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<th><strong>Title</strong></th>
<th>Assessment of sample quality in soft clay using shear wave velocity and suction measurements</th>
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<td>Donohue, Shane; Long, Michael (Michael M.)</td>
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Title of paper: Assessment of sample quality in soft clay using shear wave velocity and suction measurements

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INTRODUCTION
Sampling disturbance in soft clays may result in poor estimates of geotechnical parameters, leading to potentially significant and costly design errors. Evaluation of sample quality is, therefore, essential if design parameters derived from laboratory tests are to be deemed reliable. A number of different approaches have been traditionally used to evaluate sample disturbance. Techniques that are considered reliable include measurements of volumetric strain (Kleven et al., 1986), and the normalised change in void ratio, $\Delta e/e_0$ (Lunne et al., 1997). Most of these approaches, however, require reconsolidation back to in-situ stresses, a process that may require a number of days of testing. This is a particular problem for offshore sampling, where rapid assessment of sample quality could significantly improve efficiency.

A number of studies in recent years have observed that laboratory determined shear wave velocities ($V_s$), and corresponding small strain shear modulus, $G_{\text{max}}$:

$$G_{\text{max}} = \rho V_s^2$$

(1)

are generally lower than the in-situ equivalent, and have attributed this difference to sampling disturbance (Shiwakoti et al. 2000; Porcino & Ghionna 2004). These studies involved reconsolidation of laboratory specimens back to their in-situ stress, before measurement of $V_s$. For a quick assessment of sample quality, Hight & Leroueil (2003), Nash (2003) and Landon & DeGroot (2007) used portable bender element kits to measure $V_s$, immediately after removal from the subsurface on unconfined samples. Hight & Leroueil (2003) also suggested simultaneous soil suction ($u_r$) measurements, enabling differences between unconfined and in-situ stress state to be taken into account.

The use of suction measurements for sample quality evaluation was introduced by Ladd & Lambe (1963), who proposed using the ratio $u_r/\sigma'_{ps}$ to evaluate disturbance, where $\sigma'_{ps}$ is the effective stress for a “perfect” sample. Calculation of $\sigma'_{ps}$ is, however, not straightforward and requires knowledge of Skempton’s pore pressure parameter, $A_u$.
(consequent to the release of deviatoric stress), and $K_0$ (coefficient of earth pressure at rest). Authors such as Tanaka et al. (1996) and Carrubba (2000) have recently used $u_r$, normalised by the in-situ vertical effective stress ($\sigma'_{v0}$) to evaluate disturbance. Tanaka et al. (1996) suggested that for high quality samples of normally to lightly overconsolidated clay, $u_r$ is approximately $\frac{1}{5} \sigma'_{v0}$ to $\frac{1}{6} \sigma'_{v0}$. Recently, Tanaka & Tanaka (2006) and Tanaka (2008) suggested that suction does not have a consistent relationship with in-situ vertical effective stress and that this hypothesis needs to be treated cautiously. Ladd & Lambe (1963) and Hight & Leroueil (2003) recognised that when taken alone, “$u_r$ cannot indicate the amount of destructuring that has occurred”.

This paper describes the use of unconfined $V_s$ and $u_r$ measurements to assess the quality of soft clay samples. Samples of varying quality are assessed using conventional techniques, whose results are compared to assessments derived according to $V_s$ and $u_r$ measurements. A tentative criterion for quantifying sample disturbance is proposed, which is based on $V_s$ and $u_r$ measurements.

**DESCRIPTION OF SITES AND TECHNIQUES**

The soft soils investigated during this study were located at Onsøy in Norway and at Ballinasloe and Bogganfin in Ireland (Table 1). A number of samplers of varying quality were used, the dimensions and features of which are given in Table 2.

**Onsøy, Norway**

The Onsøy test site is the main soft clay research site used by the Norwegian Geotechnical Institute (NGI). Onsøy is underlain by an extensive deposit of uniform marine clay, as described by Lunne et al. (2003).
In this paper comparisons are made between Sherbrooke block, 76mm steel and 54mm composite piston samples at two depths (approximately 10m and 13m). The Scandinavian displacement approach was adopted for the piston sampling, wherein the sampler (with the piston in front of the sampling tube) was pushed down to the desired depth without preboring.

