Spatial Variability of Levees as Measured Using the CPT

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ABSTRACT: The spatial variability of a soil deposit is something that is commonly discussed but difficult to quantify. The heterogeneity as a function of lateral distance can be critical to the design of long engineered structures such as highways, bridges, levees, and other lifelines. This paper presents a methodology for using CPT measurements to quantifying the spatial variability of cone tip resistance along a levee in the California Bay Delta. The results, presented in the form of a general relative variogram, identify the distance at which the maximum spatial variability is achieved for a given soil strata. This information helps define minimally correlated stretches of levee for proper failure and risk analysis. Presented herein are methods of interpreting, calculating, and analyzing CPT data to arrive at the quantified spatial variability with respect to different static and seismic failure modes common to levee systems.

1 INTRODUCTION

Spatial variability of engineering properties in soil strata is inherent to the nature of soil. Spatial variability is controlled primarily by the depositional environment where high energy systems usually deposit materials with high spatial variability (e.g. alluvial gravels) and low energy systems usually deposit materials with low spatial variability (e.g. lacustrine clays). This spatial variability is generally taken into account in geotechnical design in a qualitative empirical manner through appropriately spaced borings to assess the changing subsurface conditions. There are times when quantifying the spatial variability can be useful, particularly when addressing engineered structures that cover large spatial distances. This paper addresses the need for quantifying spatial variability of soil deposits associated with levee systems in the California Bay Delta. Methods for using the CPT to quantify spatial variability as part of ongoing research into levee risk analysis are discussed.

The primary goal of defining the spatial variability is to determine the level of correlation, or conversely the statistical independence, between levee segments (often called levee reaches). In risk analysis the length of a levee reach can have a large impact on the resulting probability of failure for a series system such as a levee or embankment. Quantifying the spatial variability determines what an appropriate reach length is with respect to the different failure mechanisms that levees are subjected to (Moss and Eller 2007). Current practice tends towards neglecting the spatial variability (DWR 2009) or using a prescribed levee reach length (van Manen and Brinkhuis 2005) that has little to do with the actual spatial variability and the failure mechanism of concern.

2 CPT DATA

The primary data set for this study is a limited number of CPT soundings from an island in the CA Bay Delta. Figure 1 shows the location of 12 CPT soundings that were performed in 1998 as part of a grouting project to stabilize a levee made of primarily granular material. In this study we use the pre-grouted CPT soundings that were measured along the levee crest. This data set is too limited to perform a statistically robust spatial analysis but is useful in demonstrating the methodology and for providing some sense of the spatial variability of the levee and foundation soils. The methodology presented here is general and can be applied to other types of in situ measurements (e.g., SPT, Vs, etc).

Estimates of the measurement uncertainty related to CPT soundings are included in this analysis. Measurement uncertainty is the uncertainty due to the measuring process that can be reduced through careful measurement techniques, standardized testing equipment, proper calibration, and uniform procedures. Typical values of total measurement uncertainty (equipment+procedure+random uncertainty) are on the order of 5% to 15% coefficient of variation for a modern CPT (Kulhawy and Mayne 1990).

