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Spatial Variability of Subsurface Soil Conditions Causing Roadway Settlements

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Abstract. Settlement of problematic soils constituting the roadway subgrade may result in pavement distress and structural failure, requiring periodic pavement patching and resurfacing. Many of these problems occur as a result of the settlement of soft cohesive and organic soils. Due to the extent of roadway projects and the limited frequency of boring locations, spatial variability of subsurface soil conditions, and sometimes due to an inadequate extent of exploration, these problematic soils may not be identified suitably during subsurface explorations. An extensive subsurface exploration program was implemented for detailed characterization of subsurface conditions for a relatively short section of an existing roadway experiencing continuing settlements. This paper presents some of the exploration results, assesses the spatial variability of the subsurface soil conditions, and comments on the effect of spatial variability of subsurface conditions on the roadway's performance.

Keywords. soil variability, field tests, cone penetration test, coefficient of variation, roadway settlements

1. Introduction

Settlement of problematic soils constituting the roadway subgrade may result in pavement distress and structural failure requiring either periodic pavement patching and resurfacing or permanent remediation such as ground improvement. Due to the extent of roadway projects, spacing between boring locations, and budget constraints, spatial variability of subsurface soil conditions and existing problematic soils may not be identified properly during subsurface explorations.

The geotechnical engineering field has more variability and uncertainty involved compared to the other fields of civil engineering. As reported by Phoon and Kulhawy (1999), geotechnical variability comes from three primary sources of uncertainties; inherent variability, measurement error, and transformation uncertainty.

An extensive subsurface exploration program was implemented to characterize soil and groundwater conditions in detail for a section of an existing roadway experiencing continuing settlements. The detailed exploration program was needed to analyze both the continuing settlements at the site and assess the feasibility of various ground improvement and deep foundation alternatives to remediate the ongoing settlements.

Conventional methods to remediate subgrade settlements caused by problem soils include removal of weak soils and replacement with new suitable engineered fill, near-surface chemical stabilization such as lime or cement, or preloading/surcharging with or without wick drains. However, when problem soils are relatively deep, or long term settlement tolerances are low, these conventional methods can sometimes prove ineffective or too costly. New technologies and extended application of old technologies have led to use of several methods for the remediation of existing roadway subgrade settlements. Because each method has equipment related depth limitations and differing degrees of applicability in certain soil types, it is crucial for each project to determine the soil types and their variations across the site.

This paper presents some of the exploration results, assesses the spatial variability of the subsurface soil conditions, and comments on the effect of spatial variability of subsurface conditions on the roadway's performance.

2. Project Site

The project site was located in the northeastern part of the State of Ohio in the United States. The site is located adjacent to a lake. The roadway was originally built as a two-lane roadway and it was extended to four lanes in the early 1990s. Because of the presence of very soft and soft soils at the site, a lightweight fill was used as part of the subgrade during the expansion to reduce loads transferred to the soft soils below. Due to inadequate bearing capacity on the north side of the roadway, light poles were not installed on that side during the expansion.

After the completion of the expansion, an approximately 180 m long section of the roadway, especially on the westbound lanes, continued to settle, causing significantly poor pavement conditions with dips, cracks, and large potholes. Several repair projects, involving asphalt patching and complete lane resurfacing, have been done on this problem section of the roadway over the years.

The roadway has continued to settle, and has most likely accelerated due to the additional pavement thickness needed to level the previously settled roadway. Engineers at the State's Department of Transportation became more alert to the continued settlements once the settlements reached a level such that the curb on the north side had sunk below the existing roadway grade. The roadway has a curve at this location, and the outer edge of the curve is on the north side of the roadway. The super-elevation on the north side of the roadway was also lost due to the settlements.

