



<b>Title</b>	Suction Measurements as Indicators of Sample Quality in Soft Clay
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<b>Publication date</b>	2009
<b>Publication information</b>	Donohue, Shane, and Michael (Michael M.) Long. "Suction Measurements as Indicators of Sample Quality in Soft Clay" 32, no. 3 (2009).
<b>Publisher</b>	ASTM International
<b>Item record/more information</b>	<a href="http://hdl.handle.net/10197/4897">http://hdl.handle.net/10197/4897</a>
<b>Publisher's statement</b>	This is a preprint of an article published in Geotechnical Testing Journal, 32 (3): -, available at: <a href="http://dx.doi.org/10.1520/GTJ101416">http://dx.doi.org/10.1520/GTJ101416</a> .
<b>Publisher's version (DOI)</b>	10.1520/GTJ101416

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# Suction measurements as indicators of sample quality in soft clay

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## ABSTRACT

Soil samples removed from the ground during sampling possess a suction in their unconfined state. This suction may vary depending on the degree of disturbance induced during the sampling process. The objective of this work is to examine the feasibility of using suction measurements for sample quality assessment. A number of suction measuring techniques are reviewed and examined on samples of varying quality from two well-characterised soft clay sites, Onsøy in Norway and Ballinasloe in Ireland. Most of the techniques tested gave comparable results, although the cell pressure loading method provided the most variable measurements. The Japanese and University of Massachusetts Amherst suction probe techniques provide relatively quick and consistent suction measurements, requiring less than half an hour to stabilise.

In terms of sample quality the Sherbrooke block samples consistently exhibit higher suctions than the 76 mm, 54 mm and continuous soil samplers for the Onsøy test site. Suctions measured on the Japanese 75mm samples are similar to those measured on the block samples. The 5° displacement sampler provides the highest suctions on the Ballinasloe samples. It is observed that the quality of samples indicated by suction measurements is similar to that inferred from the normalised change in void ratio ( $\Delta e/e_0$ ) criterion.

**KEYWORDS:** clays, disturbance, sampling, site investigation, suction

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## Introduction

Considerable attention has been devoted to the issue of sampling disturbance, developing reliable means for quantifying the degree of disturbance and estimating its effect on laboratory test results. Disturbed samples may result in poor estimates of strength and stiffness parameters from triaxial and oedometer tests, which may, in turn, lead to hazardous under-design or costly over-design errors. Although recent improvements to sampling techniques and equipment may have reduced the effects of sampling disturbance, evaluation of sample quality remains essential if design parameters are to be considered reliable.

A number of different techniques have been utilised by researchers for the evaluation of sample quality. These include measurements of volumetric strain during consolidation, radiography, shear wave velocity, and soil suction ( $u_r$ ). Techniques that are considered reliable, such as measurement of volumetric strain during consolidation (Kleven et al., 1986) and the change in void ratio normalised by the initial void ratio,  $\Delta e/e_0$  (Lunne et al., 1997), require reconsolidation back to in-situ stresses before measurement, a process which may require one or more days testing.

The use of suction measurements as indicators of sampling disturbance was first suggested by Ladd and Lambe (1963), and has since been used by several researchers (e.g. Hight et al. 1992; Tanaka et al. 2001; Poirier et al. 2005). Samples taken by pushing a tube into the ground are subject to mechanical strains and total stress release, which, in turn lead to a change in pore water pressure. Once the sample is extruded, the tendency for the soil to expand is resisted by the development of surface tension forces at the air-soil boundary. The resulting pore water pressure in the sample has a negative value, i.e. suction. The value of suction measured on a sample is dependant on the in-situ stress state, pore size and soil compressibility

characteristics, as well as other factors such as drilling and sampling procedures, transportation and sample preparation. This is illustrated in Fig. 1 (Ladd and DeGroot, 2003), which shows a hypothetical stress path of the entire sampling procedure (from drilling to preparation) for a tube sample of a lightly overconsolidated clay. As shown in Fig. 1, the effective stress of the sample after the final preparation stage ( $\sigma'_s$ ), is considerably reduced as a result of damage to the soil structure during the sampling and specimen preparation process.

