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Estimating spatial correlations under man-made structures on soft soils

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ABSTRACT

The vertical spatial correlation functions, under and next to a pre-existing dyke on a soft soil, have been estimated using cone penetration test (CPT) data. Distinct differences were found between different locations in reference to the dyke body, i.e. under the crest of the dyke, under the toe and slope of the dyke and in the polder. The results strongly suggest that deformations caused by the dyke construction change the spatial correlation, especially in soft soils. It is hypothesised that the change in spatial correlation due to deformation, within close proximity of the dyke, will impact the calculated reliability and should therefore be considered when using limited CPT data to estimate the vertical correlation at an existing dyke.

INTRODUCTION

The statistical properties of a soil strongly affect the calculated reliability of any geotechnical structure. Alongside the point statistics, e.g. the mean and standard deviation, the spatial correlation structure is also important, with the scale of fluctuation being a convenient measure of the spatial correlation (Hicks et al., 2007), although it is not straightforward to determine. The scales of fluctuation are usually thought to be caused by the geological deposition process, although it is reasonable to assume that they will be altered by soil deformation. Several studies have estimated the scale of fluctuation using CPTs from an actual project, e.g. Hicks and Onisiphorou (2005), Lloret-Cabot et al. (2012; 2014) or have utilised CPT campaigns specifically designed to evaluate the spatial variability at a particular site, e.g. Jaksa et al. (1999) and O'Neill and Yoon (2003). These studies all assume that each layer has a unique scale of fluctuation, undisturbed by any soil deformation.

In the Netherlands, there are 14,000 km of rural dykes which must be assessed, in order to understand the risk faced by communities or to the infrastructure protected by them. Good estimations of the scales of fluctuation in areas under and around linear infrastructure such as these, in combination with a reliable estimate of the point statistics, will help in such assessments. Moreover, at least half of the rural dyke system is built on soft materials, so it is important to know the effect that a dyke has on the underlying soft layers; in this case, on the spatial correlations of material properties.

In this study, the effect of a 2 m high rural dyke, built and maintained since around 1600 A.D., on the (vertical) spatial variability of the underlying compressible soft material has been analysed. The scale of fluctuation has been estimated for different sections along and parallel to the embankment, and the stress history has been considered in the interpretation of the results. The analysis was carried out using a dataset of 100 CPTs, located along the crest of the dyke and adjacent to the dyke. From the CPT data, different soil layers were distinguished and the vertical scales of fluctuation for one of the soil layers determined.