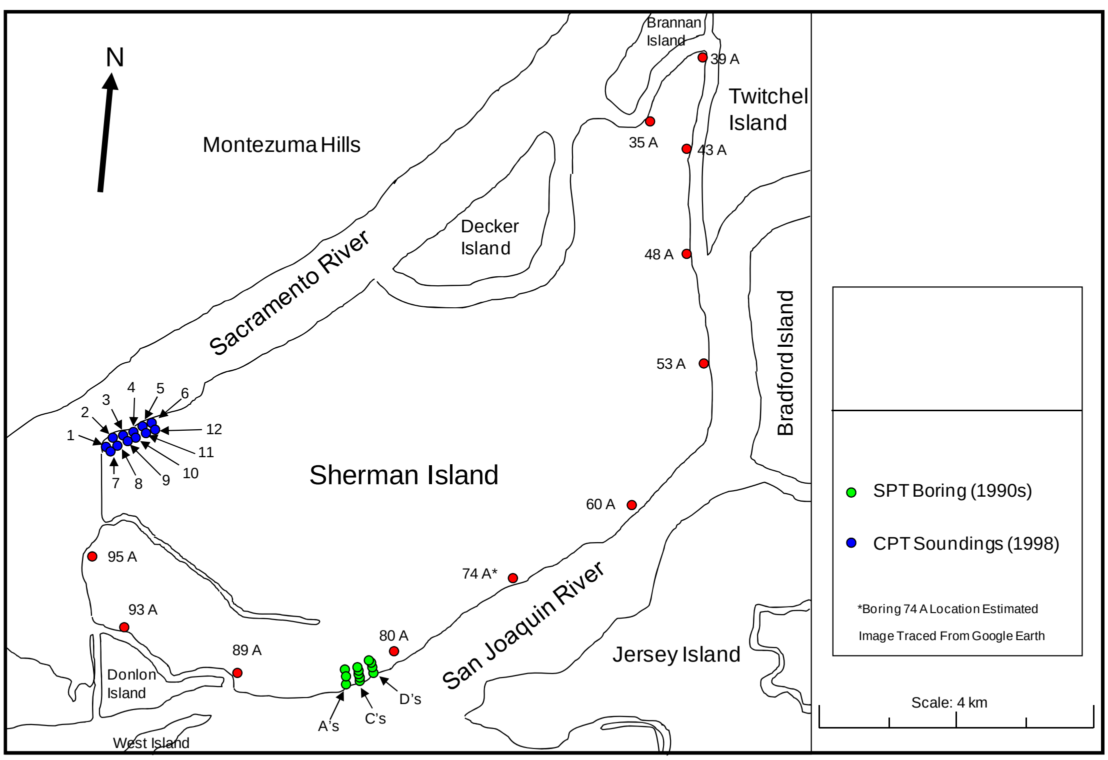

Figure 1. Map of Sherman Island (California Bay Delta) showing the location of SPT and CPT subsurface information. Twelve CPT were available for this levee (six along the levee crest and six in the free field) covering a distance of approximately a kilometer along the south west corner of the island.

3 DATA INTERPRETATION

In cone penetration testing, data is recorded in a relatively continuous manner in comparison with other in situ measurements that record data at discreet depths. This continuous sounding is useful for looking at the vertical heterogeneity of the soil profile but the data must be aggregated to look at the horizontal heterogeneity. Figure 2 shows the geomorphic or stratigraphic interpretation of the profile. The levee crest soundings pushed through approximately 5 m of stiff material which is the levee itself, approximately 15 m of soft material which is the peaty organic foundation material, and then tipped out in a dense material at the base. Unfortunately not all the soundings were provided with sleeve measurements, but when there are sleeve measurements the peaty organic soil layer can be easily identified by very low continuous tip resistance in conjunction with high variable friction ratio.

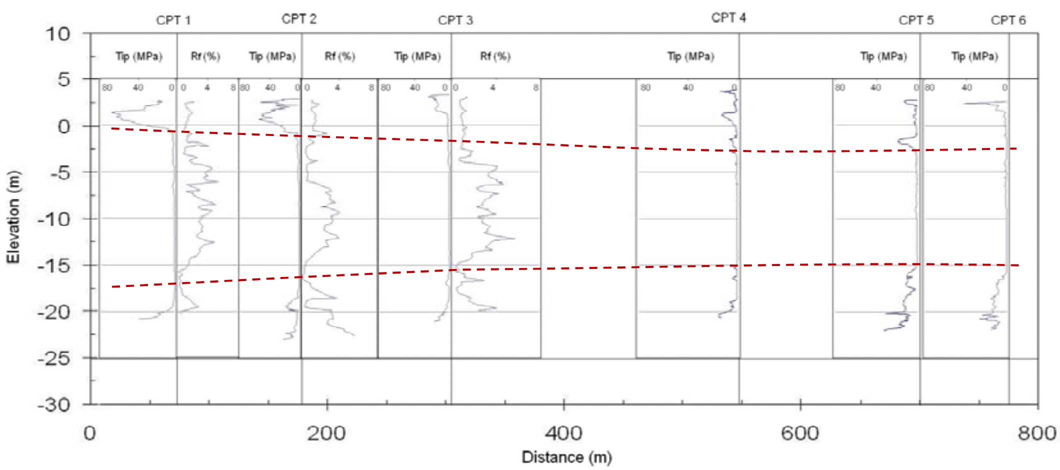

Figure 2. Six levee crest CPT soundings spatially located with respect to each other. Shown are the sounding and an interpretation of soil stratigraphy.

The electronic files for these soundings were not available so the traces were digitized by hand at relatively consistent sampling intervals but with an emphasis on not aliasing any peaks or troughs. Because the traces were not digitized at a precisely uniform sampling interval the spatially weighted average, as opposed to the sample median, was the appropriate central tendency calculated. The tip resistance measurements from the soundings were then corrected for effective overburden pressure (Moss et al. 2006). The overburden corrected tip resistances were then aggregated into central tendency and dispersion values per layer for each sounding to prepare the data for spatial variability analysis.