Ladd and Lambe (1963) proposed using the ratio  $u_r/\sigma'_{ps}$  to evaluate sample disturbance, where  $\sigma'_{ps}$  is the effective stress for a “perfect” sample. Calculation of  $\sigma'_{ps}$  is not straightforward however, and requires knowledge of Skempton’s pore pressure parameter,  $A_u$  (corresponding to release of deviatoric stress) and  $K_0$  (coefficient of earth pressure at rest). Due to the difficulty in calculating  $\sigma'_{ps}$ , a number of authors such as Tanaka et al. (1996) and Carrubba (2000) have used  $u_r$  normalised by the in-situ vertical effective stress ( $\sigma'_{v0}$ ) to evaluate disturbance. Although this may be somewhat inaccurate without resorting to pore-water pressure measurements, in most practical cases the location of the water table is well known, and it is usually a reasonably accurate assumption to assume hydrostatic conditions with depth. Tanaka et al. (1996) and Tanaka (2000) compared  $u_r$  versus  $\sigma'_{v0}$  for a range of soft clays around the world using the standard Japanese piston sampler and the Japanese suction measurement approach. Using this purely empirical approach, they found that values of  $u_r$  for most high quality samples of normally consolidated to slightly overconsolidated soft clays are approximately 1/5 to 1/6  $\sigma'_{v0}$ . All of the reported values were considerably lower than  $\sigma'_{ps}$ . Recently, Tanaka and Tanaka (2006) and Tanaka (2008) suggested that suction may not vary systematically with  $\sigma'_{v0}$  and the 1/5 to 1/6 of  $\sigma'_{v0}$  assumption needs to be treated cautiously.

The aim of this paper is to assess the use of a number of different suction measuring techniques, detailed in the literature, for sample quality evaluation. Methods employed included the filter paper method (Ridley et al. 2003), the cell pressure loading technique (Nelson et al. 1971), a small scale tensiometer (Long et al. 2007), a Japanese approach (Tanaka et al. 1996) and the University of Massachusetts Amherst (UMass) suction probe (Poirier et al. 2005). Suction measurements were performed on all samples immediately after extrusion, or in the case of the UMass probe, after removal from the ground. Samples were generally unconfined during testing, except when using the cell pressure loading approach.

### **Description of Test Site and Sampling Techniques**

The soft soils investigated during this study were located at Onsøy in Norway and at Ballinasloe in Ireland. A summary of the basic engineering properties of these materials is provided in Table 1. A number of samplers of varying quality were used on these sites, the dimensions and features of which are given in Table 2.

#### *Onsøy, Norway*

The Onsøy marine clay test site is located about 100 km southeast of Oslo, just north of the city of Fredrikstad. Several research programmes have been carried out by the Norwegian Geotechnical Institute (NGI) at the Onsøy test site over the last 40 years. This uniform marine clay deposit consists of a weathered crust less than 1m thick underlain by 8m of soft clay with iron spots, organic matter and shell fragments and by 36m of homogenous soft to firm plastic clay over bedrock (Lunne et al. 2003).

In this paper comparisons are made between the Sherbrooke block sampler, Geonor / NGI 76 mm steel fixed piston sampler, Japanese 75 mm fixed piston sampler, Geonor / NGI 54 mm composite sampler and a prototype 110 mm diameter fixed piston sampler designed to yield continuous samples. A summary of the key features of the samplers is given on Table 2.

The Sherbrooke block sampler (Lefebvre and Poulin 1979) uses a combination of a high pressure water jet and sharp cutting knives to carve an annular void, from within which the sample is retrieved. It has been shown that high quality samples can be obtained using this technique (Hight et al. 1992; Lunne et al. 2003). Samples of 250 mm in diameter and up to 350 mm high are extracted from within a 450 mm diameter borehole, which is stabilised by water.

The Geonor / NGI 54 mm composite fixed piston sampler (Andresen and Kolstad 1979) has been used frequently in Norway for a number of years. The displacement method is used, wherein the sampler (with the piston in front of the sample tube) is pushed down to the desired sampling depth without pre-augering. During sampling, the inner rods and the piston are fixed in a locked position and the outer rods are pushed down at a constant rate. This approach was also adopted when acquiring samples using the Geonor / NGI 76 mm steel fixed piston sampler.

The Japanese 75 mm fixed piston sampler is described in detail by Tanaka et al. (1996). The Japanese method of carefully pre-augering down to the sampling depth was used for acquiring samples.

The continuous sampler, which described by Donohue and Long (2007), was pushed continuously into the ground, having first excavated a starter pit from 2 to 3 m depth. In this technique, the sampler is placed at ground level and then pushed using a hydraulic system and a reaction frame into the ground in a similar manner to CPTU.

Samples were acquired at two depths of approximately 10 m and 13 m. Block, 76 mm and 54 mm samples were taken at both depths, whereas continuous and Japanese samples were only taken at approximately 10 m and 13 m respectively.

