuation can be calculated from the following relationships according to the best-fit autocorrelation model:

Single exponential	$\delta = 2/\lambda$	
Cosine exponential	$\delta = 1/\lambda$	
Second-order Markov	$\delta = 4/\lambda$	(8)
Squared exponential	$\delta = \sqrt{\pi}/\lambda$	

In this paper, the scales of fluctuation provided by the two presented methods are compared and discussed.

4 THE CASE STUDIED OF SCANZANO JONICO SITE

The town of Scanzano Jonico is set in Matera district, near the Ionian coast in Basilicata Region (Fig.1). The site under investigation is situated outside the town of Scanzano Jonico adjacent to the seaside.

Here a geological and geotechnical investigations have been performed in order to design holiday houses. Accordingly, 9 boreholes were performed in two zones called A and B (Fig.2).

Nine samples from zone A and 15 from zone B are taken for performing laboratory tests as grain size distribution, Atterberg consistency limits, direct shear strength tests. Such results were presented by Cherubini and Lupo (2002). Moreover, five mechanical CPTs were executed in zone A whose measurements will be discussed further on.

Fig.1 Location of Scanzano Jonico town.

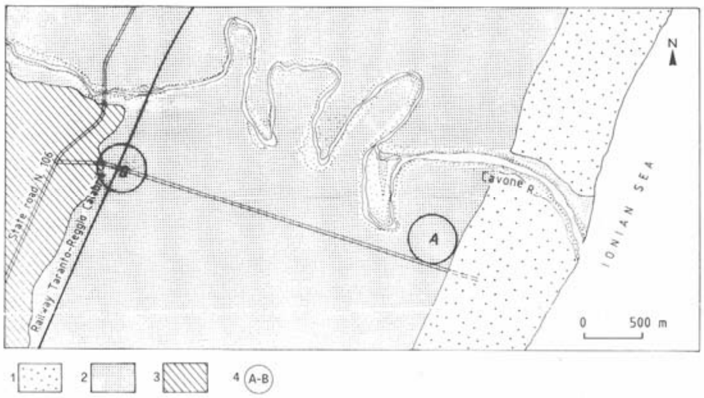


Fig.2 Lithological sketch of the studied zone falling in the territory of Scanzano Jonico town: 1) sandy beach deposits; 2) recent alluvium; 3) marine terraces; 4) sampling zones.

4.1 Geological features

The outcropping soils on the Ionian coast of the Basilicata region (Italy) mainly consist of sands, silty sands and silts. Especially, the area under investigation is made up of recent alluvial deposits formed at the end of a long series of marine terraces (Cotecchia and Magri, 1967). As the area of Scanzano Jonico territory is concerned (Fig.2), the marine terraces define the immediate Ionian hinterland and are stepped to varying degrees. They are conglomerate and rise over 300m above sea level. This area belongs to the sedimentary cycle of the Bradanic Foredeep mainly represented in the zone by Holocene and Pleistocene sediments (Pescatore, 1983).

Here the following lithostratigraphical sequence is described from the bottom upwards.

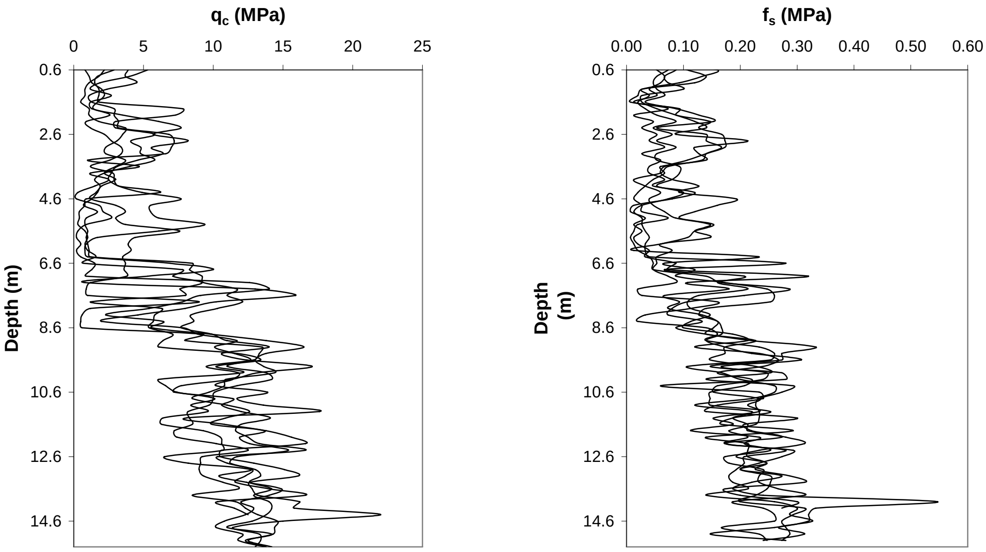
- Calabrian blue clay formation: this consists of clayey silts, in places sandy and grey-blue in colour. These soils have been investigated by means of borehole sampling to a maximum depth of approximately 30m below the surface, but on the basis of surveys carried out on adjacent sites they can be considered to extend to depths not greater than 50m from the surface. They are soils with a well known lithological, paleontological and geotechnical profile and that outcrop widely in the hinterland. Observations and measurements made on samples of this clay taken from the inhabited part of Scanzano Jonico, situated a little to the South of the studied zone, suggest they are found with natural water contents close to the plastic limits.