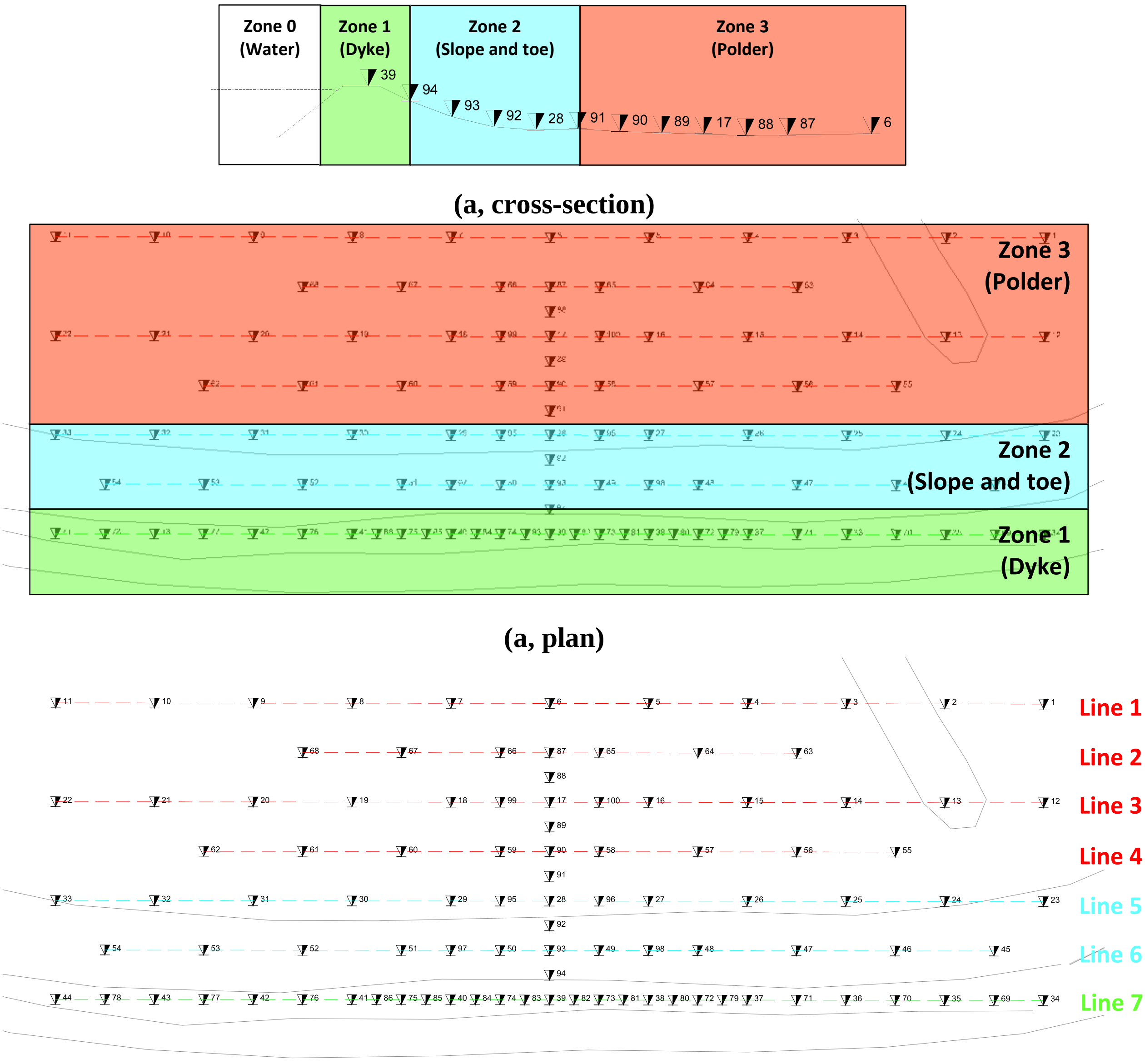
Note that the scales of fluctuation estimated from the detailed measurements can be used in finite element and Monte Carlo analyses to quantify the slope reliability (Varkey et al., 2017). Including measured data directly into analyses can also allow a reduction in uncertainties, usually giving a reduction in the calculated probability of failure (e.g. as in other work from the same research group as the Authors (Li et al., 2016; Vardon et al., 2016)) and/or required partial safety factors (De Gast et al., 2015). This has recently been extended to include the consequence of failure, using the random material point method to quantify the run-out of slopes (Wang et al., 2016).

LOCATION OF SITE INVESTIGATION

The location of the site investigation was Leendert de Boerspolder, a polder located close to Leiden in the Netherlands. This location is typical of the west of the Netherlands; a dyke founded on soft material in order to defend or 'create' land from water. This particular dyke appears on maps of Balthasar (1611), and has been maintained first by local farmers and later by the local water authority 'Hoogheemraadschap van Rijnland'. The material of the dyke itself is not naturally deposited and consists of sand, silt, clay and rubble.

The building and maintenance of this man-made embankment has caused the soft layers to compress. It was hypothesised that this compression will influence the scales of fluctuation, thereby shortening the vertical correlation distance. In this paper the scales of fluctuation of the peat layer starting directly under the dyke have been investigated.

An extensive site investigation was performed, comprising 100 CPTs in a grid (as shown in Figure 1), and was designed to obtain the scale of fluctuation in different directions. The grid of CPTs was parallel to the dyke, with CPT Nos. 34-44 and 69-86 located on the crest of the dyke (Zone 1, Line 7), CPT Nos. 45-54, 92-94, 97 and 98 on the slope of the dyke (Zone 2, Line 6), and CPT Nos. 23-33 and 95-96 located at the toe of the dyke (Zone 2, Line 5). The remaining CPTs were located in the polder next to the dyke (Zone 3, Lines 1-4).



(b)

Figure 1. CPT grid (50m x 15m): (a) main testing zones; (b) CPT locations.

The CPTs were performed within a time period of two weeks, using a class 1 CPT cone with an a-factor of 0.85. The normalised cone resistance was derived from the measured cone resistance and penetration pore pressure, and is defined as:

$$q_t = q_c + u_2\ (1 - a) \tag{1}$$

where q_c is the measured cone resistance, u_2 is the penetration pore pressure measured behind the tip of the cone and a is the net area ratio (in this case a = 0.85).