4 SPATIAL VARIABILITY FRAMEWORK

For this study a particular graphical representation of the spatial variability called a general relative variogram (Issaks and Srivastava 1989) has been chosen because of its utility (Moss 2009). The general relative variogram indicates the length of a levee reach by defining the distance needed to achieve the maximum continuous spatial variability (i.e., the distance needed to achieve minimum statistical correlation). The general relative variogram is also compatible with point estimates of measurement uncertainty represented by one half the squared coefficient of variation. Figure 3 shows a theoretical general relative variogram with an exponential function representing the variability with distance and showing the measurement uncertainty at zero distance. Variograms were originally developed for petroleum and mining exploration but have found favor in geotechnical engineering because of their applicability, statistical flexibility, and ease of use (e.g., Thompson et al. 2007).

The general relative variogram of the foundation soils for a reach are constrained by the geomorphology and depositional environment of the soil, and the general relative variogram of the levees are constrained by the borrow material, construction methods, and level of maintenance. Spatial variability in other levee studies, if is accounted for at all, is treated as a fixed pseudo-probabilistic value with an ambiguous mathematical basis. However, probability of failure calculations are highly sensitive to the reach length and a robustly defined reach length will provide a quantitative basis for eliminating this sensitivity.

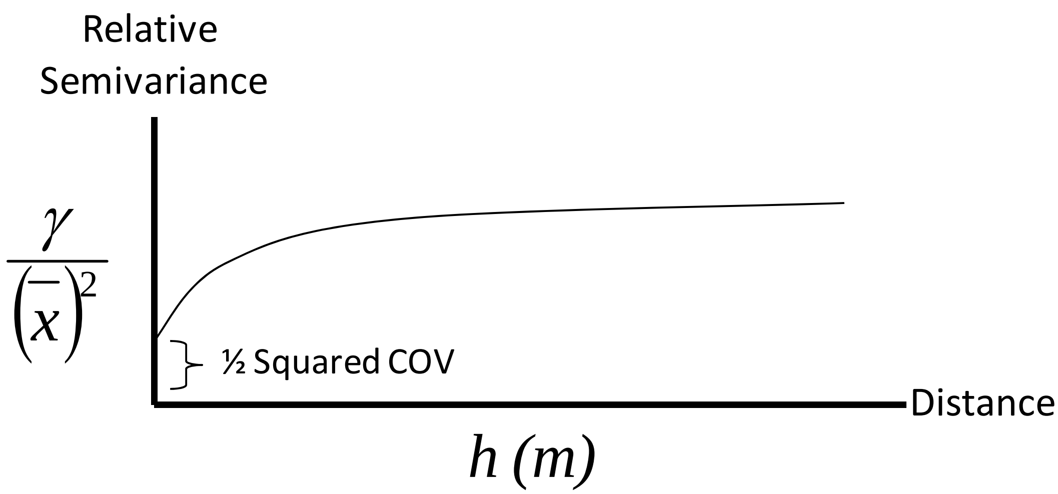

Figure 3. Conceptual diagram of exponential curve of a general relative variogram. The x-axis is the separation distance. The y-axis is the semivariance divided by the squared mean of data for a given separation distance. The intercept value is one half the squared coefficient of variation, a point estimate of measurement uncertainty. The reach length where the variance is at a maximum and the statistical correlation is at a minimum is at the plateau.

5 PROBABILITY OF FAILURE

Quantifying the spatial variability and defining the reach length for a particular failure mechanism is critical for accurately calculating the probability of failure. The probability of failure of a single component can be calculated in a number of ways. If statistical data is available then a frequency analysis can be performed to assess the likelihood of failure in a given time frame (e.g., annualized frequency of failure) and geographic location. In most engineering situations there does not exist sufficient or detailed failure statistics to warrant a frequency analysis, therefore the component probability of failure must be based on available information such as relevant lab or field test data, numerical modeling, scale model test results, physical or analytical analogs, and a general understanding of the physics controlling the failure mechanism. The defined or assumed probability distributions of the loading and resistance are then posed in a reliability format to estimate the probability of failure using first order second moment (FOSM), first order reliability method (FORM), second order reliability method (SORM), and/or Monte Carlo Simulations (MC).