**Ballinasloe and Bogganfin, Ireland**

The Ballinasloe and Bogganfin test sites (Donohue, 2005), located in the midlands of Ireland, are both underlain by post glacial lacustrine clay. Although generally uniform, the soils contain some thin silt laminations (1mm to 2mm).

For this work, comparisons are made between 100mm ELE fixed piston and open drive U4 samples. Samples were obtained with the ELE sampler using standard (30°) and modified cutting edges (5°). In addition to the Scandinavian displacement approach, the conventional technique of sampling from the bottom of a shell and auger (open percussive) borehole was used. Interestingly, the moisture content and bulk density of the Ballinasloe U4 samples (Table 3) are quite different from the piston tubes indicating that the material, which is known to have a high coefficient of consolidation, \( c_h \) (Long and O’Riordan 2001), has possibly been densified by drainage of excess pore pressure from the silt lenses during sampler driving. The moisture content and bulk density of the U4 samples from Bogganfin, however, do not appear to be significantly different from the piston tubes.

**Testing Techniques**

In-situ \( V_s \) measurements were obtained from the seismic cone (SCPT - Eidsmoen et al., 1985) and Multichannel Analysis of Surface Waves (MASW - Long & Donohue
2007; Donohue & Long 2008) techniques. Measurements of shear wave velocity, using these techniques, may be performed relatively quickly (30 minutes for MASW, 120 minutes for SCPT) at an onshore sampling location, although offshore seismic cone measurements will take longer. $V_s$ was measured on unconfined samples, using bender elements (vertically propagating, horizontally polarised) and interpreted using both first arrival and cross correlation techniques. Shear wave velocities should ideally be measured in the same direction in both the laboratory and the field in order to mitigate the effect of anisotropy; however, in the present case, stiffness anisotropy was not significant, as discussed by Donohue (2005).

Measurement of $u_r$ was made using a number of techniques (Donohue & Long 2009), such as the filter paper method, the cell pressure loading technique, a small scale tensiometer and a Japanese approach. Of these, Donohue & Long (2009) found the Japanese approach (Tanaka & Tanaka 2006) to be the best combination of speed and accuracy. In this technique a saturated high-air-entry disk (air entry value of 200 to 300 kPa) is used, which has small pores of uniform size. The disk acts as a membrane between air and water and once it is saturated with water, air cannot pass through the disk due to the ability of the contractile skin to resist the flow of air. A specimen is placed on the high-air-entry ceramic disk, without a membrane, and the suction is simply monitored until it becomes constant. Using this simple approach, suctions may be measured relatively quickly, in less than 30 minutes (Tanaka 2008). Suction measurements detailed in this paper are computed from the mean of these techniques. At Onsøy, a suction probe developed by the University of Massachusetts, Amhurst (Poirier et al., 2005), was also used. Using this approach, suctions may be measured in less than 15 minutes. Measurements of $V_s$ and $u_r$ were performed on all samples either immediately after extrusion, or after removal from the ground (block samples).
ASSESSMENT OF SAMPLE QUALITY USING CAUC TRIAXIAL TESTING

A summary of the most important parameters, obtained from anisotropically consolidated undrained (CAUC) triaxial tests carried out on the soils under study, are given in Table 3.

Onsøy

An assessment of both the consolidation and shearing parameters (Table 3), indicates that the block samples are generally of superior quality, although the deeper 76mm sample appears to be of good quality. CAUC stress-strain curves and stress path plots are shown in Figure 1(a and b). Results are shown for Block, 76mm and 54mm diameter samples from a depth of approximately 10.3m. The block samples are clearly superior to both the 76mm and 54mm diameter samples, exhibiting a much clearer peak at a lower strain and a greater degree of strain softening post peak. The 54 mm diameter specimens exhibit the lowest undrained shear strength ($s_u$) and highest strain at peak stress ($\varepsilon_f$). The stress paths (plotted in $s'$, $t'$ space) followed by the block specimens reach a slope close to the “perfect” slope of 1 horizontal to 3 vertical, pre-peak, corresponding to minimum plastic volumetric strain (Lunne et al., 1997), indicating that much of the natural structure has been retained.

Ballinasloe and Bogganfin

According to the consolidation and shearing stage parameters, the 5° modified piston tube produced superior samples (Table 3) particularly when used with the displacement approach at Ballinasloe. Typical CAUC stress-strain and stress path plots for Ballinasloe and Bogganfin are shown in Figure 1(c,d,e and f), and a number of different responses are discerned. Interestingly, the U4 and 30° conventional specimens show
dilative behaviour, in comparison to contraction exhibited by the modified piston tubes, consistent with the densification observed previously. The stress-strain plots indicate that the modified piston tube samples are superior, with more clearly defined peaks occurring at lower strains and there is greater strain softening post peak.

