Assessment of Soil Variability Structure at McArthur Falls Generating Station

Michael Van Helden, P.Eng.
University of Manitoba, Winnipeg, Manitoba, Canada
James Blatz, P.Eng.
University of Manitoba, Winnipeg, Manitoba, Canada
Kent Bannister, P.Eng.
Manitoba Hydro, Winnipeg, Manitoba, Canada

ABSTRACT
In order to improve confidence in the use of probabilistic approaches for design, the ability to measure, model and understand the role of spatial variability in the assessment of geotechnical structure stability needs improvement. The current project was undertaken assess the probability of failure of a system of dykes at McArthur Falls Generating station for Manitoba Hydro. The current paper describes a site investigation conducted at McArthur Falls to assess the spatial correlation of soil structure and the uncertainty of engineering soil parameters. The results of the site investigation program will be used to select statistical distributions and spatial correlation functions for use in a Monte-Carlo probabilistic slope stability model.

RÉSUMÉ
Le projet en cours a été entrepris pour évaluer la probabilité d'échec de la pente pour un système de digues à la station de génération de Manitoba Hydro située a McArthur Falls, Manitoba, Canada. Ce document décrit une investigation de site effectuée a McArthur Falls pour évaluer la corrélation spatiale de structure de sol et l'incertitude des paramètres du sol. Les résultats du programme de l'investigation de site vont être utilisés pour sélectionner les distributions statistiques et les fonctions de corrélation spatiale pour l'usage dans un modèle probabiliste de stabilité de pente de Monte-Carlo.

1 INTRODUCTION

Geotechnical engineers deal with uncertainty and variability perhaps more than any other field of civil engineering. Soil and rock properties are variable, thus creating a risk to any system that relies upon a geotechnical structure, such as building or bridge foundations, flood protection dykes and diversion channels. Traditional approaches towards the assessment of stability involve the use of global factors of safety to offset any uncertainties that may affect the performance of designed structures. In doing so, measureable and quantifiable sources of uncertainty such as soil property variability are grouped together with all other sources of uncertainty, resulting in an true level of reliability that cannot be quantified. Consequently, structures and systems designed deterministically without account for uncertainty and variability could compromise either economic efficiency or safety.

Probabilistic methods serve as an alternative to traditional approaches by providing a methodology for the assessment of soil parameter variability and modeling the effect on performance. Soil property variability is perhaps the most commonly identified source of uncertainty since it is easiest to quantify (Vanmarcke 1977, Christian et al. 1994, El-Ramly et al. 2002). Statistical analyses of typical laboratory testing has been used in many instances to estimate the statistical distributions of soil parameters (Li et al. 2005, Van Helden et al. 2007, El-Ramly et al. 2003, Cherubini 2000). Since laboratory tests are conducted on small volumes of soil, typically obtained from discrete, relatively widely spaced points within potential sites or regions of interest, assessing the spatial variability of advanced strength parameters would require large numbers of tests on samples taken at a very close spacing, which would be grossly expensive. The Vane Shear Test (VST), or field vane, has been used extensively because it measures the in-situ response to undrained loading, can be conducted at close spacing in the field and is relatively inexpensive (Chiasson et al. 1995, Christian et al. 1994, Phoon and Kulhawy 1999). Christian et al. (1994) estimated the autocorrelation function for the VST and showed that the measurement error and inherent spatial variability could be separated using a geostatistical analysis of the spatial variance of VST measurements. Jaksa et al. (1997) pointed out that the minimum spacing between field measurements affected the autocorrelation function and the extrapolated measurement error. While VST measurements can be taken at various depths within a single borehole to assess the vertical scale of variability, the allowable spacing can potentially be similar to the vertical autocorrelation distance for cohesive deposits, making it difficult to assess the vertical correlation structure.

