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# Observations and Considerations Regarding Estimating Horizontal Scales of Fluctuation around Linear Infrastructure

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**Abstract:** Measuring soil variability has many challenges. One of the challenges is soil deformation, which can change the spatial correlation structure arising from the original geological processes. In particular, this is important in the assessment of existing structures. In this paper, the effect of existing structures on the horizontal spatial correlation is investigated using a dataset consisting of 100 CPTs in close proximity. These data were collected under and adjacent to a dyke structure which has caused considerable deformations. Using CPTs in zones where deformation has not occurred has allowed a quantification of this effect. The impact of the dyke is shown to dominate the natural scale of fluctuation.

Keywords: CPT, field test, scales of fluctuation, spatial variability.

## 1 Introduction

Large parts of the Netherlands are situated below sea level and are protected from flooding by dykes. Dykes are often constructed on soft soils, such as peat and clay, which have been deposited during the Holocene era. One characteristic of these soils is that they are significantly compressed by the weight of any soil body on top. Moreover, many dykes in the Netherlands are decades, or centuries, old and have been maintained by adding additional material.

It has been extensively reported that the spatial variability of a soil affects the reliability of structures (Griffiths and Fenton 1997; Hicks and Samy 2002; Popescu et al. 2005; Jaksa et al. 2005; Hicks and Spencer 2010; Hicks et al. 2014; Li et al. 2016). In the majority of cases examined in literature, single soil layers have been considered (notable exceptions include Liu et al. (2017), de Gast et al. (2018) and Hicks et al. (2019)) and spatial variability has been represented by a single scale of fluctuation in each direction. However, where a soil layer has been deformed by a structure, it can be reasonably assumed that the scale of fluctuation will also be impacted.

A recent case study (de Gast et al. 2017) presented a site investigation of 100 cone penetration tests (CPTs) in an area of 50 m × 15 m. The CPTs were undertaken on the crest of a dyke, on its slope and in the polder which the dyke protected from flooding. From the stratigraphy, it could be seen that the dyke had deformed (compressed) the underlying soil by as much as 1.1 m (half the height of the dyke). This led to the opportunity to measure its impact on the scale of fluctuation, as is presented herein.

## 2 Obtaining Spatial Correlations

Comprehensive theoretical overviews on how to quantify the spatial variation in soils are given by Vanmarcke (1977), Campanella et al. (1987), Wickremesinghe and Campanella (1993), and Fenton (1999a, b). The scale of fluctuation  $\theta$  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:

1. Remove the (in this paper, linear) trend from the group of CPTs considered;
2. Calculate the experimental correlation function from the CPT data (where several sets of data are available, the experimental correlation function is the mean of the individual experimental correlation functions);
3. Calculate the scale of fluctuation by systematically testing a theoretical correlation function generated with different scales of fluctuation. The scale of fluctuation is selected so as to obtain the minimum error between the theoretical and experimental correlation functions.

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The experimental autocorrelation function is determined from

$$\hat{\rho}(\tau) = \frac{\hat{\gamma}(\tau)}{\hat{\gamma}(0)} \tag{1}$$

where  $\hat{\gamma}$  is the experimental covariance function given by

$$\hat{\gamma}(\tau) = \frac{1}{(t-1)} \sum_{j=1}^t (x_j - \hat{\mu})(x_{j+\Delta j} - \hat{\mu}) \tag{2}$$

and where  $\hat{\mu}$  is the estimated mean (or trend) of the dataset,  $j$  is a counter representing the index of the first of a data pair at lag distance  $\tau$ ,  $\Delta j$  represents the index spacing of a specific pair of observations for a non-uniformly distributed dataset, and  $t$  is the number of pairs of data at a lag distance of  $\tau$ .

Although there are many theoretical correlation functions, in this work the Markov autocorrelation function has been used. It is given by

$$\rho(\tau) = e^{\frac{-2|\tau|}{\theta}} \tag{3}$$

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

$$E(\theta) = \sum (\rho(\tau) - \hat{\rho}(\tau))^2 \tag{4}$$

### 3 Leendert de Boerspolder CPT Data

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, with a height of 1.9 m and a horizontal crest to toe distance of 7.5 m, appears on the maps of Balthasar (1611). Its building and maintenance has caused the soft soil layers to compress, and it has been hypothesised that this compression will influence (i.e. reduce) the vertical scale of fluctuation (de Gast et al. 2017).

An extensive site investigation was performed, comprising 100 CPTs in a grid oriented parallel to the dyke (as shown in Figure 1), and was designed to obtain the scale of fluctuation in different directions. The CPTs were grouped into Zones depending on their location in relation to the crest, slope and toe of the dyke, and in the polder (Fig. 1(a)); in Lines parallel to the alignment of the dyke (Fig. 1(b)); and into Groups in which the main direction is perpendicular to the dyke (Fig. 1(c)). CPT Nos. 34-44 and 69-86 were located on the crest of the dyke (Zone 1, Line 7), CPT Nos. 45-54, 92-94, 97 and 98 were located on the slope of the dyke (Zone 2, Line 6), and CPT Nos. 23-33 and 95-96 were 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).