SHEAR WAVE VELOCITY RESULTS

Unconfined shear wave velocities ($V_{s0}$) and corresponding in-situ $V_s$ are presented in Figure 2. As shown in the figure, at Onsøy the MASW and SCPT $V_s$ profiles are almost identical (Long & Donohue 2007). $V_s$ was also measured on unconfined specimens of completely remoulded material. Sample cuttings were remoulded at their in-situ density and water content. The highest velocities recorded for Onsøy samples were those of the block samples immediately after removal from the ground. These values were greater than those measured on the same blocks in the laboratory, in Ireland. This large reduction in $V_s$ could be due to transportation damage, or to some other time effect. The lowest $V_s$ was measured on the 54mm diameter piston samples.

Shear wave velocities measured on samples of Ballinasloe and Bogganfin clay are significantly lower than their in-situ equivalent (Figures 2b and 2c). The 5° modified piston tube samples exhibit consistently higher velocities than either the 30° conventional or U4 samples. $V_s$ of the U4 samples from Ballinasloe is similar to the remoulded $V_s$, indicating poor quality, in accordance with what was found with the CAUC test data.

The shear wave velocities measured in the laboratory are normalized using the in-situ $V_s$ data and compared with $\Delta e/e_0$ in Figure 3 for all sites. The relationship between these parameters has been characterised with Pearson’s correlation as follows: $r=-0.78$, $p<0.001$, $n=22$. The block samples from Onsøy exhibit the highest normalised $V_s$, and the U4 samples from Bogganfin and Ballinasloe are characterised by the lowest normalised
For Ballinasloe and Bogganfin, the modified 5° piston tube samples are clearly superior, particularly when used in conjunction with the displacement technique at Ballinasloe.

**SUCTION RESULTS**

Suction values measured at each of the sites are presented in Figure 4 and compared to $0.2\sigma'_{v0}$, as suggested by Tanaka et al. (1996), for high quality samples. The block samples from Onsøy exhibit the highest suctions and lie closest to $0.2\sigma'_{v0}$. It is again uncertain whether, for the block samples, the difference between in-situ and laboratory suctions are due to measurement technique, transportation damage or to some other time effect.

The 5° displacement samples possess consistently higher suctions for Ballinasloe, and lie closest to $0.2\sigma'_{v0}$. Suctions measured on the piston samples from Bogganfin are slightly higher than for the U4 samples, although the differences between the different piston samples are negligible.

Suctions measured on the samples from all sites are normalised using the in-situ vertical effective stress ($\sigma'_{v0}$) and compared with $\Delta e/e_0$ in Figure 5. There is a significant correlation between these parameters ($r=-0.67, p<0.001, n=22$) which tends to a suction value of about $0.2\sigma'_{v0}$ for $\Delta e/e_0 = 0$. This trend is also observed for the individual sites under investigation.

**COMBINATION OF $V_s$ AND $u_r$**

Having observed the relationships between shear wave velocity and suction with $\Delta e/e_0$, the following normalized parameters have been derived empirically to evaluate disturbance:
\[ L_{\text{vs}} = \frac{V_{\text{insitu}} - V_{s0}}{V_{\text{insitu}} - V_{\text{remoulded}}} \] (2)

\[ L_u = \frac{0.2\sigma'_{v0} - u_r}{0.2\sigma'_{v0}} \] (3)

The use of remoulded shear wave velocities in \( L_{\text{vs}} \) takes into account the lowest possible \( V_s \), when the sample is completely destructured. A \( L_{\text{vs}} \) of zero would be considered completely undisturbed, as \( V_{s0} \) would equal the in-situ \( V_s \). The use of the \( L_u \) parameter is supported by the trend recognised in Figure 5, which, as mentioned previously, gives a suction value close to \( 0.2\sigma'_{v0} \) at \( \Delta\epsilon/\epsilon_0 = 0 \). This also takes into account the conclusions of Tanaka et al. (1996). Where a material has a \( u_r \) greater than \( 0.2\sigma'_{v0} \), as is the case with Singapore clay (Tanaka 2008) and Bothkennar clay (Hight, 2000), a similar extrapolation will be required, although it is believed that \( 0.2\sigma'_{v0} \) is relevant to the sites under investigation here. The use of \( \sigma'_{ps} \) (Ladd and Lambe, 1963), or \( \sigma'_{v0} \) instead of \( 0.2\sigma'_{v0} \) in \( L_u \), may be more relevant to sites where higher suctions are measured, although this would make determination of sample quality difficult for the sites investigated here, as the differences in \( L_u \) would be very small.