THEORETICAL BACKGROUND

The scale of fluctuation θ is a measure of the spatial correlation of material properties with respect to a trend. The following process can be used to estimate it from CPT data:

(a) Remove the (linear) trend from the group of CPTs considered;
(b) Calculate the experimental correlation function from the group of CPTs;
(c) Calculate the theoretical correlation function by minimising the error between the experimental and theoretical correlation functions.

The experimental correlation function is determined from:

$$\hat{\rho}(\tau) = \frac{\hat{\gamma}(\tau)}{\hat{\gamma}(0)} \tag{2}$$

where

$$\hat{\gamma}(\tau) = \frac{1}{(t-1)} \sum_{j=1}^{t} (x_j - \hat{\mu}_j)(x_{j+\Delta\tau} - \hat{\mu}_{j+\Delta\tau}) \tag{3}$$

and where $\hat{\mu}_j$ is the estimated mean (or trend) of the dataset, τ is the lag distance, $j = 0, 1, 2, \cdots, k$, with k being the total number of observations, and t is the number of pairs of data at a lag distance of $\Delta\tau$. The theoretical Markov correlation function can be estimated as:

$$\rho(\tau) = e^{\frac{-2|\tau|}{\theta}} \tag{4}$$

and hence, the error between the experimental and theoretical correlation functions can be calculated as:

$$E(\theta) = \sum \left(\rho(\tau) - \hat{\rho}(\tau)\right)^2 \tag{5}$$

and thereby minimized.

As suggested by Vanmarcke (1983), a more flexible theoretical correlation function, made up from different correlation functions, can also be used. For example, equation 4 can form the basis of the weighted summation:

$$\rho(\tau) = c_1 e^{\frac{-2|\tau|}{\theta_1}} + c_2 e^{\frac{-2|\tau|}{\theta_2}} + \cdots + c_i e^{\frac{-2|\tau|}{\theta_i}} \tag{6}$$

where

$$0 \leq c_i \leq 1 \text{ and } \sum_i c_i = 1 \tag{7}$$

in which c_i are the weightings of the separate correlation functions, with each corresponding to a scale of fluctuation denoted by its subscript.

ANALYSIS

Using equations 1-7, the vertical scales of fluctuation have been estimated for the seven parallel lines of CPTs shown in Figure 1. These lines, starting from the top of Figure 1(b), are associated with three distinct zones, as indicated in Figure 1(a): Zone 1 is directly under the dyke, where it is thought mainly vertical compression has occurred; Zone 2 is under the slope and at the toe of the dyke, where vertical compression, horizontal shear and rotation have occurred; and Zone 3 is in the polder, where the influence of the dyke is limited or not present, and any deformation is likely to be compression caused by atmospheric influences or consolidation due to pumping. With reference to Figure 1, Lines 1-4 are located in Zone 3, Line 5 is at the toe of the dyke, Line 6 is in the slope of the dyke, and Line 7 is at the centre of the dyke crest.

In Figure 2, the q_t values from all CPTs are shown, from which the linear trends per CPT line (in blue) have been identified and removed, i.e. to give the de-trended tip resistance for the whole site, shown as black dots. The experimental correlation function was derived from the de-trended CPT groups (i.e. with $\hat{\mu}_j$ equal to zero). The summary of the trend removal is given in Table 1, in which $\hat{\mu}$ is the mean of the original (i.e. before de-trending) data, and where the standard deviation is derived from the de-trended data. Calculating the coefficient of variation (CoV) using the identified standard deviation and $\hat{\mu}$ shows a consistency in the data, with an average CoV of 0.19.