In a series system, such as a levee, when any single component fails then the entire system fails. This is a non-redundant system and as engineers it is something that we try to avoid at all costs. Unfortunately levees are non-redundant and subjected to many factors on the load and resistance side that makes for particularly fragile levee components or levee reaches. In a system the total system probability of failure (p_F) of components that are positively correlated is defined as (Ang and Tang 1990);

$$p_F = p(E_s) \text{ where } E_s = E_1 \cup E_2 \cup \ldots \cup E_n \quad (1)$$

where E_i represents failure of each i component (which in this case is a levee reach), and E_s is union of all the component failures. The bounds of the probability of failure for the system are (Ang and Tang 1990);

$$[\max_i p_{Fi}] \leq p_F \leq [1 - \prod_{i=1}^{n}(1 - p_{Fi})] \quad (2)$$

which states that the lower bound is defined by the maximum component probability of failure, and the upper bound is the compliment of the product of all component reliabilities (one minus the component probability of failure). For small component probability of failure values the right hand side of the inequality becomes (Ang and Tang 1990);

$$[1 - \prod_{i=1}^{n}(1 - p_{Fi})] \approx \sum_{i=1}^{n} p_{Fi} \quad (3)$$

This means that the upper bound probability of failure of the system is the sum of the component probabilities; the more components in a system the higher the upper bound on the system probability of failure. Therefore if we reasonably define the reach length for a particular failure mechanism from spatial variability analysis, we can bound the system probability of failure on the low side as the maximum probability of failure for any reach, and on the high side as the sum of the probability of failure for each reach.

6 SPATIAL VARIABILITY RESULTS

Shown in Figures 4 and 5 are the general relative variograms of the levee embankment and the near surface peaty organic foundation soil. The limited amount of CPT soundings restricts this analysis to qualitative at best, but does not limit our explanation of the methodology. The two variograms include a representation of the measurement uncertainty (assumed to be a 15% coefficient of variation) at zero distance. The average separation distance between CPT soundings is 0.134 km.

The levee embankment variogram (Figure 4) shows a plateau at roughly one half of a kilometer separation distance. Within that distance the maximum spatial variability is achieved in this soil layer. The distance to the plateau can be taken as the levee reach length when considering failure mechanisms associated with the levee embankment material. The overall magnitude of the semivariance is high, showing high variability between separation distances for the tip resistance measurements of the sandy material. Comparing the variogram of the peaty organic foundation soil (Figure 5) to that of the levee embankment we see that a plateau is reached within a much shorter separation distance. The magnitude of the normalized semivariance is much lower with respect to the levee embankment, showing less variance between separation distances, but the variance rapidly becomes constant at the plateau. The peaty organic soil also had very low tip resistance compared to sandy soil, often an order of magnitude or more lower, which dramatically influenced the magnitude of the normalized semivariance.

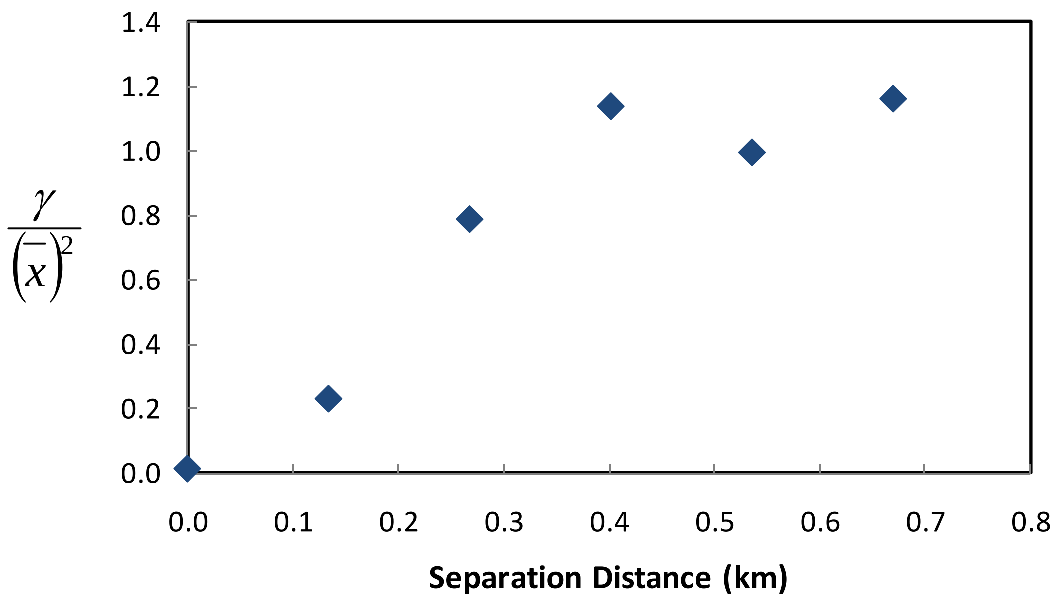

Figure 4. General Relative Variogram of the levee embankment material. A plateau is apparent at roughly one half a kilometer separation distance.