The Cone Penetration Test (CPTu) has the distinct advantage that measurements can be taken in the vertical direction at very small scales, potentially allowing for the detection of small-scale variability. The CPTu has been correlated to effective strength parameters for cohesionless soils (Robertson 1990), but has only been correlated to undrained strength parameters for cohesive soils, since the penetration test is conducted under undrained conditions. Also, the application of Cavity Expansion Theory and Critical State Soil Mechanics has allowed CPTu measurements to be related to the over-consolidation ratio, OCR (Mayne 1991). Although the capability to directly measure effective strength parameters in-situ has not yet evolved, the CPTu can be an effective means to measure the spatial correlation structure of cohesive soils.

2 SITE DESCRIPTION

The McArthur Falls Generating Station is located on the Winnipeg River system in Manitoba, Canada. The current study focused on Dyke 17W, the longest (7 km) of several dykes at the McArthur Falls station. Dyke 17W is up to 6 m in height, with side slopes of 1.5H:1V (dry side) and 2.2H:1V (wet side). The dyke is composed of compacted fill obtained from a glacial till borrow source, and is typically a silty clay material, with trace to some sand and gravel inclusions. The dyke is founded on a high plastic glacio-lacustrine clay deposit, with similar characteristics to those reported by Garinger et al. (2004). The dyke itself is not of particularly large scale or risk level, however was deemed an appropriate candidate for the research project due to site access considerations and a need for higher quality site-specific data. Recent changes to the Canadian Dam Association guidelines (CDA 2007) may require higher dyke crest elevations at the site. In order to achieve this, an analysis of the impact of raising the dyke elevation to the stability of the dyke is required. Deterministic analysis of the dyke with average strength parameters provides an estimated factor of safety that is lower than expected for a structure with no observed signs of instability and only minor long-term settlements since construction in 1955.

A probabilistic stability analysis accounting for spatial variability of the soil layers is being applied to more provide an assessment of risk and uncertainty along this dyke. A site investigation program was undertaken for the current project, including undisturbed sampling, index and advanced strength laboratory testing and CPTu testing. The majority of site investigation activities for the current project were focused on the CPTu Test-Site, located approximately 2 km from the south end of the dyke, as shown in Figure 1. Boreholes were drilled adjacent to the dyke to retrieve undisturbed Shelby tube samples for laboratory testing. CPTu soundings were conducted in a grid layout, spaced horizontally between 1 and 10 m. Additional CPTu soundings were conducted along the toe and along the crest of the dyke, spaced between 10 and 1000 m.

3 CONE PENETRATION TESTING

The CPTu measurements included the tip resistance (q_c), the sleeve friction (f_s) and the pore-pressure immediately behind the cone tip (u_2). A summary of the range of CPTu measurements with elevation is shown in Figure 2 for soundings located adjacent to the dyke fill. The upper few metres of the profiles characteristically show higher tip resistance and sleeve friction, with lower pore-pressure response, on average. These upper few metres are typically composed of inter-bedded, highly over-consolidated silts and clays, known locally as the upper complex zone. Below the upper complex zone, the tip resistance and sleeve friction are lower and more consistent with depth. The lower portion of the clay deposit is typically normally consolidated to lightly over-consolidated, soft and massive in structure.

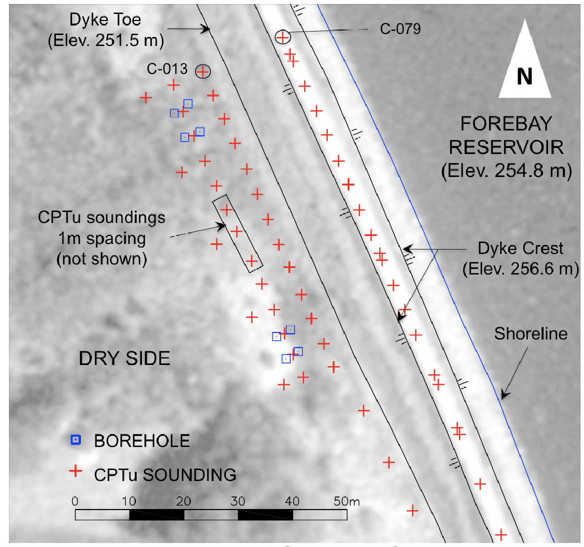

Figure 1. Plan location of CPT Test Site at McArthur Falls Dyke 17W (after Van Helden et al. 2009).