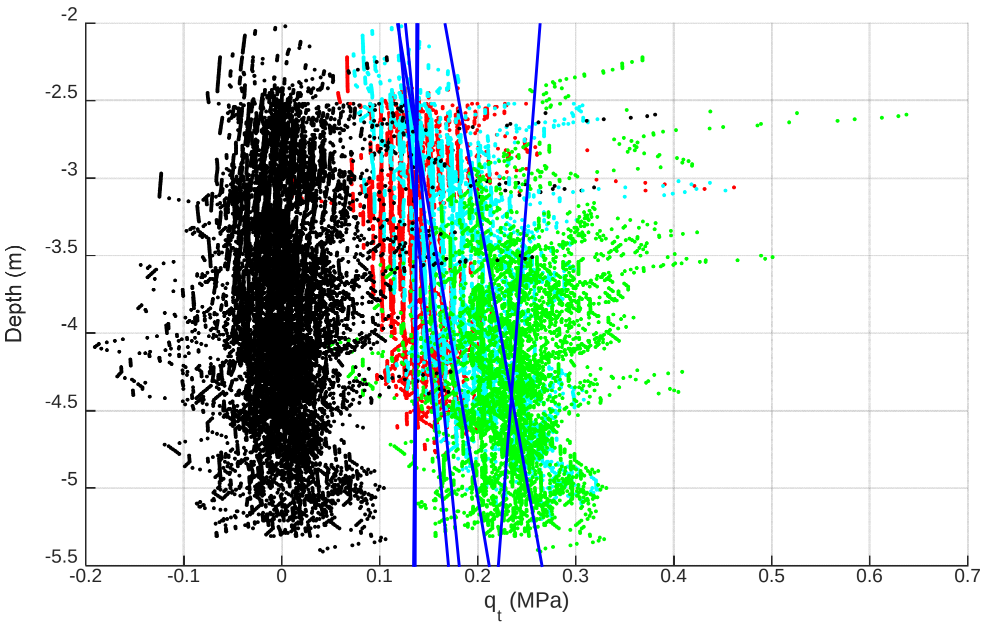


Figure 2. CPT-data q_t: in red, CPT Lines 1-4; in cyan, CPT Lines 5 and 6; and in green, CPT Line 7. The linear trends (blue) are identified per line and the de-trended data (black) are used to calculate the experimental correlation function.

The experimental correlation function has been calculated for each CPT line. The theoretical correlation function has then been estimated by minimising the error with respect to the experimental correlation function. Note that, while constructing the experimental correlation function, larger lag lengths are calculated with a decreasing amount of data and so the results can become increasingly erratic. Therefore, a choice has to be made on how much of the correlation function should be taken into account when estimating the error. In this case, the selected correlation functions are a reasonable balance between calculating large correlation lengths and maintaining accuracy. Figure 3 shows the experimental correlation functions and their theoretical fits. In most cases, a best fit has been obtained by adding two Markov correlation functions using equations 6 and 7. Where there are two distinct scales of fluctuation, the smaller scale of fluctuation is always dominant, i.e. it has a higher weighting coefficient than the larger scale of fluctuation.

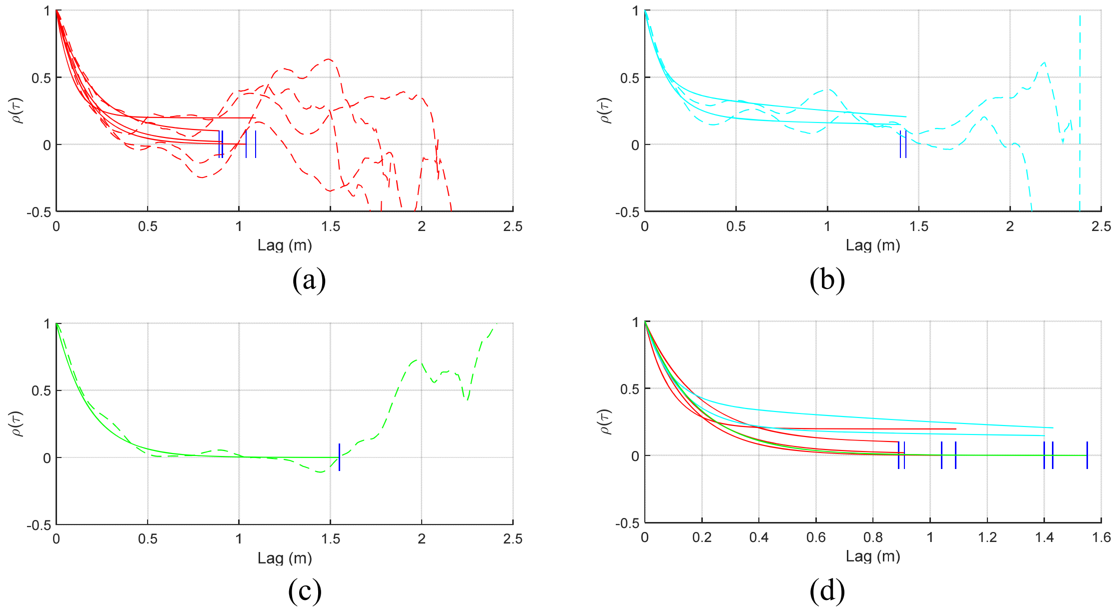


Figure 3. Experimental correlation functions and their theoretical fits: (a) Lines 1-4 (Zone 3); (b) Lines 5-6 (Zone 2); (c) Line 7 (Zone 1); (d) comparison of all fitted solutions.