- Sandy deposits: this consists of mainly medium-fine grained and silty sands, that in places contain silt and clay lenses varying from 20 to 50cm in thickness. The overall thickness of this formation can be considered to be several tens of metres.

- Recent alluvium: This is a recent fluvial and/or marine alluvial, the lithological contents of which may be significantly different from zone to zone with respect to their origin and the environment in which they were formed. They are usually represented by sands, silty sands and sandy silts of low to medium density. In some zones, mixed in with the above mentioned lithological terms, gravels and pebbles of varying dimensions may be found. The investigations indicate the thickness of these soils ranging from 7.0 to 9.0m approximately. Near the paleo or actual river-beds, the alluvial material may even reach greater thicknesses (15-20m).

As far as the hydrogeology is concerned, the water table, that is located slightly above the sea level, has a gradient of the order of 0.2-0.3%. In particular, in zone A (Fig.2), near the coast, situated at a height above the sea level of slightly less than 3m, the groundwater is located approximately 2m below the surface of the soil.

4.2 Lithological classification



a) b)

Fig.3 Measurement profiles for the 5 cone penetration tests from zone A: a) tip resistance q_c; b) sleeve friction f_s.

Five mechanical CPTs are performed in zone A outside Scanzano Jonico town (see Fig.2). Tip stress q_c and sleeve friction f_s profiles are plotted in Fig.3.

As can be drawn by means of a visual inspection, two strata of sandy soils can be recognized with a boundary interface at 7-9m depth: the first stratum is characterized by a point resistance with maximum values that don't exceed 10MPa. The second stratum has greater q_c and f_s punctual values, with maximum value exceeding 15MPa. From laboratory tests, the grain size distribution of soils in zone A is quite variable with depth: it varies from silty clays, to clayey silts and silty sands. It is worth noticing the fairly sandy deposits are found under 7m depth, while the finer soils lie at lower depth. The lithological classification of zone A, has been carried out by means of CPTs through normalising the tip and side resistance according to the following expressions (Lunne et al., 1999):

$$Q_t = \frac{q_c - \sigma_{v0}}{\sigma'_{v0}}. \tag{9}$$

$$F_r = \frac{f_s}{q_c - \sigma_{v0}} \cdot 100. \tag{10}$$

where σ'v0 and σv0 are the effective and total vertical stress respectively. Such parameters define the index Ic as follows:

$$I_c = \sqrt{\left[(3.47 - \log(Q_t))^2 + (\log(F_r) + 1.22)^2\right]}. \tag{11}$$

whose ranges of values are correlated to soil behaviour type (Lunne et al., 1999) and plotted in Fig.4 for two out of 5 CPTs referring to zone A in Scanzano Jonico territory: CPT4 and CPT5.

From Fig.4 it is evident that the lower part of each CPT profiles (under 7m) is made up of sandy soils (clean to silty sands and mixtures of sands and silts) with a fairly limited variability of the index Ic, while the upper part is characterized by a high variability of Ic from sand mixtures to clay soils.