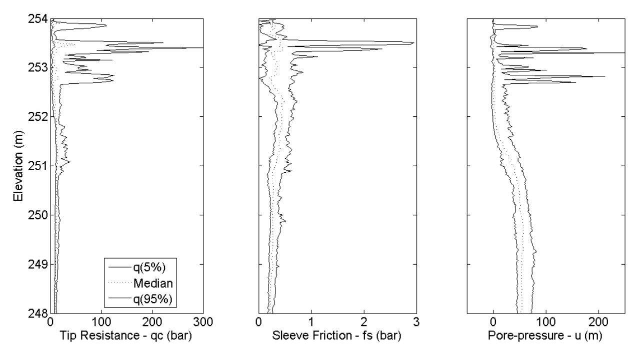

Figure 2. Range of CPTu measurements with elevation, foundation clays only.

3.1 Geostatistical Analysis

The autocorrelation function $R_x(\delta)$ describes the degree of correlation between measurements of a spatial variable x separated by some lag distance, δ. As the lag distance increases, the degree of correlation between separated measurements tends to decrease. The distance at which the autocorrelation decreases to zero is known as the range, a. The experimental autocorrelation $R_x(\delta)$ function can be estimated, as follows, for a stationary (de-trended or constant mean) spatially-correlated random field from a set of equally spaced measurements (Baecher and Christian 2003):

$$R_x(\delta) = \frac{1}{(n-\delta)\sigma_x^2} \sum_{i=1}^{n-\delta} \left(z(x_i) - \mu_x\right)\left(z(x_{i+\delta}) - \mu_x\right)$$

Where n is the number of measurements, σ_x^2 is the sample variance and μ_x is the sample mean. This formulation assumes stationarity; that is that the mean and variance of x are constant in space.

The vertical autocorrelation $R_{xv}(\delta)$ was estimated for CPTu soundings C-001 to C-052 located adjacent to the dyke in foundation clays only. The minimum lag spacing was the spacing of the CPTu measurements (5 cm). Autocorrelation was estimated using each of the CPTu measured parameters (q_c, f_s and u_2). As shown in Figure 3, the range varies depending on which parameter is used to compute the autocorrelation function. The estimated range for q_c, f_s and u_2 was approximately 0.7 m, 1.5 m and 2.8 m, respectively. The mechanisms of soil behaviour that are measured by each of the sensors are thought to influence the scale at which measurements are correlated. It is speculated that the cone tip measures a smaller-scale “micro-variability”, while the shaft friction and pore-pressure sensors measure a larger scale response within the surrounding soil. Furthermore, the effect of measurement noise and micro-variability of the clay structure is accentuated in q_c profiles in soft clays, resulting in a more erratic variation with depth. Measured sleeve friction tends to be more continuous in soft clay, as does the pore-pressure.

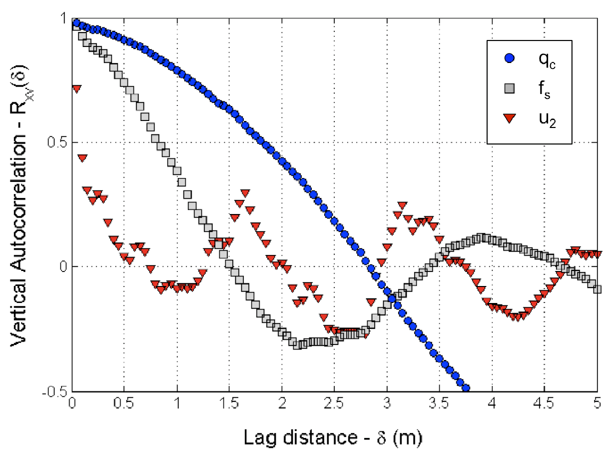

Figure 3. Vertical autocorrelation within a single CPTu sounding.

