Effect of soil structure on in-situ field vane and seismic piezocone tests in Champlain Clay

M.A. Styler, W. McQueen
ConeTec Investigations, Richmond, BC, Canada

J.A. Howie
Department of Civil Engineering – University of British Columbia, Vancouver, BC, Canada

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ABSTRACT
In this paper we report on the interpretation of field vane shear testing at the National Canadian Geotechnical Research site in Gloucester, Ontario. Previously published investigations of the Champlain/Leda clay that underlies this site have observed cemented particle aggregates. We examined three different techniques for estimating the yield-stress ratio from field vane test results in the Champlain/Leda clay that underlies this site. We observed that all three vane interpretation methods provided similar results that were larger than laboratory reported values. We performed a seismic piezocone test and calculated the ratio of the shear stiffness to net tip resistance. For this soil, it appears that strength is a better indication of cemented particle bonds than stiffness.

RÉSUMÉ
Dans cet article, nous faisons état des interprétations suite aux essais in situ au scissomètre effectués au « Site No. 1 de recherche canadienne en géotechnique à Gloucester » en Ontario. Des études précédentes des dépôts argileux de la Mer de Champlain ont observé la présence d'aggégats de particules cimentés. Nous avons analysé trois différentes techniques pour estimer le rapport de la surconsolidation du cisaillement au scissomètre dans les dépôts argileux de la Mer de Champlain. Nous avons observé que les résultats obtenus à l'aide des trois méthodes de cisaillement au scissomètre sont similaires et ils étaient plus grands que ceux obtenus en laboratoire. Nous avons effectué des tests sismiques au piézocône et calculé le rapport de la rigidité au cisaillement avec la résistance de la pointe du cône. Pour ce type de sol, il semble que la force est un meilleur indicateur de la liaison des particules cimentées que la rigidité.

1 INTRODUCTION

The over consolidation ratio (OCR) is the ratio of the maximum historic effective stress to the current effective in-situ stress. Strength and deformation behaviour of soils depend on OCR in as much as OCR is indicative of the initial soil state. OCR can be obtained by collecting undisturbed soil samples and performing and interpreting consolidometer tests in a laboratory. OCR can also be estimated from in-situ field vane test results. This in-situ estimate takes less time, effort, and money to obtain as it does not require undisturbed sampling and laboratory testing. In this paper we examine three methods (Chandler 1988, Mayne and Mitchell 1988, and Larsson and Åhnberg 2005) to obtain OCR from field vane test results. We performed field vane testing at the National Geotechnical Research Site in Gloucester, Ontario on 18-Decemebr-2014. We compared the interpreted OCR to published OCR values for the Champlain clay at this site.

The OCR for the soil at Gloucester is particularly interesting. The geological unit is Champlain Clay, which is also called Leda Clay in some publications. It is a marine clay with an open soil fabric that results in high in-situ water contents and void ratios. Locat and Lefebvre (1986) recognized that even though there has been no erosion, these soils are over-consolidated in terms of strength and under-consolidated in terms of water content. In a consolidometer plot (void ratio versus log (σ'_v)), the initial state for these soils plots above the normal consolidation line. This is a region often described as an "impossible soil state". DeGroot and Ladd (2012) attributed the over-consolidation of the Champlain Sea Clays to a poorly understood physic-chemical phenomenon that leads to inter-particle bonding. Bjerrum (1974) attributed the behaviour of the Leda clays of Eastern Canada to a cementing agent uniformly distributed on the surfaces of the soil particles. This was supported by an observed high (6% dry weight) calcium carbonate content on a sample of Leda clay from a landslide in Quebec. Leroueil et al. (1997) compared the large-strain response of undisturbed and remolded specimens of these sensitive clays of Eastern Canada. From consolidated isotropically drained triaxial tests, they observed friction angles of 44° for undisturbed soils and 30° for remolded. SEM photographs showed that these soils are comprised of extremely angular 5 – 10 μm bonded aggregates. Leroueil et al. (1997) attributed the decrease in friction angle to a reduction in bonding and angularity for these aggregate particles. Due to this potential particle contact bonding, the ratio of undrained strength to vertical effective stress (s_u/σ'_{v0}) is higher than expected for a normally consolidated soil of the same plasticity. DeGroot and Ladd (2012) made a similar observation in sensitive James Bay clay. In 1D compression tests, Leroueil et al. (1983a) found that the yield stress for Champlain Clay, and therefore OCR, depends on the consolidation strain rate. In this paper, we are using the term yield-stress-ratio (YSR) for nonmechanical apparent overconsolidation of Champlain/Leda Clay and OCR for mechanical over-consolidation.