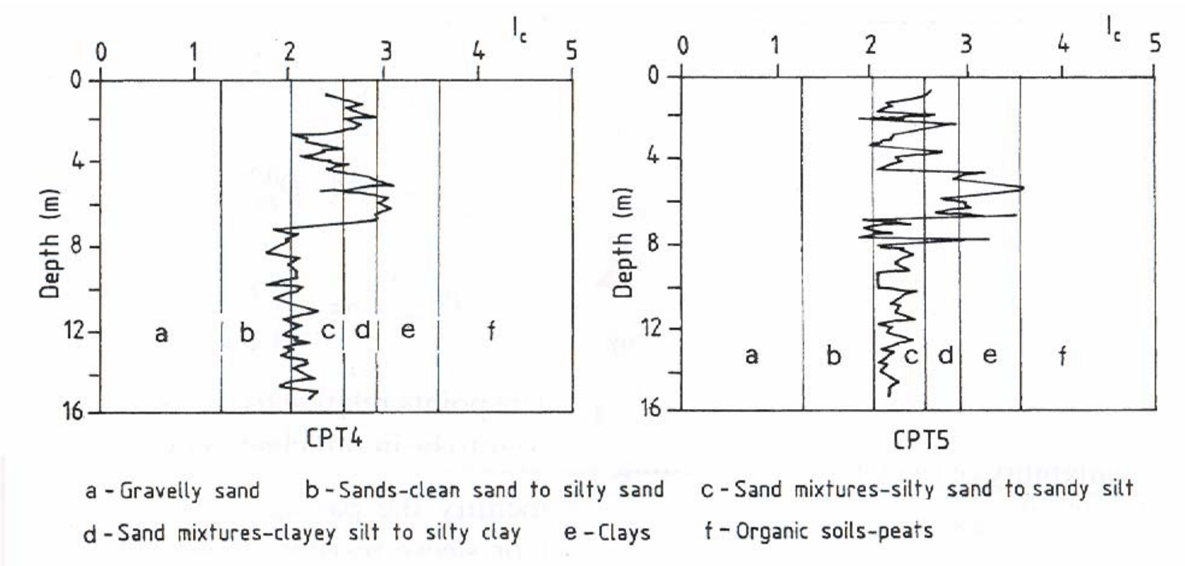


Fig.4 Evaluation of grain size distribution from the 2 CPTs from zone A, by means of index I_c (After Cherubini and Lupo, 2002)

4.3 Variance-based layer interface recognition

Variability studies on q_c and f_s profiles are carried out by Cherubini and Lupo (2002) to detect interfaces by means of Intraclass Correlation Coefficient profiles RI (Wickremesinghe and Campanella, 1991) at about 6, 7 and 9m depth. Fig.5c) - d) illustrate only the RI profiles from CPT4 and CPT5.

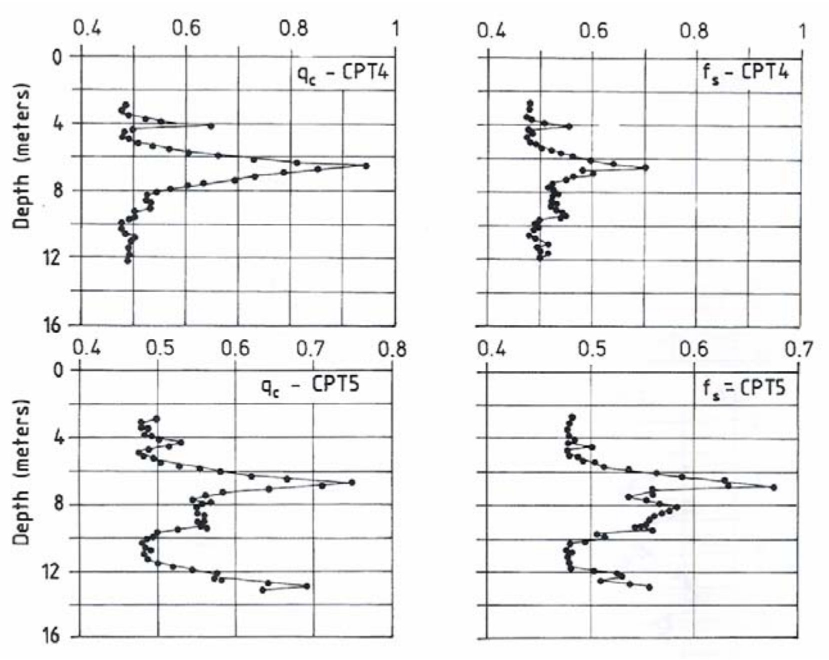


Fig.5 Intraclass coefficient ratio RI related to q_c and f_s profiles along depth (After Cherubini and Lupo, 2002).