A tentative criterion combining \( V_s \) and \( u_r \) is proposed in Figure 6 for the quantification of sample disturbance. This involves plotting \( L_{\text{vs}} \) against \( L_u \). The relationship between these parameters is again significant (\( r=0.83 \), \( p<0.001 \), \( n=26 \)). The \( \Delta\epsilon/\epsilon_0 \) criterion, which classifies sample quality into either “very good to excellent”, “good to fair”, “poor” or “very poor”, was used to develop the \( V_s \) and \( u_r \) classification proposed here. Both the \( L_{\text{vs}} \) and \( L_u \) values of each of the samples tested were associated to a sample quality level according to the corresponding level they would match within the \( \Delta\epsilon/\epsilon_0 \) classification system, as shown in Figure 6. As shown, the degradation of block sample
quality between sampling in Norway and testing in Ireland has not decreased the quality of the samples out of the very good to excellent zone. This criterion also confirms the superiority of the 5º displacement samples at the Irish sites.

The $L_{vs}$ - $L_u$ technique has an advantage over the $\Delta e/e_0$ criterion, in terms of speed of measurement, particularly if a portable suction probe is used. It is recognised, however, that in addition to unconfined measurements of $V_s$ and $u_r$, this approach requires an in-situ measurement of shear wave velocity which may be time consuming, depending on the particular technique selected and the site conditions.

CONCLUSIONS

Estimation of sample quality is usually performed after reconsolidation of samples back to in-situ stresses, an inefficient process, which may take a number of days to be carried out. The use of unconfined shear wave velocity and suction measurements, as discussed in this work, makes it possible to assess rapidly sample quality.

Samples of varying quality were tested using conventional assessment techniques, performed in conjunction with $V_s$ and $u_r$ measurements, at three soft clay sites. Reasonably clear relationships were observed between the various parameters at each of the sites. Unconfined $V_s$ measurements were found to be best correlated with the parameters used traditionally for assessing disturbance.

A tentative empirically derived criterion, based on samples tested in this project, was proposed to quantify sample disturbance combining both $V_s$ and $u_r$ measurements. The proposed $L_{vs}$ - $L_d$ sample disturbance criterion classifies samples similarly to conventional methods, such as $\Delta e/e_0$. The $L_{vs}$ - $L_d$ technique has a significant advantage over the $\Delta e/e_0$ criteria in terms of speed of measurement, particularly if a portable suction
probe is used. Further work using this criterion on different materials is important so as to test its usefulness.

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NOTATION

AR  area ratio = \( \frac{(D_e^2 - D_c^2)}{D_c^2} \)

\( A_u \)  pore pressure parameter corresponding to release of deviatoric stress

\( D_c \)  internal diameter at cutting edge

\( D_e \)  external diameter of cutting shoe

\( D_i \)  internal diameter

\( e_0 \)  initial void ratio

\( G_{\text{max}} \)  small strain shear modulus

\( \text{ICR} \)  inside clearance ratio = \( \frac{(D_i - D_c)}{D_c} \)

\( K_0 \)  ratio of horizontal to vertical in-situ effective stress
L vs  normalised shear wave velocity parameter for sample quality assessment
L u  normalised suction parameter for sample quality assessment
OCR  overconsolidation ratio
q t  corrected piezocone end resistance
s'  mean effective stress = (σ'1 + σ'3)/2
s u  undrained shear strength
t'  shear stress = (σ'1 - σ'3)/2
u r  soil suction
V s  shear wave velocity
V s0  unconfined shear wave velocity
V vh  vertically propagating horizontally polarised shear wave
w  moisture content
α  sampler cutting edge angle
Δe/e0  normalised change in void ratio
ε f  strain at peak in triaxial test
ε vol  volumetric strain
σ'1  major principal effective stress
σ'3  minor principal effective stress
σ' v0  in-situ vertical effective stress
σ' ps  perfect sampling stress (Ladd and Lambe, 1963)
ρ  bulk density