3. Cone Penetration Tests

Cone penetration tests with pore pressure measurements (CPTu) were conducted at 17 different locations at this site. Although they were CPTu tests, the cone penetration tests are simply referred to as CPT in this paper. Some tests were terminated at relatively shallow depths and some tests were performed outside the zone experiencing settlements, and are therefore eliminated from consideration in this paper. The results obtained from nine different CPT soundings were examined and used for the analysis presented herein. Depths of the nine CPT soundings ranged from 14.34 m to 36.30 m. Each CPT location was pre-drilled (3.02 m on average) to penetrate a hard layer present under some parts of the roadway. Since only a few of the CPT soundings penetrated deeper than 25 m, the test data up to this depth are considered for the spatial variability analysis. The nine CPT tests were performed within an approximately 110 m length of the roadway section. The roadway at the site has almost a level grade.

4. Soil Variability Model

Subgrade soil layers are formed by various geological, environmental, and physical-chemical processes. Because of these natural processes, the soil properties have spatial variability both in vertical and horizontal directions. As presented by Phoon and Kulhawy (1999), this spatial variation in the vertical direction can be separated into two components: deterministic trend function $t(z)$ and fluctuating component $w(z)$ as follows:

$$\xi(z) = t(z) + w(z) \tag{1}$$

where ξ is the soil property and z is the depth. Similarly, the spatial variation of the soil property, ξ, in horizontal direction can be presented as:

$$\xi(x) = t(x) + w(x) \tag{2}$$

where x is the distance in horizontal direction. The fluctuating components $w(z)$ and $w(x)$ in Eqs. (1) and (2) represent the inherent variability.

The inherent soil variability can be modeled using random field theory, and the variability can be prescribed by the coefficient of variation (COV) and the scale of fluctuation (Phoon and Kulhawy, 1999). The COV is defined as:

$$\mathrm{COV}_{\xi} = \frac{\sigma_{\xi}}{\mu_{\xi}} \tag{3}$$

where σ_ξ is the standard deviation and μ_ξ is the mean value for the variable ξ. In this paper, the spatial variability of several soil parameters across the site was assessed by using the COV values obtained from the CPT data.

Phoon and Kulhawy (1999) investigated the COV values of various soil parameters obtained from laboratory tests and field measurements reported in the literature and summarized the typical values. They have noted that most COVs reported in the geotechnical literature are based on total variability analyses. Therefore, the reported COVs in the literature may be considerably larger than the actual inherent soil variability because of several reasons, one of which is soil data from different geologic units are mixed.

Although it is important for the reliability-based design to assess inherent soil variability for geologic units separately, for some projects it is also important to understand soil variability across the project site considering all different geologic units present. For example, when ground improvement is planned at a site, the improvement usually needs to penetrate through different soil layers and sometimes be applied to different layers. Since each ground improvement method has its own advantages, limitations, and applicability to different soil types, the soil variability at a site would affect the selection of the improvement method. For roadway projects, even if it is a relatively small section along the roadway, the subsurface conditions could be quite different along the alignment. Significantly different geologic units and soil types with varying properties can be present at any elevation along the problematic section of the roadway, i.e. in the horizontal direction.

The coefficient of variation of soil variability in the horizontal direction at the project site at different elevations is investigated using the CPT data and presented in this study. The parameters investigated are: (1) cone tip resistance, q_c, (2) sleeve friction, f_s, (3) SPT-N_{60}, and (4) undrained shear strength, $\underline{s_u}$. The spatial variability assessment performed includes both directly measured and estimated soil properties. While the cone tip resistance and the sleeve friction are directly measured in-situ data, SPT-N_{60} and undrained shear strength are estimated parameters based on correlations using the in-situ data collected during CPT soundings.

The estimated SPT-N_{60} and undrained shear strength, s_u, values were calculated by using a commercially available software which uses the in-situ CPT data to estimate various soil properties based on the published correlations in the literature. The software uses the cone tip resistance and soil behavior type index to estimate SPT-N_{60} values and uses corrected cone tip resistance, total overburden pressure, and vertical cone bearing factor to estimate undrained shear strength, s_u, values.

5. CPT Results and Soil Variability

5.1. Cone Tip Resistance

Cone tip resistance, q_c, measurements obtained from the CPT soundings are shown in Figure 1(a). There are no CPT data presented at very shallow depths, because holes were pre-drilled so that the CPT soundings would be able to pass any hard layers below the pavement. Figure 1(b) shows the upper boundary, lower boundary, and mean of the measurements across the site and their variations with depth. The variation of the COV of cone tip resistance with depth is shown in Figure 1(c). The figure shows that the COV values drop significantly past 20 m depth. While the average COV for depths up to 20 m is 95%, the average value is 39% for depths below 20 m. The dashed lines in Figure 1(c) show the average COV values.