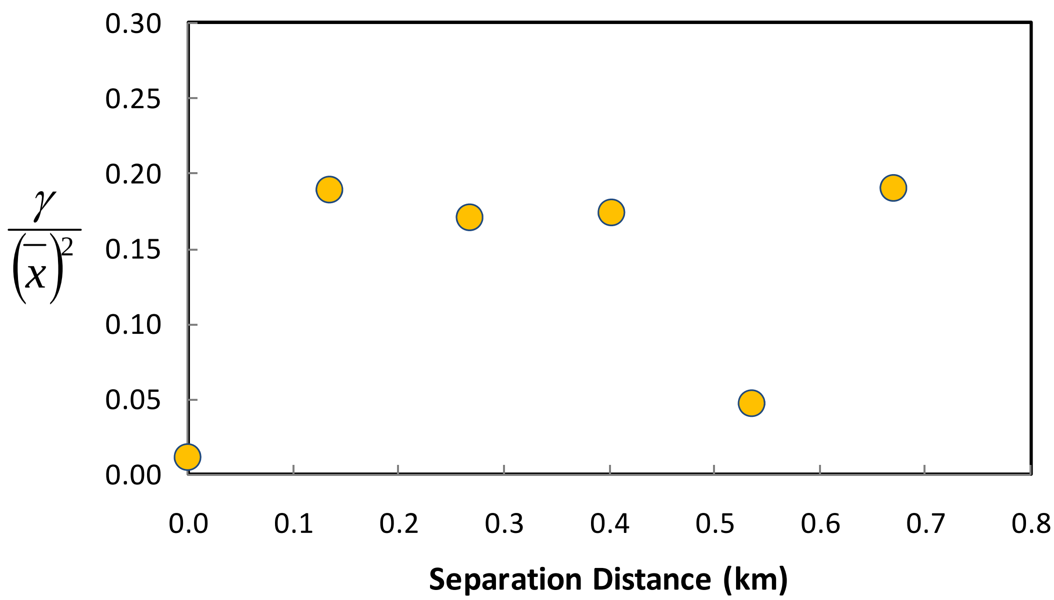

Figure 5. General relative variogram of the peaty organic foundation material. The plateau at a shorter separation distance is consistent with the smaller scale depositional environment of peaty organic materials.

The decrease in the normalized semivariance at a separation distance of just over a half a kilometer can be attributed to the lack of data pairs at these longer separation distances. For this limited study we have a set of 6 soundings available to us at an average spacing of 0.134 km. The first data point on the plot at zero separation distance is the measurement uncertainty, the second data point is based on 5 data pairs, the third 4 data pairs, the fourth 3 data pairs, the fifth 2 data pairs, and the sixth 1 data pair. This is a meager amount of data and the accuracy of the data points at the larger separation distances can become increasingly unrepresentative of the true semivariance. Interpretation of a variogram emphasizes the initial slope and the separation distance at which the plateau is reached. A theoretical exponential curve similar to that shown in Figure 3 would be fit to the data, and the decrease in semivariance with separation distance would be ignored because of the paucity of data.

7 CONCLUSIONS

The spatial variability results provide guidance on how to properly carry out a failure analysis of a levee system as a function of the failure mechanism of concern. For failure mechanisms in the levee embankment and the peaty organic foundation soil respectively the probability of failure must be calculated for the weakest or critical cross-section within each levee reach, making this a system probability of failure analysis. The levee reach length for the levee embankment material is much longer than the levee reach length of the peaty organic foundation soil and this must be taken into account. One approach to calculating the system probability of failure would be to find a representative critical cross-section for each soil layer, calculate the component probability of failure for that levee reach, and then assuming it is representative of each reach determine the system probability of failure by summing the reaches as in Equation 3. This provides the upper bound on the probability of failure for the system. The component probability of failure (or the probability of failure for a single reach) provides the lower bound or least conservative estimate of the probability of failure for the system.

This paper demonstrates a methodology for arriving at the quantified spatial variability using CPT data. The limiting factor in this analysis is the lack of data both in quantity and at reasonably equal spatial intervals to perform a robust statistical analysis. The spacing intervals should be controlled by the scale of the geomorphic features that are important to the design of the engineered structure and the controlling failure mechanisms. The authors strongly encourage practitioners when they are planning a site investigation to first consider the geomorphology, then consider the scale of the geomorphic features with respect to the engineering design. This will lead to subsurface investigations that can quantify not only the vertical heterogeneity but also the horizontal heterogeneity with respect to the structure or lifeline.

8 AKNOWLEDGMENTS

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