2 BACKGROUND

ASTM-2573-08 covers field vane testing and must be followed to obtain the undrained strength index $s_{u,FV}$. This field vane strength is calculated using Equation 1. This equation is for a rectangular vane with an H/D ratio equal to 2. This equation can be derived from a limit equilibrium analysis between the torque and an assumed uniform shear stress developed over the cylindrical surface area circumscribed by the vane blades.

$$s_{u,FV} = \frac{6T_{max}}{7\pi D^3} = 0.86\frac{T}{\pi D^3} \quad [1]$$

As previously mentioned, in 1D compression tests the apparent preconsolidation pressure for the soils at Gloucester are strain-rate dependent. Furthermore, Sheahan et al. (1996) and Diaz-Rodriguez et al. (2009), among others, have observed a strain-rate dependence for the strength of clays in laboratory experiments. The field vane test may show strain-rate dependence of strength and partial consolidation effects at different rotation rates. The strain rate in the field vane test is governed by the angular velocity. Randolph (2004) and Einav & Randolf (2006) also concluded that the shear strain rate in geotechnical vane testing depends on the angular rate and not the peripheral velocity. Their conclusions were based on continuum mechanics. Styler et al. (2014) reached the same conclusion following rheological studies of rotating fluid cylinders.

Most OCR estimates from the field vane test are based on the ratio of the vane strength to the initial vertical effective stress ($s_{u,FV}/\sigma'_{v0}$). The methods examined in this paper all use this ratio, but require different soil properties.

Chandler (1988) contributed to previous work done by Jamiolkowski by comparing $s_{u,FV}/\sigma'_{v0}$ to oedometer OCR values on a log-log plot. This resulted in a linear relationship on the log-log plot for each soil. Each soil had a similar slope on the log-log scale, and reached a similar $s_{u,FV}/\sigma'_{v0}$ for the normally consolidated state. Chander (1988) compared $(s_{u,FV}/\sigma'_{v0})/(S_1)$ versus OCR; where S_1 was the normally consolidated strength ratio predicted following Bjerrum's relationship with the plasticity index for young clays. Essentially, the ratio of the measured strength to a normally consolidated strength, ($s_{u,FV,}/s_{u,FV\text{-}NC}$) is plotted against OCR and forms a straight line with a slope equal to m. In Chandler's dataset, the average value for S_1 was 0.25 and for the slope m was 0.95. This relationship, with these average coefficients, was rearranged to solve for the YSR in Equation [2].

$$YSR = \left(\frac{S_{u,FV}}{\sigma'_{v0}}\frac{1}{0.25}\right)^{\frac{1}{0.95}} \quad [2]$$

Mayne and Mitchell (1988) examined the relationship between OCR and the normalized field vane strength. He presented a large dataset of paired values and proposed the relationship given in Equation [3]. This equation uses an empirical coefficient α_{FV} given in Equation [4] as a function of the plasticity index. Following this equation, if the soil is normally consolidated then the strength ratio is the reciprocal of α. This provides a similar relationship to the one proposed by Bjerrum and used by Chandler (1988); but it is based on a calibration with a large dataset. Similar to the equation proposed by Chandler (1988), Equation [3] reduces to the ratio of the measured strength to a normally consolidated strength, ($s_{u,FV,}/s_{u,FV\text{-}NC}$).

$$YSR = \alpha_{FV}\left(\frac{S_{u,FV}}{\sigma'_{v0}}\right) \quad [3]$$

$$\alpha_{FV} = 22(PI)^{-0.48} \quad [4]$$

Larsson and Åhnberg (2005) investigated the effect of excavating slope crests on the in-situ test response. This provided an experimental program that covered a range of over consolidation ratios for the same clay soil. They proposed a correction factor for OCR in order to estimate laboratory measured undrained strength from field vane tests. This relationship began as an equation for the preconsolidation pressure: $\sigma'_c=s_{u,fv}/(0.45w_L)$, where w_L is the liquid limit. From their dataset, they calibrated an exponent for this pre-consolidation pressure equation. Their work has been rearranged to solve for YSR as shown in Equation [5].

$$YSR = \left(\frac{1}{0.45w_L}\frac{S_{u,FV}}{\sigma'_{v0}}\right)^{1.11} \quad [5]$$

3 SITE INVESTIGATION

We performed our investigation at the Canadian Geotechnical Research Site in Gloucester, ON. This site is located southeast of Ottawa at 8013 Ottawa Regional Rd 8 Ottawa, Ontario.