5.2. Sleeve Friction

Sleeve friction, f_s, measurements obtained from the CPT soundings are shown in Figure 2(a). Figure 2(b) shows the upper boundary, lower boundary, and mean of these measurements across the site and their variations with depth. The variation of the COV of sleeve friction with depth is shown in Figure 2(c). The sleeve friction COV values are higher compared to the cone tip resistance COV values. The COV values drop past 20 m depth similar to the cone tip resistance, however the drop is smaller. While the average COV for depths up to 20 m is 102%, the average value is 66% for depths below 20 m, as shown by the dashed vertical lines in Figure 2(c).

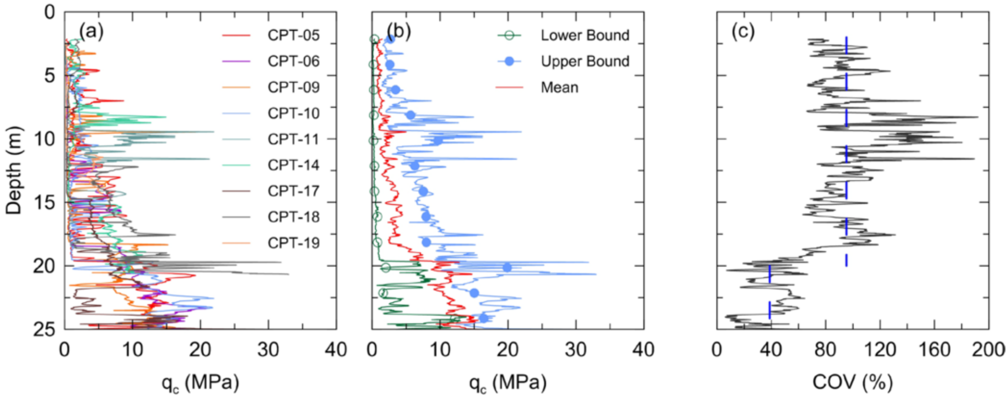

Figure 1. Cone tip resistance, q_c, and its variation at the site.

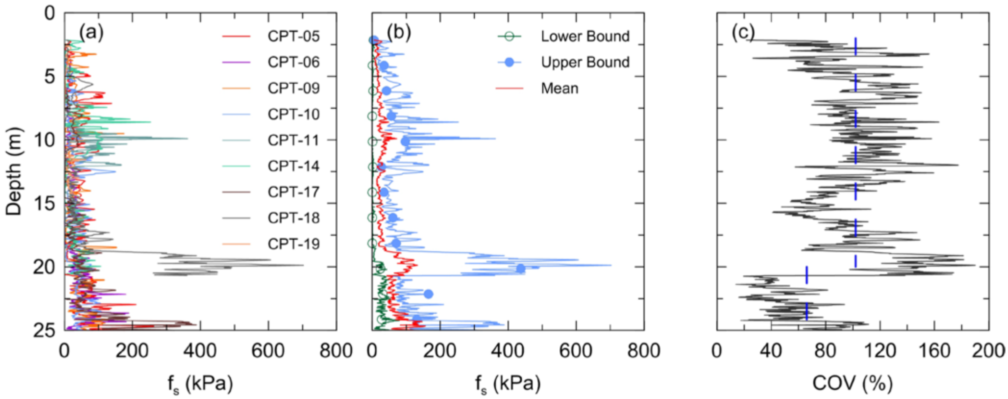

Figure 2. Sleeve friction, f_s, and its variation at the site.

6. Horizontal Distributions and Trends

Although it is very common for COVs in the vertical direction to be evaluated and published in the literature, this is not the case in the horizontal direction, for example at a certain depth across a project site. Phoon et al. (1995) reported variations and scale of fluctuations of some geotechnical properties in the horizontal direction. Stuedlein et al. (2012) investigated the horizontal coefficients of inherent variability and attempted to develop horizontal random field model parameters using CPT data.