4.4 ESDA techniques applied to CPT measurements

The spatial variation of q_c and f_s profiles have been studied but only two of them are reported here (CPT4 and CPT5), for which RI profiles give the boundary interface at 7m (see Fig.5).

However, the first step undertaken is to reduce the measurement errors by means of: (1) recognising outliers in measurement values, and (2) reducing the influence of local spikes. For accomplishing the two tasks, the Box-plot and the moving window methods are applied. The resulting smoothed profiles applied to the two strata for each q_c and f s measurements are shown in Fig.6-7.

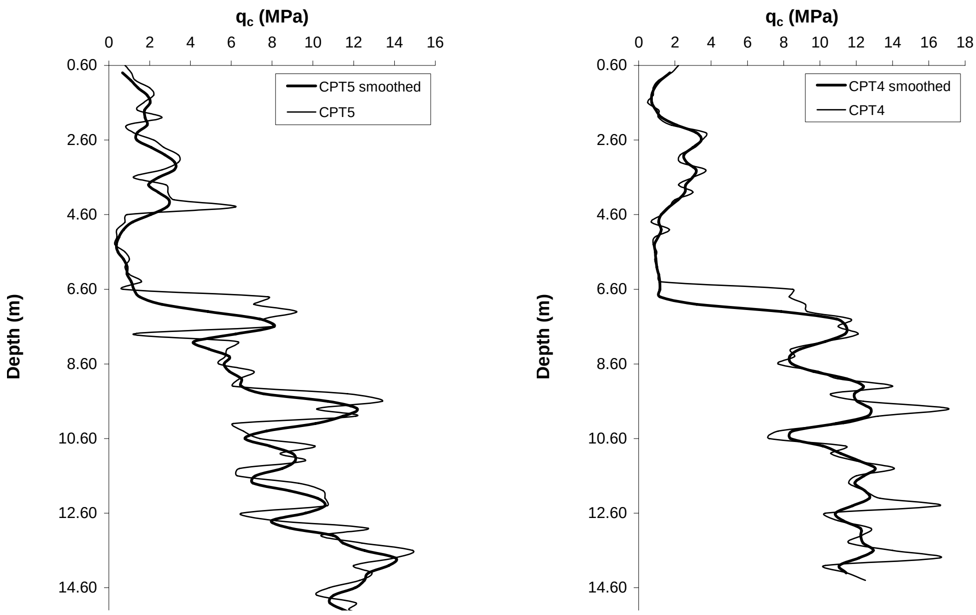


Fig.6 Measured and smoothed profiles of q_c from CPT4 and CPT5.

After that, the trend functions for the two homogeneous soil units are plotted for the two CPTs (Fig.8). According to the rule of simplicity in trend investigation, linear functions are considered for the 4 cases. These linear functions shall provide residuals (Fig.9), according to Eq. (3), which verify the stationarity condition in a weak sense. Therefore, whether the stationarity condition is not satisfied, a higher order polynomial is given to the trend function.