### *Ballinasloe, Ireland*

The Ballinasloe test site is located approximately 170 km west of Dublin and about 70 km east of Galway in the midlands of Ireland. As is common with sites in the centre of Ireland, a layer of peat overlies the deeper soft soils. The soft soil beneath this layer of peat is post-glacial lacustrine clay, which was laid down during the retreat of the glaciers some 18,000 years ago. The samples acquired during this project were taken from this deposit, which comprises intermittent layers of silt and clay (varved clay). These laminations of clay and silt are relatively thin and in general less than 1mm to 2 mm thick. The material is also quite sensitive, and the sensitivity values given in Table 1 may be quite conservative. At similar soft soils in Ireland, it has been suggested (Long and O’Riordan 2001; Long and Gudjonsson 2004) that additional disturbance due to insertion of vane and T-bar tools result in a measured strength that is too low, thus leading to reduced sensitivity values.

The soft clay deposit may sub-divided into two layers, based on their anisotropically consolidated undrained (CAUC) triaxial test failure envelopes, and also on their colour which changes from grey to brown between these layers (Donohue and Long 2009). The upper clay extends to about 5.5 m depth and the lower clay extends from 5.5 m to 7.5 m depth.

For this project samples were obtained using the 100 mm diameter, 1 m long ELE fixed piston sampler, which is the most common “high quality” sampler used in the UK and Ireland. The cutting edge of the sampling tube was modified from the normal 30° to 5°, as recommended

by Hight and Leroueil (2003). Samples were obtained using two distinct methods. In the first method, the standard techniques of sampling from the bottom of a shell and auger (open percussive) borehole was used. This is referred to as the “5° conventional sampler” in this paper. In the second method, the sampler was pushed down to the desired sampling depth without pre-augering. This is referred to as the “5° displacement sampler” in this paper.

One set of samples were also recovered using thick-walled open drive U4 tubes (100 mm diameter, 450 mm long). It was necessary to screw two tubes together to achieve recovery. Despite several attempts it proved possible to only recover one sample. Donohue and Long (2009) reported a lower moisture content and higher bulk density on samples taken using this sampler, and attributed this to densification by drainage of excess pore pressure from the silt lenses during sampler driving.

### **Suction Measuring Techniques**

A number of different suction measurement techniques are available and in use by practitioners worldwide. Long and Lunne (2003) summarise a large number of these techniques. Each of the techniques tested in this study, with the possible exception of the more complex UMass suction probe, are straightforward and would be easy to implement into any site investigation programme.

#### *Filter paper*

A piece of dry filter paper is placed in contact with a soil sample and sealed in place to prevent evaporation. The filter paper absorbs moisture until its water content is in equilibrium with the magnitude of soil suction. Its water content is measured and the suction is determined from



previously established correlations. These correlations may be developed by measuring the equilibrium moisture content on a specimen of known suction. This can be achieved, for example, by loading the sample to a given stress in the oedometer and then unloading it rapidly and carefully, followed by immediate application of the filter paper. Calibration formulae developed by Chandler et al. (1992) and Leong et al. (2002) are given below for matrix suction measurements using Whatman No. 42 filter paper, at various values of water content ( $w_f$ ).

$$\text{Chandler et al. (1992):} \quad \log u_r = 4.842 - 0.0633w_f \quad w_f < 47 \% \quad (1)$$

$$\log u_r = 6.05 - 2.48 \log w_f \quad w_f \geq 47 \% \quad (2)$$

$$\text{Leong et al. (2002):} \quad \log u_r = 4.945 - 0.0673w_f \quad w_f < 47 \% \quad (3)$$

$$\log u_r = 2.909 - 0.0229w_f \quad w_f \geq 47 \% \quad (4)$$

The formulae of Chandler et al. (1992) were used to determine suctions on the samples tested in this study, as it was observed that this calibration provided results similar to those from other measuring techniques, whereas the equations of Leong et al. (2002) resulted in considerably lower suctions. For example, the water content of a piece of Whatman No. 42 filter paper attached to a 76 mm tube sample from Onsøy was 120.7% after weighing, which according to the appropriate Chandler et al. (1992) equation (Eq. 2) gives a suction of 7.7 kPa. This compares to a value of just 1.4 kPa for the equivalent Leong et al. (2002) equation (Eq. 4).

Ridley et al. (2003) suggested that when using the technique, the sample, with attached filter papers, should be placed between perspex discs, sealed with multiple layers of cling film and placed inside plastic bags. The sample should then be left for 7-10 days in a temperature controlled environment so that the moisture content of the filter paper comes into equilibrium

with that of the soil. Temperature variations are to be avoided as they will cause evaporation and condensation, leading to interference in the moisture transfer process and resulting in erroneous measurements. For this study, samples were stored at a constant temperature of 20°C. Ridley et al. (2003) also recommended using a filter paper diameter of 75 mm on a specimen with a diameter of 100 mm. As a number of the samples tested in this project had diameters that were less than 100 mm, filter paper diameters of 35 mm and 50 mm were used on 54 mm and 75 mm samples respectively. In order to check on this choice of filter paper size, 35 mm filter papers were also used on 75 mm samples and the suctions obtained from both diameters compared well. In this study filter papers were placed above and below the soil sample as a repeatability check. Ridley et al. (2003) state that an accuracy of  $\pm 10\%$  can be achieved with this method, provided sufficient care is taken during the procedure.