3.1 Site description

This site consists of a thick deposit of fine-grained marine sediments, known in the literature as both Champlain Sea Clay and Leda Clay (Locat et al. 1985). It is a Holocene soil deposited after the last glacial period with an YSR ranging from 1 to 2 (Bozozuk 1972, Lo et al. 1976, Morissette 2001). Nader et al. (2015) identified a lightly overconsolidated crust for the top 5 m over normally consolidated clay. Crawford and Bozozuk (1990) attributed the slight overconsolidation to quasi-preconsolidation and/or reserve resistance from periodic lowering of the ground water table. Leroueil et al. (1983a) found that the preconsolidation pressure, and therefore OCR, depends on the consolidation strain rate. This observation was used to explain the difference between laboratory testing, which produced a higher OCR, and what was observed in long term field consolidation.

Locat and Lefebvre (1986) recognized that even though there has been no erosion, these soils are over-consolidated in terms of strength and underconsolidated in terms of water content. They attributed this to the leaching of salt water after deposition of these soils. These soils have water contents higher than the Liquid Limit (Bozozuk 1972, Leroueil et al. 1983a, Nader et al. 2015). Atkinson (2010) and others, have assumed that the soil at the liquid limit has an effective stress of 1.7 kPa and is on the critical state line. These high water contents and typical in-situ effective stresses put the soil far into the wet-side of the critical state line; contrary to the observed preconsolidation pressures and OCRs. The K_0 value (σ'_h/σ'_v) is 0.6-0.7 as measured by in-situ fracturing tests (Lefebvre et al. 1991).

3.2 Testing programme

We performed a seismic-piezocone test (SCPTu). The results from this test can be evaluated following the work presented by Eslaamizaad and Robertson (1996) and Schnaid and Yu (2007). In these works, the ratio of the small strain stiffness (G_0) to the tip resistance is compared to an effective-stress normalized tip resistance. This comparison is capable of separating cemented and aged soils from uncemented young soils. The work performed by Schnaid and Yu (2007) was only on sands. They used q_c, the uncorrected tip resistance. In sands, the uncorrected tip resistance (q_c) is approximately q_t. Furthermore, q_c is much greater than the overburden stress. In this work, it was necessary to correct the tip resistance for both the overburden stress and unequal end areas. Schnaid and Yu also evaluated an effective stress normalized tip resistance using an effective stress exponent of 0.5; which is equivalent to Q_{tn} as normalized by Zhang et al. (2002). Consequently, in this work we compared $G_0/(q_t-\sigma_{v0})$ to Q_{tn}. The SCPTu we performed at Gloucester was examined within this framework to see if it supported the hypothesis for cemented particle bonds in Champlain-Leda clay.

We performed four FVSTs using an electric rate-controlled motor at the surface, a down-hole torque load cell, and a rectangular four-bladed vane. The surface motor was attached to and rotated the deployment rods at a controlled rate. The torque was measured down-hole above the vane. The four-bladed rectangular vane was 150mm in height and 75mm in diameter (H/D=2). It had a blade thickness of e = 1.88 mm and vane stem diameter of d = 15.93 mm. This vane has a vane area ratio V_A = 9.5% and a circumference ratio of α = 3%. We deployed the vane through a mud-rotary supported borehole. The test holes were not through the test embankment.

Figure 1 is a picture of the downhole vane hung over the mud-rotary borehole by the clamping mechanism in the uphole torque load cell. Hollow stem auger casing was used to start the hole because the frame for the vane motor was designed to clamp to hollow stem auger. Below the first string of hollow stem auger the hole was supported by recirculated drilling mud. The bore-hole was drilled out to a depth 0.6 m above the target testing location. The vane was deployed to the bottom of the hole by successively adding 1-m length rods through the vane motor. The vane was advanced from the bottom of the hole to the target testing depth by pushing the top of the deployment rods. The torque motor was clamped to the deployment rods and activated. The torque motor rotated the rods at 10.9°/min. After 90° rotation, the torque motor rate was increased to remold the soil through 10 full rotations. The torque motor was then run at 10.9°/min to perform the remold test.