The trends of CPT measurements, q_c and f_s, along the roadway alignment at various depths (5, 10, 15, and 20 m) are investigated and presented in Figure 3 and Figure 4. The dashed lines in the figures show the property trend lines at each depth analyzed. The COV values at each depth are also shown in the figures.

Figure 3 shows that the cone tip resistance, q_c, fluctuates along the roadway alignment with no consistent trend at different depths. For example, while the q_c trend decreases along the roadway alignment at 10 m depth, the trend is opposite at 15 m depth, i.e. increases along the roadway alignment. The trend at 20 m depth is almost level with the lowest COV value among the depths presented in Figure 3.

The horizontal distribution and the trends of sleeve friction, f_s, at different depths are shown in Figure 4. The figure shows that, similar to the cone tip resistances, there is no clear trend of sleeve friction along the roadway alignment. For example, while the f_s trend decreases along the roadway alignment at 5 m depth, the trend increases at 20 m depth. In addition, while the COV of cone tip resistance is the lowest at 20 m depth among the four depths presented (Figure 3), the COV of sleeve friction is the highest at 20 m depth among the four depths presented (Figure 4).

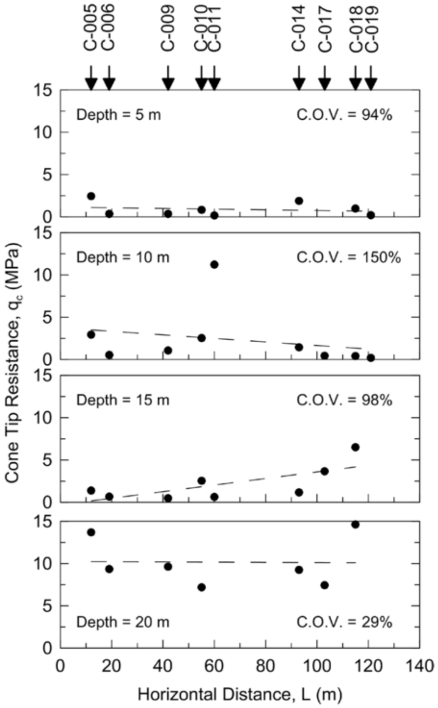

Figure 3. Sample horizontal distributions of cone tip resistance, q_c, along the roadway.

The variation of the COV of spatial variability of the sleeve friction, f_s, in the horizontal direction is plotted versus the mean f_s in Figure 5(b). No trends in the COV are present as the mean f_s varies from 5.3 to 156.2 kPa and the COV for f_s range between 14 and 190%.

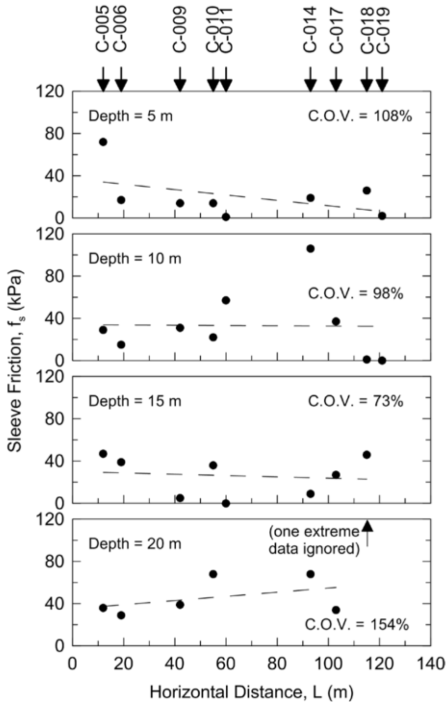

Figure 4. Sample horizontal distributions of sleeve friction, f_s, along the roadway.

7. Coefficient of Variation of Soil Variability

The spatial variability in the horizontal direction at the site is presented for the following parameters: (1) cone tip resistance, q_c, (2) sleeve friction, f_s, (3) SPT-N_{60}, and (4) undrained shear strength, $\underline{s_u}$. While the cone tip resistance and the sleeve friction are in-situ data, SPT-N_{60} and undrained shear strength are estimated parameters based on correlations using the in-situ CPT data collected.