Filter paper can be used to measure either total or matrix suction. When the paper is placed in direct contact with the soil, water flow will occur until equilibrium is achieved and the measurement made is of matrix suction. When the filter paper is not in contact with the soil, only water vapour flow will occur and the measurement made is of total (i.e. matrix plus osmotic) suction. In this study only measurements of matrix suction are acquired. Standard procedures for carrying out filter paper tests can be found in ASTM D5298-94, and Ridley et al. (2003).

### *Cell pressure loading*

Early measurements of suction involved applying a confining stress in the triaxial cell under undrained conditions, in order to elevate the pore pressure to an easily measurable value. This approach, used by Skempton (1961), involved applying a cell pressure ( $\sigma_r$ ), equal to the total

overburden stress, allowing the measured pore pressure ( $u$ ) to stabilise and then determining the suction ( $u_r$ ) indirectly as follows:

$$u_r = \sigma_r - u \quad (5)$$

In the UK, for the studies on Bothkennar clay reported by Hight et al. (1992), a similar technique was used except that  $\sigma_r$  was taken to be half the total overburden stress. In a slight modification to this procedure, other researches have gradually increased the confining pressure, made a number of measurements at various values of  $\sigma_r$  and then determined  $u_r$  by extrapolation, as shown on Fig. 2. The cell pressure increments are applied until the pore water pressure response ( $\Delta u / \Delta \sigma_r$ ) exceeds 95%. The suction value is taken as that corresponding to the intercept with the vertical axis. This approach was recommended by Broms (1980) and has been used here. Baldi et al. (1988), in a review of the various procedures, state that the accuracy of this approach depends on the assumption of an initially saturated specimen and measuring system, and prior elimination of any trapped air in the system. Burland and Maswoswe (1982) warn that filter paper drains should not be used, as these substantially affect initial sample suction. For these reasons, Doran et al. (2000) stated that  $u_r$  cannot be measured accurately using a standard triaxial set-up.

In this study tests have been carried out during the saturation stage (without filter paper drains) of standard CAUC triaxial tests. All samples were trimmed to a diameter of approx. 50 mm. At least four or five increments of cell pressure were used, usually 25 kPa, 50 kPa,  $\frac{1}{2}\sigma'_{v0}$ , 150 kPa and 200 kPa, and then plotted as shown in the example for Onsøy clay on Fig. 2 to make an estimate of suction.

### *Small scale tensiometer*

It is possible to measure suction in soil samples using probes which are small-scale versions of tensiometers developed for agricultural irrigation purposes. A typical tensiometer consists of a reservoir of water, a porous filter and a system for measuring stress. Water is transferred from the reservoir into the soil, via the porous filter until the stress holding the water in the reservoir comes into equilibrium with the stress holding the water in the soil. This stress is equal to the soil suction.

At least two small-scale tensiometers are available commercially. These are produced by Soil Moisture Corporation in the US ([www.soilmoisture.com](http://www.soilmoisture.com)) and SDEC in France ([www.sdec-france.com](http://www.sdec-france.com)). The Soil Moisture probe, which was used in this study, contains a ceramic cup, 6 mm in diameter and 25 mm long. These probes have a limited suction range of about 85kPa, due to cavitation. In the range 85 to 100 kPa air comes out of solution, making the suction reading inaccurate. Above this range, water breaks into vapour causing the tensiometer to lose all of its water. Before testing, the tensiometer calibration was checked using a vacuum pump. Long et al. (2007) used this system in parallel with the cell pressure loading technique to study sample quality.

With the small-scale tensiometer an issue arose as to whether to push the porous ceramic cup straight into the sample, or to first core a small hole into the sample before insertion of the cup. It was thought that either method of insertion could cause some additional disturbance. Both methods were therefore tested and it was found that simply pushing the cup into the sample caused cracks to appear, particularly when testing the more brittle Onsøy samples. The approach adopted, therefore, was to core a small hole in the sample using a thin-walled 6 mm tube and the ceramic cup was then pushed into this hole. The diameter of the tube was slightly smaller than

that of the ceramic cup to enable adequate contact between the cup and the sample. Careful saturation of the tensiometer was also required to ensure it was functioning correctly. The tensiometer was stored in de-aired water to maintain saturation, and before each test the water in the reservoir and ceramic cup were pressurised in order to purge air from the system.