The horizontal autocorrelation $R_{xh}(\delta)$ was estimated for various sub-layers within the clay layer. For each sub-layer, measurements from each CPTu sounding were averaged over the depth interval of the sub-layer (Δz), and the horizontal autocorrelation of the spatial averages was examined. The minimum horizontal spacing between soundings was 0.88 m. Figure 4 shows the effect of the averaging interval on the calculated autocorrelation for sleeve friction. A single sub-layer from 4 to 8 m depth was divided in two depth intervals, from 4 to 6 m and 6 to 8 m. As shown, there was little observed difference in the resulting autocorrelation function for sleeve friction. Figure 5 shows the horizontal autocorrelation for each of q_c, f_s and u_2 in the 7 to 9 m depth interval. Extrapolation of the data to a lag of δ=0 to obtain the intercept describes the portion of the sample variance due to inherent spatial variability. According to the data shown in Figure 5, the autocorrelation extrapolated to the origin yields approximately $R_{xh}(\delta\tilde{=})$ = 0.2, 0.4 and 1.4 for q_c, f_s and u_2. These results are thought to be inconclusive.

Autocorrelation of the sleeve friction f_s in both the vertical and horizontal directions appears to follow a continuous curve. Although the results discussed here are limited and preliminary, they would suggest that the horizontal autocorrelation distance is approximately double than that in the vertical direction. Phoon and Kulhawy (1999) suggested the horizontal correlation distance to be in the order of 10 to 20 times the vertical distance, although they did not give specifics towards the depositional nature of the soil (e.g. alluvial, lacustrine or marine). Further analysis is required to gain confidence in the results presented here.

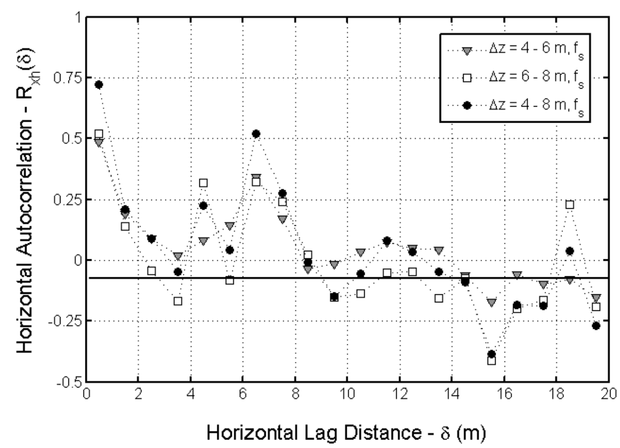

Figure 4. Effect of depth averaging interval on horizontal autocorrelation of sleeve friction.

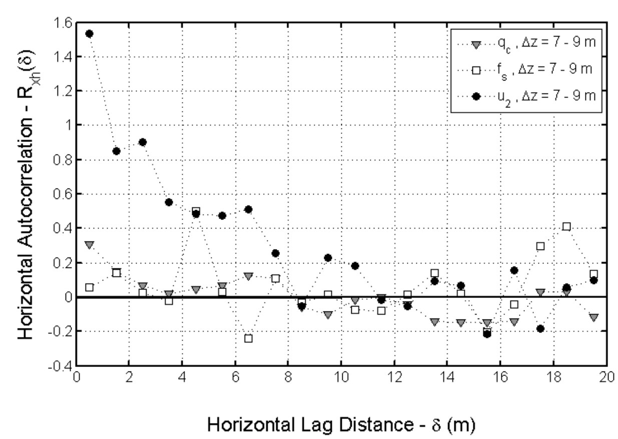

Figure 3. Vertical autocorrelation within a single CPTu sounding.

4 SUMMARY

The assessment of soil variability has been identified as an important step in probabilistic slope stability analysis. As probabilistic methods become more popular and useful, the methods of measuring and modeling spatial variability need improvement. The current project used the Cone Penetration Test (CPTu) to estimate the vertical and horizontal autocorrelation functions for the various CPTu measurement parameters (q_c, f_s and u_2). While vertical autocorrelation results seemed encouraging, cross-hole methods of assessing horizontal autocorrelation require further consideration. The results presented here are part of an ongoing research project for Manitoba Hydro.

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