Figure 1. Up-hole torque motor holding downhole vane load cell and rectangular (150mm by 75 mm) vane over mud-rotary supported borehole at Gloucester, ON

4 RESULTS

Figure 2 shows the results of the SCPTu we performed. This profile shows a 2 m thick crust over the softer clay. The shear wave velocity profile is shown in the fifth column. This was used to calculated G_0 with $G_0 = \rho V_S^2$, where ρ is the bulk density of the soil. ***Figure 3*** is a plot of the ratio of the small strain shear modulus to the net tip resistance versus Q_{tn}, the effective stress normalized tip resistance. This figure also includes interpreted bounds for cemented unaged soils as proposed by Schnaid and Yu (2007). Our SCPTu plots on the lower bound for the range of uncemented and unaged soils.

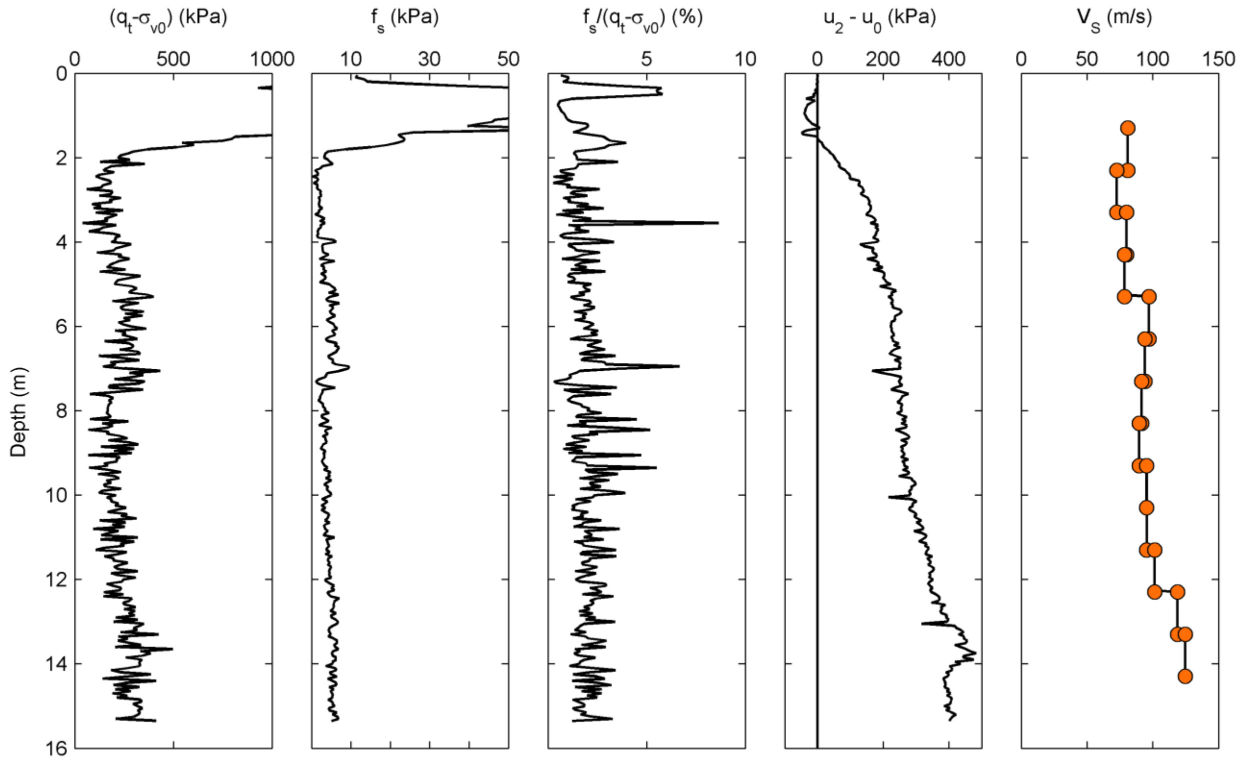

Figure 2. SCPTu profile collected at Gloucester, ON

Figure 4 shows the recorded rotation-torque curves for these vane tests. All of the tests show a rapid drop in resistance after the peak. The field-vane strength is reported in ***Table 1***. This table also includes three additional estimates of the undrained strength using different assumptions for the distribution of shear stress over the cylindrical surface of the vane.