A minimum sample height of 45 mm was used to ensure the ceramic cup was fully inserted. After insertion into the soil sample it requires at least 12 hours for the tensiometer to come into equilibrium with the soil.

#### *“Japanese” method*

In this technique a saturated high-air-entry disk 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. Careful deairing of the measuring system is required.

Recent studies in Japan, for example, have made use of this technique (Tanaka et al. 1996; Tanaka et al. 2001; Tanaka 2008). A specimen is placed on the high-air-entry ceramic disk (air entry value of 200 to 300 kPa), without a membrane, and the suction is monitored until it becomes constant. In this technique measurements are being made of matrix suction. In the study of Tanaka et al. (1996) and other similar Japanese studies the transducer had a suction measuring capacity of 100 kPa.

In this study, the high-air-entry porous stone was saturated using de-aired water immediately prior to placing the sample onto it. After placement, the suction was monitored using a pressure transducer, with a resolution of  $\pm 1$  kPa. Very small suction values were measured during the first few tests with this method. This was later found to be due to a poor

seal around the side of the ceramic disk, which resulted in a dissipation of suction. It is recommended, therefore, to embed the disk within a pedestal and allow it to stand slightly proud. A layer of grease should then be applied around the edge of the disk.

The result of a typical test using this technique is shown in Fig. 3, for a 100 mm diameter sample from a block of Onsøy clay. As shown the pore pressure reached a constant minimum value approximately 10 minutes after placing the sample on the pedestal. This minimum value of 13kPa is therefore taken as the suction ( $u_r$ ) for this sample. After achieving the minimum value, the suction gradually dissipates. Unfortunately, as the porous disk had a diameter of 100mm, this technique could not be tested on samples with a diameter less than 100 mm.

#### *University of Massachusetts Amherst (UMass) suction probe*

Soil suction was also measured using the UMass external 35 mm diameter suction probe (Poirier et al. 2005). The probe consists of a pedestal into which a 16 mm diameter, 5 bar ceramic stone filter is mounted. Below this filter is a small pressure transducer with a capacity of 1380 kPa. The probe was saturated using deaired water, following the procedure of Ridley and Burland (1999). In order to minimise evaporation, a layer of grease was applied around the edge of the porous stone, which is slightly proud of the surface of the pedestal. The soil surface onto which the probe was to be placed was firstly prepared using a razor blade to ensure it was level. After placement, the area around the probe was covered in a layer of cling film to prevent drying. The probe remained in place until the readings reached equilibrium, which usually occurred after 5-15 minutes. During this study, the UMass probe was only used at the Onsøy test site, on block samples in the field, immediately after removal from the ground. This work was performed by UMass personnel.

## Test Results

The five techniques described in the previous section have been tested on specimens from each of the samplers detailed above. Donohue and Long (2007, 2009) provide a detailed account of the sample quality, determined from CAUC triaxial tests, on each of the samples tested in this paper. One of the sample quality criteria used in that study, the normalised change in void ratio ( $\Delta e/e_0$ , Lunne et al., 1997) measured during the consolidation stage, is shown in Fig. 4 for each of the samples tested at both sites. It is clear that for the Onsøy site the block samples are the highest in quality and the 54 mm samples are the lowest quality samples. Donohue and Long (2009) reported that the 5° displacement and U4 samplers resulted in the highest and lowest quality samples respectively, for the Ballinasloe site.

### *Onsøy - Samples from approximately 10 m depth*

Suction test results for Onsøy samples from 10 m depth are shown in Fig. 5. All five suction measuring techniques were employed on the block sample from this depth. The filter paper located on the top of the sample (Fil.pap.1) resulted in a lower moisture content (and therefore higher suction) than that located on the bottom (Fil.pap.2), which equated to a difference in suction of 2.8 kPa. It should be noted that the UMass work was performed in the field, within about 20 minutes of the block being extracted from the ground, whereas each of the other tests were performed in the laboratory some two to three weeks later, following transportation of the samples from Norway to Ireland. This may partly explain the higher suction measured using the UMass probe. It is clear from Fig. 5 that the cell pressure loading technique produced the most variable results, relative to the others, on each of the samples tested.

Taking into account the mean of the three suction measuring techniques tested on all samplers (tensiometer, cell pressure loading, and filter paper), the block samples exhibit the highest suction (11.3kPa), followed by the 76mm (8kPa), the 54mm (5.7kPa) and the continuous (5.6kPa) samplers. The quality of each of these samples inferred from the CAUC triaxial test results reported by Donohue and Long (2009) show a similar pattern to the measurements of suction presented here. In their work the Block samples were considered to be the highest quality samples followed by the 76mm and 54mm samples.