REFERENCES
Brooker, E.W., and Ireland, H.O. (1965). Earth pressures at rest related to stress history,


<table>
<thead>
<tr>
<th>Property</th>
<th>Onsøy</th>
<th>Ballinasloe</th>
<th>Bogganfin</th>
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<td>Moisture content (%)</td>
<td>55 – 67</td>
<td>29 - 42</td>
<td>24 - 45</td>
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<tr>
<td>Bulk density (Mg/m(^3))</td>
<td>1.6 – 1.7</td>
<td>1.8 – 2.0</td>
<td>1.8 – 2.2</td>
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<td>1.5 – 1.8</td>
<td>0.7 – 1.3</td>
<td>0.6 – 1.3</td>
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<tr>
<td>Clay content (%)</td>
<td>51 – 69</td>
<td>40 - 49</td>
<td>25 - 40</td>
</tr>
<tr>
<td>Liquid limit (%)</td>
<td>55 – 70</td>
<td>32 - 39</td>
<td>29 - 43</td>
</tr>
<tr>
<td>Plasticity index</td>
<td>25 – 50</td>
<td>15 - 21</td>
<td>12 - 25</td>
</tr>
<tr>
<td>Sensitivity (field vane)</td>
<td>6 - 8</td>
<td>3 - 5</td>
<td>1.5 – 3</td>
</tr>
<tr>
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<tr>
<td>q(_t) (kPa)</td>
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<td>200 - 300</td>
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Table 1. Basic site properties (definitions supplied in notation index). * estimated from relationship with plasticity index (Brooker and Ireland, 1965)
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<th>Sampler</th>
<th>Length (mm)</th>
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<th>D_e (mm)</th>
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<th>D_i (mm)</th>
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<th>ICR (%)</th>
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Table 2. Summary of the dimensions and features of the samplers used (definitions supplied in notation index)
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<th>Sample method</th>
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<th>ρ (Mg/m³)</th>
<th>σ'v0 (kPa)</th>
<th>εvol (%)</th>
<th>Δe/e₀</th>
<th>Sample Quality *</th>
<th>sₙ (kPa)</th>
<th>εₛ (%)</th>
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Table 3. Summary of CAUC tests (definitions supplied in notation index). * Sample quality from Lunne et al. (1997) where 1 = Very good to excellent, 2 = Good to fair, 3 = Poor, 4 = Very Poor
FIGURE CAPTIONS

Figure 1  CAUC stress-strain and stress path plots for (a,b) Onsøy, (c,d) Ballinasloe and (e,f) Bogganfin

Figure 2  Unconfined $V_s$ measurements compared with in-situ $V_s$ for (a) Onsøy (b) Ballinasloe and (c) Bogganfin

Figure 3  Sample quality comparison: $V_{s0}$ normalised by in-situ $V_s$ compared with $\Delta e/e_0$ on all sites

Figure 4  Suction measurements performed on samples from (a) Onsøy (b) Ballinasloe and (c) Bogganfin

Figure 5  Sample quality comparison: variation of $u_s/\sigma_{v0}'$ with $\Delta e/e_0$

Figure 6  The proposed $L_{svs}$-$L_u$ sample quality criterion applied to samples from Onsøy, Ballinasloe and Bogganfin
Very good / excellent | Good to fair | Poor | Very Poor
---|---|---|---

![Graph with data points and labels](image)

\[ V_{sd}/V_{s\text{ in-situ}} \]

\[ \Delta e/e_0 \]

Statistical details:

- Correlation coefficient: \( r = -0.78 \)
- Significance level: \( p < 0.001 \)
- Sample size: \( n = 22 \)
Very good / excellent | Good to fair | Poor | Very Poor

\( \frac{u_i}{c_{w0}} \) vs. \( e/e_0 \)

- Onsoy 54mm
- Onsoy 76mm
- Onsoy Blocks
- Ballinasloe 5\(^{th}\) displacement
- Ballinasloe 5\(^{th}\) conventional
- Ballinasloe U4
- Bogganfin 5\(^{th}\) displacement
- Bogganfin 5\(^{th}\) conventional
- Bogganfin 30\(^{th}\) conventional
- Bogganfin U4

\( r = -0.67 \)
\( p < 0.001 \)
\( n = 22 \)
$r = 0.83$
$p < 0.001$
$n = 26$