Two soft layers have been identified from the site investigation. These are: (a) a peat layer directly under the dyke and in the polder, with an average thickness of 1.8 m under the dyke and 2.1 m in the polder; (b) a clay layer below the peat, starting at the top of the layer as an organic clay and gradually transitioning over depth to a silty clay, with an average thickness of 5.5 m under the dyke and 6.3 m in the polder.

#### 3.1 Observations on horizontal scales of fluctuation at Leendert de Boerspolder

As shown in de Gast et al. (2017), the scale of fluctuation is influenced by deformations caused by loading from the dyke. For vertical scales of fluctuations, this was caused by compression of the soft soil, and related to the amount by which the layer has been vertically compressed as well as the geometry of the dyke structure.

The horizontal scales of fluctuation have been determined per Line and per Group using equations (1) – (4). The mean used to de-trend the data was calculated only from the selected CPTs. Table 1 presents the scales of fluctuation obtained. It is clearly seen that the calculated scales of fluctuation are impacted by the CPTs selected. In general, the Groups, which are measuring the scales of fluctuation in a direction perpendicular to the dyke, show relatively uniform values of 4-5 m in the peat and 4-8 m in the clay (with one higher value). In the Lines, measuring the scale of fluctuation parallel to the dyke, there is a higher range of 2-9 m in the peat and 3-20 m in the clay.