#### *Onsøy - Samples from approximately 13m depth*

Suction test results for Onsøy samples from approx. 13 m depth are shown in Fig. 6. The UMass suction probe, used in the field, again measured a notably higher suction than any of the other techniques tested here. It is uncertain whether this difference is due to measurement technique, transportation damage or to some other time effect. Donohue and Long (2009) observed a corresponding reduction in shear wave velocity ( $V_s$ ) after transportation of the samples from the site in Norway to the laboratory in Ireland. As before, the cell pressure loading technique produced by far the most variable results, both significantly higher (76 mm) and lower (Japanese) than the other measuring techniques tested.

In this case the Japanese 75 mm sampler (13.9 kPa) exhibits the highest mean suction, followed by the block (12.9 kPa), 76 mm (11.8 kPa) and 54 mm (7.2 kPa) samplers. As with the samples from 10.5 m, this pattern is similar to the sample quality inferred from CAUC triaxial test results (Donohue and Long 2007; Donohue and Long 2009), the only difference being that the block was thought to be of higher quality than the Japanese sample. These results are comparable to those reported by Tanaka (2000), who measured similar suctions (using the



Japanese measuring technique) on samples from Sherbrooke block and Japanese samplers. The filter paper technique shows excellent repeatability on each of the samples tested at this depth.

#### *Ballinasloe - Upper Clay*

Suction test results for Ballinasloe upper clay are shown in Fig. 7. Suctions measured on the samples from the 5° displacement and 5° conventional samplers were reasonably consistent between the various measurement techniques. Due to the lack of sample present in the U4 tube, only two of the techniques were tested on material from this sampler. The cell pressure loading technique again showed the most deviation, and it is notable that suction measured using the tensiometer were generally lower, relative to the other techniques, for this material. As the material is quite sensitive, this could be due to additional disturbance caused when inserting the probe. In general, the suction measured on samples from Ballinasloe are significantly lower than those measured on Onsøy clay. This is likely due to disturbance, although Tanaka et al. (2001) attributed the low measured suction of “lean” Drammen clay to the low plasticity of the material. As the Ballinasloe clays are also low to intermediate plasticity clays, this could affect the measured suction. Also the occasional presence of very thin clay and silt laminae could also affect the measured suction value.

Overall the 5° displacement sampler (4.9 kPa) exhibits the highest mean suction of the samples from the upper clay, followed by the 5° conventional (4.1 kPa), and the U4 (3.1 kPa) samplers. This pattern is again very similar to the sample quality inferred from CAUC triaxial test results (Donohue and Long 2009), at this depth.

### *Ballinasloe - Lower Clay*

Only the two 5° piston tubes were tested, as the U4 samples planned for this depth were not recovered. A number of additional tests were performed on samples from this depth, in order to estimate the repeatability of some of the techniques (Fig. 8). Suctions obtained from each of the techniques on the 5° displacement sampler and 5° conventional samplers were again reasonably consistent between the various measurement techniques.

As shown in Fig. 8, each of the techniques tested exhibited good repeatability. The measured values were consistently lower than those of the 5° displacement sampler, with a mean suction of 3.7kPa being measured on the 5° conventional sample, as against 5.3kPa for the displacement samples. The superiority of the displacement samples was also observed in the CAUC triaxial test results (Donohue and Long 2009).

### *Relationship between suction and $\Delta e/e_0$*

Suctions measured on samples from both sites are normalized using the in-situ vertical effective stress ( $\sigma'_{v0}$ ) and compared with the  $\Delta e/e_0$  quality criterion in Fig. 9. Accurate estimation of  $\sigma'_{v0}$  was supported by direct measurements of the pore-water pressure distribution with depth at Onsøy (Lunne et al. 2003). For Ballinasloe, data is available for the nearby Athlone research site (Long and O’Riordan 2001; Long 2003) which confirms hydrostatic values.

As discussed above,  $\Delta e/e_0$  (Lunne et al. 1997) was measured during the consolidation stage of CAUC triaxial tests, a relatively time consuming process when compared to some of the rapid suction measuring techniques described above. The suction values used here were taken as the mean value from the measuring techniques, as detailed above. Although there is quite a bit of scatter, a relationship exists between these parameters. In fact if the Ballinasloe U4 sample is

considered an outlier, due to densification (Donohue and Long 2009), which reduced its moisture content (in this case disturbance could have resulted in an increase in suction), the relationship is considerably improved ( $R^2 = 0.6$ ). As shown the block samples from Onsøy generally exhibit the lowest  $\Delta e/e_0$  and highest normalised  $u_r$ , indicating they are superior in quality. Interestingly, extrapolation of the trend towards  $\Delta e/e_0 = 0$  (i.e. completely undisturbed sample) gives a suction value close to  $0.2\sigma'_{v0}$ , as suggested by Tanaka et al. (1996). This trend is also observed for the individual sites under investigation. Other researchers have, however, measured suctions well in excess of  $0.2\sigma'_{v0}$ , and in some cases close to  $\sigma'_{v0}$  on high quality soft clay samples, e.g. Bothkennar clay (Hight, 2000) and Bangkok clay (Tanaka et al. 2006).