Table 1 indicates that Zone 1 results (Figure 3(c)) exhibit a single scale of fluctuation. In contrast, Zone 2 results (Figure 3(b)) exhibit most evidence for two superimposed scales of fluctuation (greatest secondary coefficient, c_2), while Zone 3 results (Figure 3(a)) show most scatter experimentally.

Table 1. Statistical properties of depth-normalised q_t data

				Line 1		Line 2		Line 3		Line 4		Line 5		Line 6		Line 7	
No. CPTs				11		7		13		9		13		13		21	
Linear trend*		(MPa)		0.139+0.001z		0.142+0.001z		0.090-0.015z		0.095-0.016z		0.065-0.027z		0.11-0.028z		0.29+0.012z	
σ		(MPa)		0.026		0.029		0.024		0.031		0.029		0.034		0.051	
$\mu_{0.5}$		(MPa)		0.14		0.14		0.14		0.15		0.16		0.22		0.24	
$CoV_{0.5}$		(-)		0.19		0.21		0.17		0.21		0.18		0.15		0.21	
c_1	θ_1	(-)	(m)	0.9	0.38	0.95	0.33	1.0	0.32	0.8	0.18	0.8	0.25	0.6	0.18	1.0	0.36
c_2	θ_2	(-)	(m)	0.1	24.5	0.05	1.6	-	-	0.2	143.3	0.2	9.2	0.4	4.3	-	-

* z = depth in meters referenced to NAP

The experimental correlation function in Zone 1 (Figure 3(c)), at the crest of the dyke, is shown to monotonically decrease and the scatter around $\rho(\tau)=0$ is limited. An estimated single scale of fluctuation of 0.36 m seems appropriate. In Zone 2 (Figure 3(b)) the theoretical best fitting correlation function has two components: a small scale of fluctuation of 0.18-0.25 m, which is the largest component of the theoretical correlation function (weighting coefficients of 0.6-0.8) and a large scale of fluctuation of 4.3-9.2 m. The main component of the scale of fluctuation in Zone 3 (Figure 3(a)) is small, 0.18-0.38 m, which dominates the theoretical correlation function with coefficients ranging from 0.8-1.0, with a large scale of fluctuation being in the range of 1.6-143.3 m. Considering the short domain over which θ_1 and θ_2 are estimated, the very large estiamates of θ_2 of 24.5 m and 143.3 m should be interpreted as an indication of the presence of a larger scale of fluctuation or limitation in trend removal, rather than as quantitative values.

A possible cause for the differences in the vertical scales of fluctuation between the zones is presented below. It is emphasised that this is a hypothesis, based upon these initial results and knowledge of the likely stress history, and therefore no firm conclusions have been made. Significantly more experimental validation is needed to confirm this hypothesis.

The scale of fluctuation in the polder (Zone 3) is the least likely to be influenced by external influences and is therefore likely to be the most closely linked to the geological deposition processes. The largest scatter in the results and multiple (i.e. two) scales of fluctuation support this hypothesis. Zone 1, at the crest, shows the greatest agreement between the experimental and theoretical correlation functions. This is consistent with the 1D compression of very soft soils, where the softer zones are compressed preferentially. At the side of the dyke (Zone 2) the largest secondary scale of fluctuation is seen. It is hypothesised that this is due to rotational deformation and shear of the material (as well as more limited compression). The horizontal scale of fluctuation is well known to be characteristically larger than the vertical scale of fluctuation, and rotational deformation may therefore increase the calculated component of the vertical scale of fluctuation.

CONCLUSIONS

The assessment of vertical scales of fluctuation from CPT profiles has been presented. The construction method and history of the maintenance appears to play an important role in influencing the spatial correlations. Based on the measured data, the scale of fluctuation has been shown to be influenced by external forces such as those leading to compression, shear and rotational deformation. Compression seems to reduce both the number of scales of fluctuation and the scatter in the experimental correlation functions, whereas rotation/shear seems to promote longer (secondary) scales of fluctuation. Therefore, these findings suggest that, when assessing new or existing slopes using methods utilising scales of fluctuation, the stress history of the location under consideration should be accounted for.

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