7.1. In-situ Soil Data

The variation of the COV of spatial variability of the cone tip resistance, q_c, in horizontal direction is plotted versus the mean q_c in Figure 5(a). The figure shows that there is an overall trend, where the COV decreases as the mean increases.

7.2. Estimated Soil Parameters

The variation of the COV of spatial variability of the estimated SPT-N_{60} values based on CPT data in the horizontal direction is plotted versus the mean SPT-N_{60} in Figure 6(a). The figure shows that there is an overall trend, where the COV decreases as the mean increases.

The variation of the COV of spatial variability of estimated undrained shear strength, s_u, based on CPT data in the horizontal direction is plotted versus the mean s_u in Figure 6(b). No trends in the COV are present as the mean s_u varies from 6.1 to 85.1 kPa and the COV for s_u range between 0.4 and 147%.

8. Coefficient of Variation for All Soils

The COV values presented so far were all based on the data collected at the same elevation across the site. The soil variability at the site was also analyzed and is presented in Table 1 by considering all the data collected, irrespective of the location and elevation. The COV values presented in the table show that subsurface conditions at the site vary significantly.

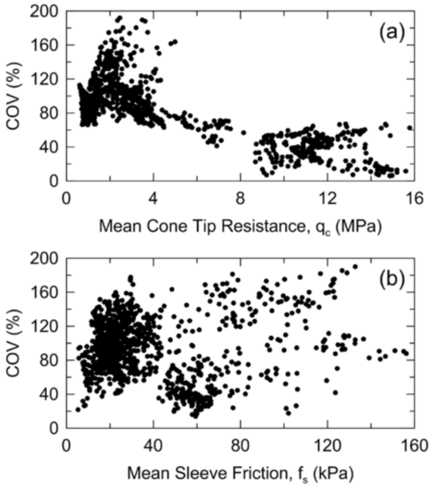

Figure 5. COV of spatial variability versus mean in-situ parameters: (a) q_c and (b) f_s.

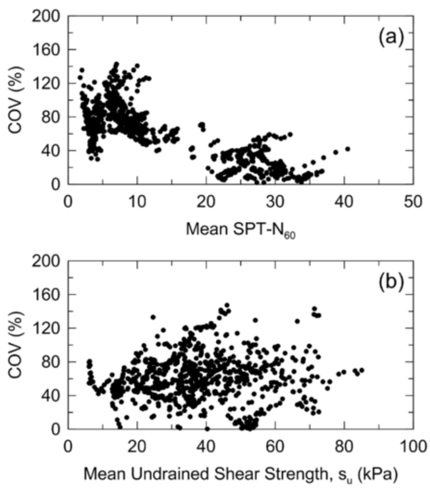

Figure 6. COV of spatial variability versus mean in-situ parameters estimated from CPT data: (a) SPT-N_{60} and (b) s_u.

Table 1. COV of soil variability based on all the data collected at the site

Property	COV (%)
In-situ data:	
Cone tip resistance, q_c	120
Sleeve friction, f_s	154
Calculated from in-situ data:	
Friction ratio, R_f	121
Estimated from in-situ data:	
SPT-N_{60}	99
Undrained shear strength, s_u	87

9. Conclusions

Due to the extent of roadway projects and the limited frequency of boring locations, spatial variability of subsurface soil conditions, and sometimes due to an inadequate extent of exploration, weak soils may not be identified suitably during the subsurface explorations. The spatial variability of the subsurface soil conditions in the horizontal direction at a project site where continuing settlements are causing pavement distress on a relatively short segment of a roadway was investigated, analyzed, and presented in this paper. The analysis results showed large spatial variability of properties throughout almost all of the depths investigated. COV values of approximately 190% were observed for the in-situ data, cone tip resistance, and sleeve friction. The COV values of approximately 145% were observed for the estimated properties using the in-situ data, SPT-N_{60} and undrained shear strength. This amount of spatial variability in soil conditions can make the selection of ground improvement method quite difficult for the remediation of roadways experiencing subgrade settlements.

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