The measured field vane undrained shear strengths agree with published values from Bozozuk (1972), Eden & Law (1980), and Yafrate & DeJong (2006); except for the vane test performed at 10.6 m. The vane at 10.6 m was approximately half of previously published results at similar depths.

All of the vanes reached failure within 2 minutes of the start of rotation. The time-factor for each test was calculated in order to show that the reported strengths do not need to be reduced for partial-consolidation strength gains. The time-factor was calculated using an estimated coefficient of consolidation of 350m^2/year. This estimate was based on published laboratory results from Lo et al. (1976) for the same soil unit. All of the time factors are less than 1.3, even when calculated using the full 5 minute rest period after vane insertion. This supports that the vane test is a measure of the undrained soil strength in this clay.

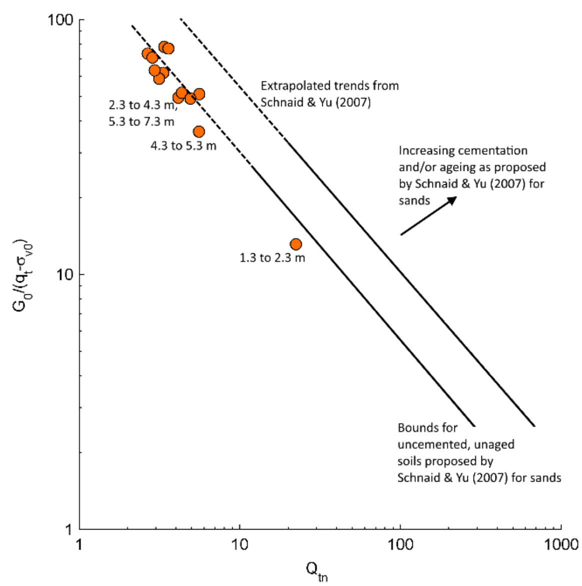

Figure 3. Gloucester SCPTu results do not show evidence of cementation as interpreted following Schnaid & Yu (2007) proposed cementation bounds developed for sands

Table 1 also includes an estimate of the initial effective stress state for each vane test. This stress state was calculated by assuming a ground water table at the ground surface and a saturated unit weight of 15.1 kN/m^3. This saturated unit weight was based on reported laboratory water content values by Bozozuk (1972). The horizontal effective stress was based on a K_0 value reported by Lefebvre et al. (1991).

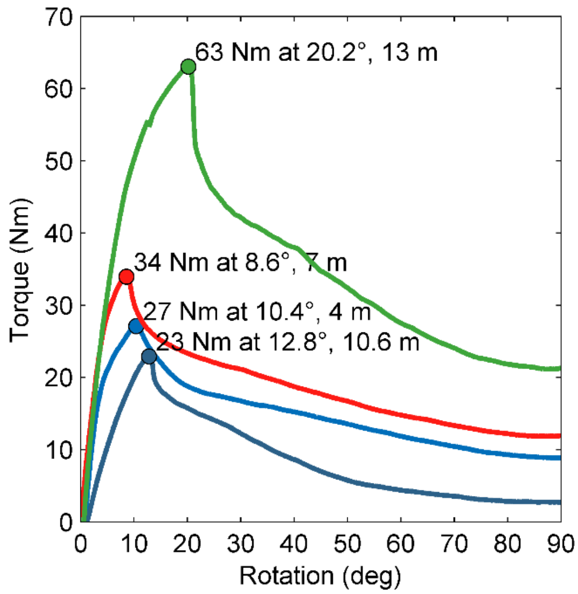

Figure 4. Torque-rotation curves for four field vane shear tests at Gloucester, ON

Table 1. Summary of vane results from testing at Gloucester, ON

Depth (m):	4.0	7.0	10.6	13.0
Peak Torque (Nm):	27.1	34.0	22.9	63.0
Peak Torque vane rotation angle:	10.4°	8.6°	12.8°	20.2°
Time to Failure (sec):	57.7	48.9	67.7	109.1
Shear strain rate [(a)] (%/sec):	0.63	0.61	0.66	0.64
Time-Factor[(b)]:	0.70	0.69	0.72	0.81
$S_{u,FV}$ (kPa):	17.5	22.0	14.8	40.8
σ'_{v0} (kPa):	21.2	37.1	56.2	68.9
σ'_{h0} [(c)] (kPa):	13.8	24.1	36.5	44.8
S_u/σ'_{v0}:	0.84	0.61	0.27	0.60
q_t-σ_{v0} (kPa)	194	264	212	284
$N_{kt}=(q_t-\sigma_{v0})/S_u$	11	12	14	7