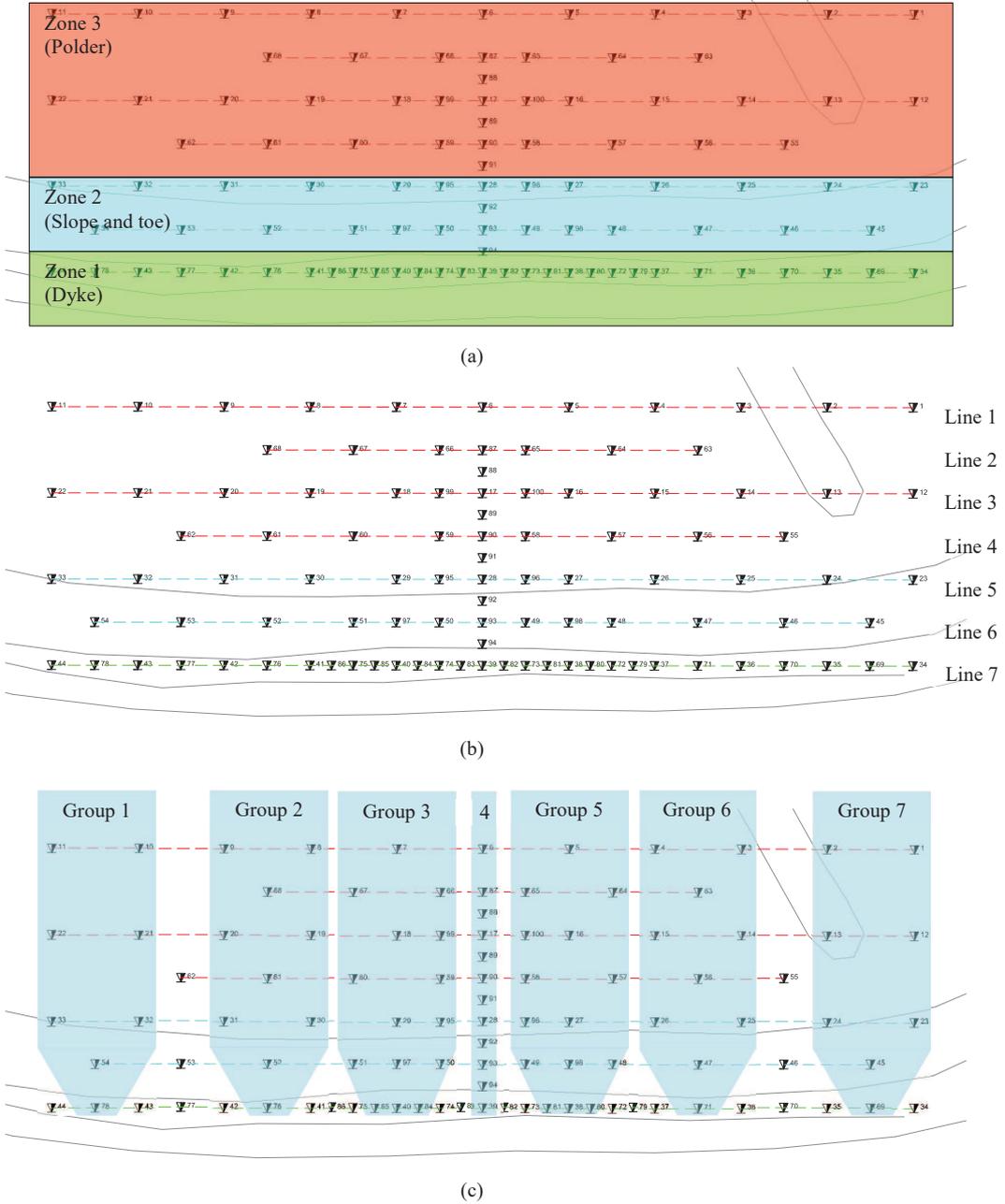


Figure 1. CPT grid (50 m × 15 m): (a) zones in testing area; (b) CPT lines parallel to the dyke body; (c) CPT groups perpendicular to the dyke body (after de Gast et al. (2017)).

Focusing on the potential cause of the similarity of the perpendicular scales of fluctuation, it is noted that the peat layer scale of fluctuation is approximately half the dyke width and the clay layer scale of fluctuation is slightly larger than the dyke width. This is consistent with deformations due to the dyke self-weight being the dominating influence, rather than the intrinsic variation caused by deposition. This can be visualised in Figure 2 (a), where the Group 4 CPTs are presented alongside an indication of the layers. It is seen that the peat and clay layers have been significantly compressed under the dyke and toe of the dyke and are therefore likely to be stiffer and stronger than soil in the polder, which is, therefore, a likely cause of the calculated scale of fluctuation being the same order of magnitude as the dyke body.

Considering the scales of fluctuation parallel to the dyke (i.e. Lines): under the dyke, in the peat (Line 7) and in the clay (Lines 6 & 7), a smaller horizontal scale of fluctuation is found than outside of the influence of the dyke (Lines 1-4). This suggests a significant influence of the loading from the dyke on the layers under the dyke. Over the ~400 years of its existence, the dyke has been maintained to preserve or increase the crest height at all locations. This means that in softer locations, where more settlement would have occurred, more material would have to be added, compressing the material and making it stiffer and stronger. This could have the influence of reducing the scale of fluctuation, albeit unevenly, which is observed. This uneven settlement can be seen in Figure 2(b), where the CPTs in Line 7 are presented. In contrast, Figure 2(c) shows that no such deformations are observed for CPTs in a line parallel to the dyke but in the polder.

**Table 1.** Horizontal scales of fluctuation, parallel to and perpendicular to the Leendert de Boerspolder dyke

		Horizontal scale of fluctuation [m]						
		Parallel to the dyke						
		Line 1	Line 2	Line 3	Line 4	Line 5	Line 6	Line 7
Peat		9	5	7	6	6	8	2
Clay		20	15	9	15	16	3	3
		Perpendicular to the dyke						
		Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7
Peat		4	5	4	4	4	5	5
Clay		8	11	6	7	5	9	4

#### 4 Considerations on the Effect of Displacements on Spatial Correlation

Both the horizontal and vertical scales of fluctuation are affected by deformations of the dyke body, with the two horizontal directions being affected unequally. In general, the observed changes in the vertical scale of fluctuation are in line with the observed compression. In the horizontal plane, a local large compression dominates any changes in calculated horizontal scales of fluctuation, although depositional history and processes may continue to play a minor role in influencing physical changes relating to maintenance.

For analyses that use the scales of fluctuation (e.g. the random finite element method (Griffiths and Fenton 2007)) to get an accurate prediction of the spatial distribution of the strength properties, soil deformations should be taken into account. To capture the impact of the original variability and the influence of the deformations it is proposed that the construction process should be modelled, although this may lead to complex computational procedures given that the deformation can also be uneven along the length of the structure.

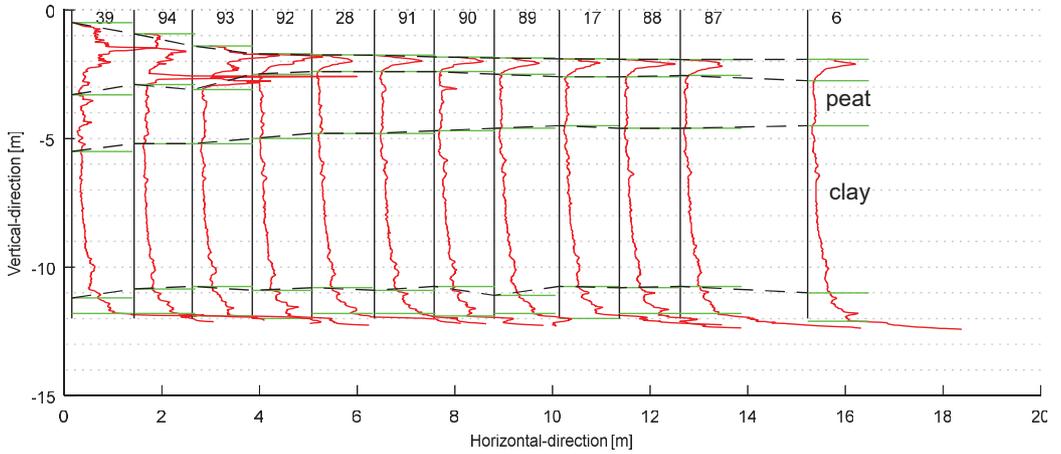
The impact of deformations on the stationarity of the statistics, i.e. the assumption of constant statistics when obtaining the scales of fluctuation, is also something that could be further investigated.