#### *Variation of suction against time*

A number of samples from Onsøy were tested again in the months following removal from the ground, in order to observe any degradation of the samples over time. Fig. 10 shows the variation of suction with time, for a number of different samplers. Each of these were examined using the same small-scale tensiometer technique. Although small variations are observed, there was no definitive drop in suction over the specified timescale, indicating minimal degradation in quality.

#### **Discussion**

A number of suction measuring techniques have been reviewed and tested on a number of samples of varying quality from two well-characterised soft clay sites, in order to determine techniques suitable for sample quality assessment. Individually they performed as follows:

- 1) Although the calibration equations used for the filter paper method were initially developed for higher suctions (i.e. lower filter paper water content) than tested here, they resulted in suction values that were comparable to the other techniques tested, particularly when the equations of Chandler et al. (1992) were applied. The technique also showed a reasonable degree of repeatability, although some differences were observed between filter papers located above and below the sample. This variability could be due to the process of removing the paper from the sample. It is essential that the filter paper is removed from the sample and sealed in a plastic bag as quickly as possible, in order to prevent desaturation. Also, the presence of residual material on the filter paper could affect the measured values. If possible, this material should be quickly brushed off the paper with a soft brush (Ridley et al. 2003). This technique, however, requires seven days for the moisture content of the filter paper to come into equilibrium with that of the soil. As a result, the filter paper approach provides the slowest measure of suction of all the techniques tested in this study, which may limit its use for assessing sampling quality.
- 2) The cell pressure loading technique, although easy to implement into the saturation stage of a triaxial test, produced by far the most variable results, relative to the other techniques tested. This variability could be related to the relatively large sample size, necessary for testing in a triaxial test. The suction value must be transferred from the body of the larger sample to the measuring transducer before measurement. The method could be improved by using a mid-height pore pressure probe, similar to that designed by Hight (1982). Also, unlike the other techniques tested in this study, the cell pressure loading approach does not provide a direct measure of suction (or water content in the case of the filter paper approach), instead requiring extrapolation of the pore pressure trend back to the cell

pressure axis. Although the method does appear to be the least reliable of all those tested, it is relatively quick and can easily be incorporated into a triaxial testing program.

- 3) As with the filter paper technique, the inexpensive small-scale tensiometer produced results that were comparable to most of the other techniques, particularly for the Onsøy test site. Suctions measured for the Ballinasloe site were, in general, slightly less than the mean suction of all techniques tested. This was possibly due to additional disturbance caused by the necessity of having to core a small hole into the sensitive Ballinasloe samples, and insertion of the probe into the soil. The tensiometer takes approximately 12 hours to stabilise and weighs very little, making it easily transportable.
- 4) The Japanese approach, which uses a high air entry porous disk, is very easy to implement and again produced results that were comparable to the results from the other techniques. The most significant advantage of this method is that suction may be measured relatively quickly, usually in less than half an hour. It may also be constructed to be portable, making it suitable for field estimation of sampling disturbance. In order to avoid dissipation, it is recommended to embed the porous disk within a pedestal, and allow it to stand slightly proud. A layer of grease should then be applied around the edge of the disk.
- 5) The University of Massachusetts suction probe, which is constructed predominantly from readily available parts, is also ideally suited for field estimation of sample quality. This device produced a stable measurement of suction within 5-15 minutes. Suctions measured on the Onsøy block samples were up to 5 kPa higher than the mean of the other techniques tested. This was the only technique tested on site in Norway, before transportation of the samples to Ireland, so it is uncertain whether this difference is due to measurement technique, transportation damage or to some other time effect.

## **Conclusions**

Five suction measuring techniques have been tested, in order to establish their suitability for assessing sample quality. The Japanese approach, UMass suction probe and small-scale tensiometer were found to be most suitable, providing relatively consistent and rapid suction measurements.

These suction measurements were then used to estimate the relative quality of specimens from a number of different samplers. For the Onsøy site, the highest suctions (and therefore least disturbed) were measured on the Sherbrooke block and Japanese tube piston samplers. The NGI / Geonor 54 mm sampler consistently exhibited the lowest suction. Also, the Scandinavian displacement technique consistently produced samples with higher suctions than the conventional pre-augering technique, when both were tested on identical modified ELE 100 mm tubes, at the Ballinasloe test site. A relationship was observed between the quality of samples indicated by suction measurements, and those inferred from the  $\Delta e/e_0$  criterion, measured during the consolidation stage of anisotropically consolidated undrained triaxial (CAUC) tests. Due to the time consuming consolidation process, suction measurements may also be significantly quicker to perform.