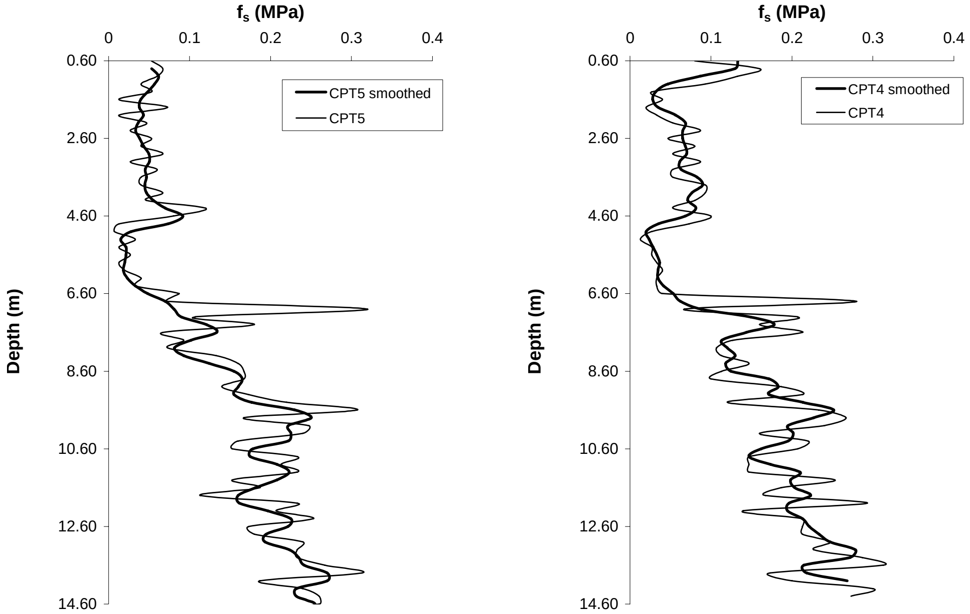
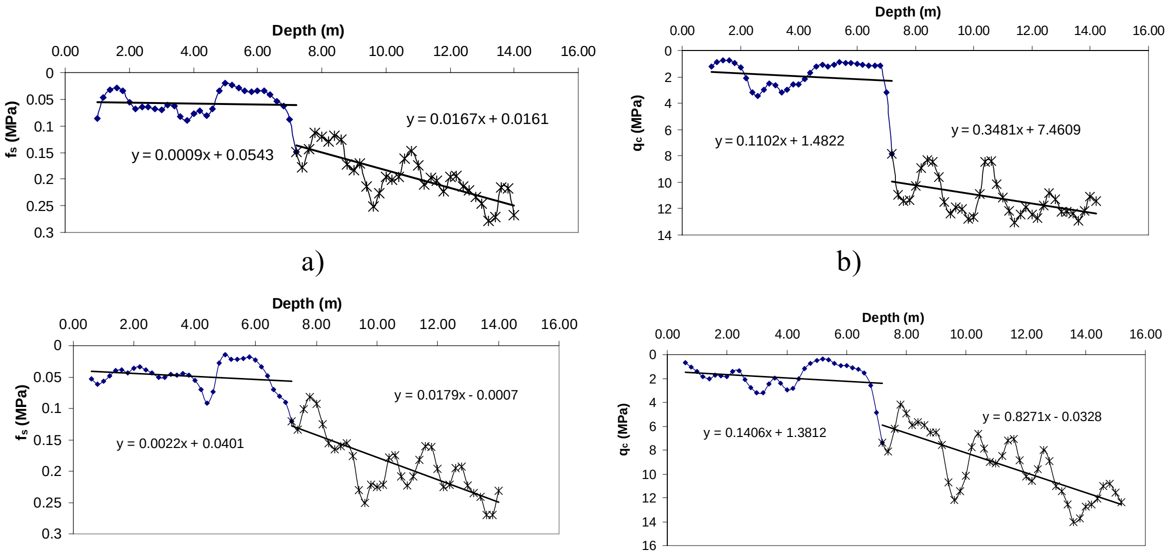


Fig.7 Measured and smoothed profiles of f_s from CPT4 and CPT5



a) b) c) d)

Fig.8 Trend functions for q_c and f_s profiles: a) and b) refer to CPT4; c) and d) refer to CPT5.

To verify the weak stationarity condition for those measures related to each homogeneous soil units, the CUSUM analysis is performed. Results of such an analysis are reported in Table 2. In Table 2, the measured and the target statistics values from CUSUM analyses are reported. The CUSUM analysis is not described here but a detailed explanations can be found in Caulcutt (1983).

In order to accept the weak stationarity hypothesis for residuals, measured statistics shall be lower than the target values corresponding to 1% of confidence level for the test is considered. It can be seen that all the residuals from the linear trend functions are then verified.

Moreover, the scales of fluctuation for q_c and f_s for the two strata, are estimated by means of the two methods previously introduced (see paragraph 3): the simplified Vanmarcke's and the sample autocorrelation function. Results are reported in Table 2. The sample autocorrelation function is estimated by moment method and the best-fit autocorrelation model. Both biased and unbiased estimators are calculated without relevant differences in sample autocorrelation functions. The best-fit autocorrelation model is the second order Markov model as the best-fit model for the 8 functions fitted. The condition on the determination coefficient of fitting autocorrelation models (Eq. 7) is also satisfied. Besides, as Table 2 shows, the scales of fluctuation from the two methods are close each other unless Vanmarcke's method provides greater values especially for the first stratum in the case of CPT4. Comparing the scales of fluctuation of the two strata, according to CPT4 and CPT5 measurements, similar values are drawn. This means the higher lithological variability of the upper layer doesn't affect the scale of fluctuation. However, results from Vanmarcke's method are fairly more approximated than the one from best-fit autocorrelation model.