#### 5 Conclusions

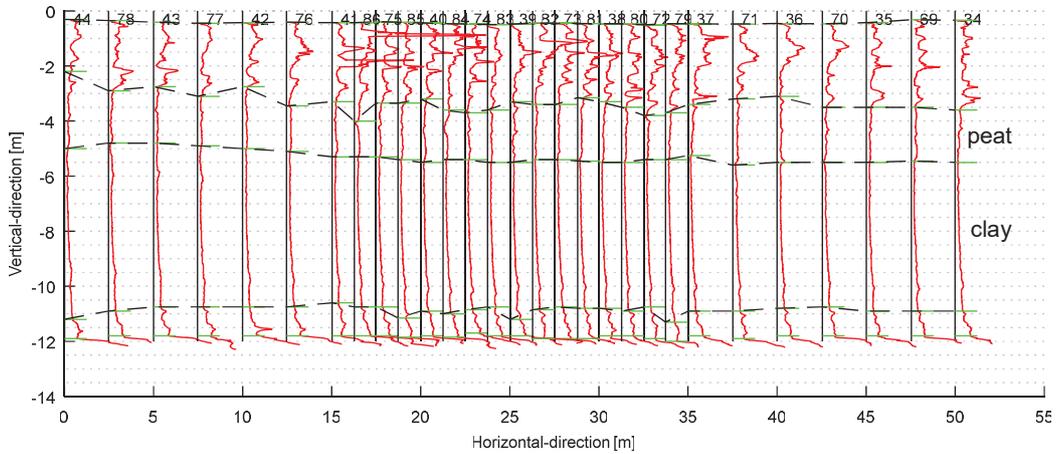
The horizontal scales of fluctuation have been calculated in two soil layers beneath a dyke. The influence of the loading from the dyke has been shown to be important, with the geometry of the dyke dominating the calculated scales. This has an important consequence for embankment reliability analysis; in particular, the assessment of existing structures, where often a best estimate of the initial scale of fluctuation is used.

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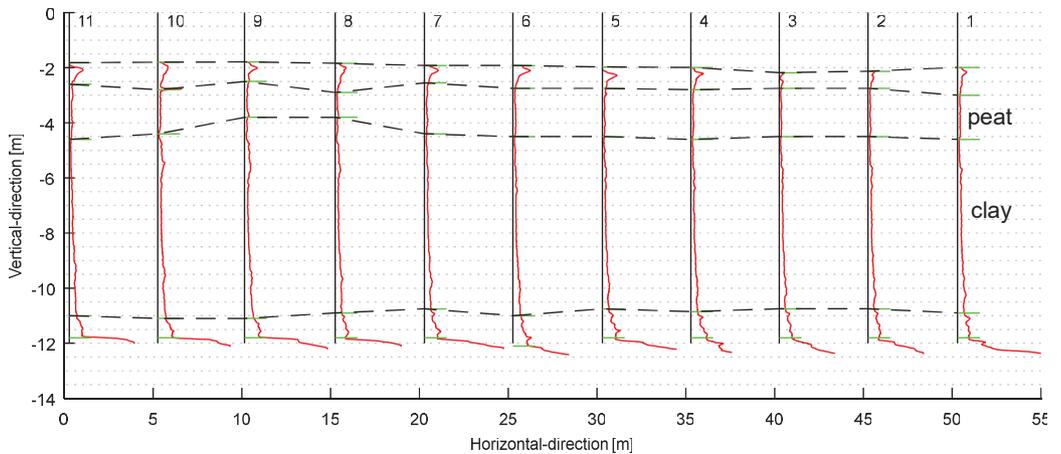
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(a)



(b)



(c)

**Figure 2.** CPT profiles of cone resistance (red lines) and layer interpretation (green markers and black dashed lines): (a) Group 4, perpendicular to the dyke; (b) Line 7, along the crest of the dyke; (c) Line 1, in the polder parallel to the dyke.

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