Little or no change in suction was observed in the months following removal from the ground indicating minimal sample degradation.

## *Acknowledgements*

Collection of samples was funded in part by the Norwegian Geotechnical Institute (NGI), the University of Massachusetts Amherst and RPS-MCOS. The authors thank Mr. Tom Lunne and Mr. Morten Sjørusen (both NGI), Dr. Don DeGroot and Dr. Melissa Landon (both UMass

Amherst) and Dr. Carl Brangan of Applied Ground Engineering Consultants (AGEC), formerly of RPS-MCOS, for their assistance. The authors would also like to thank Pierse Construction Ltd. for funding the lead author. The authors are also grateful for the assistance of Mr. George Cosgrave of University College Dublin.

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<b>Property</b>	<b>Onsøy</b>	<b>Ballinasloe</b>
Moisture content (%)	55 – 67	29 - 42
Bulk density (Mg/m <sup>3</sup> )	1.6 – 1.7	1.8 – 2.0
Initial void ratio (e <sub>0</sub> )	1.5 – 1.8	0.7 – 1.3
Clay content (%)	51 – 69	40 - 49
Liquid limit (%)	55 – 70	32 - 39
Plasticity index	25 – 50	15 - 21
Sensitivity (field vane)	6 - 8	3 – 5
OCR	1.3 – 1.7	1.1
K <sub>0</sub>	0.5 – 0.7	0.5*
q <sub>t</sub> (kPa)	500 at 10m – 675 at 14m	200 - 500
Depth to water table	0.2m	1m

Table 1. Basic site properties, where  $K_0$  = the coefficient of earth pressure at rest, OCR = overconsolidation ratio and  $q_t$  = cone resistance corrected for pore pressure effects. \* estimated from relationship with plasticity index (Brooker and Ireland, 1965)

<b>Sampler</b>	<b>Length</b>	<b><math>\alpha</math></b>	<b>External diameter</b>	<b>Internal diameter</b>	<b>AR</b>	<b>ICR</b>	<b>Drilling technique</b>
	<b>(mm)</b>	<b>(deg)</b>	<b>(mm)</b>	<b>(mm)</b>	<b>(%)</b>	<b>(%)</b>	
NGI / Geonor 54mm Piston	800	15	57.4	54.3	44	0.6	Displacement
NGI / Geonor 76mm Piston	866	9	80	76	11	0	Displacement
Sherbrooke	350	-	250	-	-	-	Pre auger
Japanese	800	6	78	75	8.2	0	Pre auger
Continuous	-	5	118	110	15	<0.5	Drop or push
ELE 100 (modified)	100	5	104.8	101.4	6.8	0	Pre auger (conventional)
ELE 100 (modified)	100	5	104.8	101.4	6.8	0	Displacement
U4	45.7	20	117.4	104.1	27	1.4	Pre augur

Table 2. Summary of the dimensions and features of the samplers used, where  $\alpha$  = cutting edge angle, AR = area ratio and ICR = inside clearance ratio

## **Figure Captions**

- FIG. 1 Hypothetical tube sampling stress path of a lightly overconsolidated clay, from drilling to sample preparation (from Ladd and DeGroot, 2003).
- FIG. 2 Example of obtaining suctions using the cell pressure loading technique on block and 54mm samples of Onsøy clay, from approximately 13m depth.
- FIG. 3 Suction measurement using the “Japanese” approach from a Sherbrooke block sample from Onsøy at 13m depth.
- FIG. 4 Normalised change in void ratio during consolidation ( $\Delta e/e_0$ ) using the sample quality criterion of Lunne et al. (1997), on samples from (a) Onsøy and (b) Ballinasloe.
- FIG. 5 Suction test results for Onsøy site at approximately 10m depth.
- FIG. 6 Suction test results for Onsøy site at approximately 13m depth.
- FIG. 7 Suction test results for Ballinasloe Upper Clay (3-5m).
- FIG. 8 Suction test results for Ballinasloe Lower Clay (5-7m).
- FIG. 9 The variation of  $u_r$  normalised by  $\sigma'_{v0}$ , with  $\Delta e/e_0$  (after Donohue and Long 2008,  $\Delta e/e_0$  sample quality criterion from Lunne et al., 1997).
- FIG. 10 Variation of Suction with time on a number of samples of Onsøy Clay using the small-scale tensiometer.





