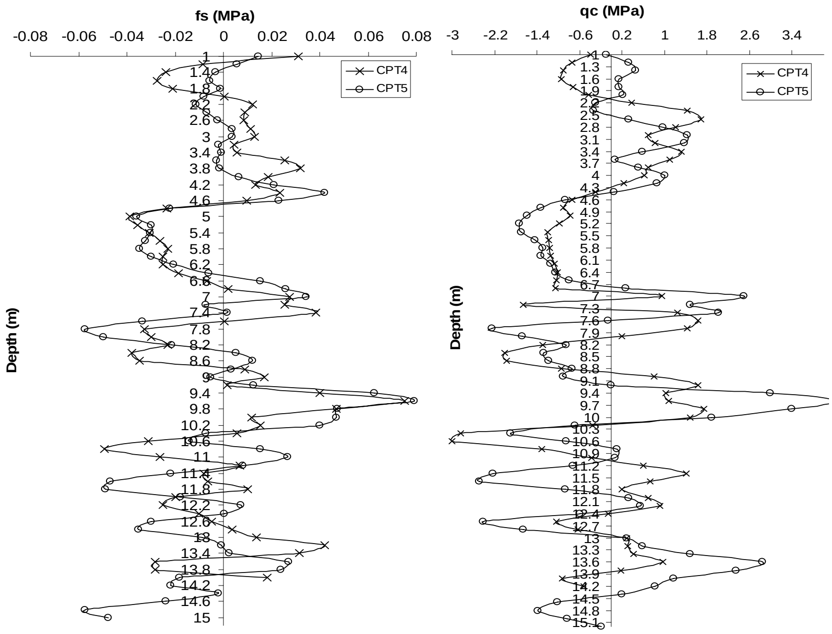


Fig.9 Residuals from linear trend functions calculated for q_c and f_s profiles from CPT4 and CPT5.

Table 2 Values of CUSUM statistics and the scales of fluctuation from CPT4 and CPT5 measurements.

CPT number	Measured parameter	Standard Deviation (MPa)	Calculated CUSUM statistics	Target values of CUSUM statistics	Scale of fluctuation (second order Markov autocorrelation model)	Scale of fluctuation (Vanmarcke's method)
CPT4	f_s (up to 7m)	0.021	6.8	6.8	0.8	1.5
	f_s (from 7.2 to 14.2m)	0.028	6	7	0.5	0.8
	q_c (up to 7m)	0.96	5.0	6.8	1.3	1.9
	q_c (from 7.2m to 14.2m)	1.3	3.3	7	0.5	0.7
CPT5	f_s (up to 7m)	0.020	3.9	6.5	0.8	0.8
	f_s (from 7.2m to 15.2m)	0.032	4.8	8.0	0.7	0.5
	q_c (up to 7m)	1.04	3.4	6.5	1.0	1.1
	q_c (from 7.2m to 15.2m)	1.64	4.1	8.0	0.7	0.7

Finally, as far as the standard deviation is concerned, it is lower for the upper layer than the deeper one, both for q_c and f_s.

5 CONCLUDING REMARKS

The paper deals with geomechanical characterization of sandy soils in Scanzano Jonico territory by means of CPT data. In such a study a great relevance has been given to exploratory spatial data analysis and random field approach for interpreting spatial correlation structures of soils.

As a matter of fact, the former method provides tools for reducing systematic errors in continuous measurements and the latter approach allows to isolate and quantify the spatial correlation of q_c and f_s measurement profiles in terms of the variance, the scale of fluctuation and the autocorrelation function. Moreover, the study has pointed out that the lithological variability of a soil doesn't affect its scale of fluctuation: accordingly, the upper sandy layer has longer scales of fluctuation than the lower one which shows higher standard deviations. Such results confirm the importance of statistical data treatment for correctly analyse the fluctuating component of in situ measurements.

The results of this study will be employed, in the companion paper, to design a pile foundation according to the reliability approach.

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