(a) Assuming linear elastic continuum to failure and using $\gamma = 2\theta$ (see Cadling and Odenstad 1950, or Styler et al. 2014)
(b) Estimated c_v of $350 m^2/yr$ using results detailed in Lo et al. (1976) and Fisher et al. (1982); assuming worst case full 5 minute rest period before vane rotation
(c) Using K_0 = 0.65 from results by Lefebvre (1991) and γ_{sat} = 15.1 kN/m^3 from laboratory water content results (Bozozuk 1972)

Table 2 compares the interpreted YSR values to published laboratory results. These published results were from approximately the same depth as the vane test. The first three rows in Table 2 contain laboratory results; the last three rows contain the interpreted field vane results.

The three vane test estimates of YSR are all similar at each depth. Compared to published laboratory results, the field vane test overestimates YSR for the three different methods. The test at 10.6 m is an exception to this observation. As previously mentioned, the 10.6 m results also disagreed with other published strength measurements and the trend of increasing strength with depth.

The difference between the field estimates and the laboratory interpretations may be due to strain rate. Leroueil et al. (1983a and 1983b) observed a strain-rate dependence in the preconsolidation pressure for Gloucester Clay. The vane test reaches failure in under a minute, which is at a much faster strain rate than consolidation testing. Following the calculations by Cadling and Odenstad (1950) the vane test is performed at an average rate of 0.64 % per second. The vane test is a large strain test that quickly shears the in-situ soil. It is reasonable to conclude that when the preconsolidation pressure shows strain-rate dependence, then in-situ estimates may be over predicted.

Table 2. Comparing estimated YSR from field vane tests to published YSR from laboratory tests

Depth (m):	4.0	7.0	10.6	13.0
Bozozuk (1972):	1.5	1.8	1.5	1.4
Morissette et al. (2001):	1.4		1.6	
Leroueil et al. (1983b):	1.8			
Chandler (1988)			1.75	1.75
Equation [2] (Chandler 1988)	3.6	2.6	1.1	2.5
Equation [3][(b)] (Mayne 1988):	3.5	2.5	1.1	2.5
Equation [5][(c)] : (Larsson and Åhnberg 2005)	3.9	2.7	1.1	2.7

(a) Using K_0 = 0.65 (Lefebvre 1991) and ϕ = 32.2° (Average CAU triaxial results from Bozozuk 1972)
(b) Using PI = 32 (Lefebvre 1991), α_{FV} = 4.2
(c) Using w_L = 55 (Lefebvre 1991)

5 EVALUATION OF RESULTS

Bjerrum (1974) characterized the Leda clays of Eastern Canada as a cemented clay. The results shown in Figure 3 conflict with that characterization. The work by Schnaid & Yu (2007) cannot be extrapolated to these clay soils, because cementation has a larger effect on strength than stiffness in these clay soils.

Leroueil et al. (1997) have shown that the cementation in this clay has a significant effect on strength. Furthermore, from our vane testing, we observed much larger YSR than what would be expected for a clay site that has not undergone any mechanical over-consolidation. Leroueil (2002) presented the effect of micro-structure on the small strain shear stiffness. His schematic figure suggested that cemented clays may be approximately twice as stiff as the same soil remolded and consolidated to the same OCR. This suggests that in clays, strength is a better indication of cementation and structure than stiffness.

6 CONCLUSION

For this paper, the field vane test was used in Champlain/Leda clay at Gloucester, Ontario. The YSR for this soil was interpreted using three different, empirical techniques. All three YSR estimates provided similar results that were higher than published laboratory test interpretations. This may be due to sample disturbance and/or a strain-rate effect on the preconsolidation pressure.

Previous publications have shown that the soil at Gloucester has cemented particle bonds. We extrapolated results for a SCPTu characterization of cementation from sands to clays. This technique was unable to identify cementation in these soils. Therefore, it is expected that for clays, the strength and YSR of the soil is a better indication of cementation than the small strain stiffness.

Further research on the in-situ characterization of natural clays is required to determine if the observations we made at Gloucester may be applicable to other cemented clays.

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