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<b>Authors(s)</b>	Long, Michael (Michael M.)
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**Names of author:** Michael Long, BE, MEngSc, Ph.D., CEng, MICE, MIEI

**Position / affiliation of author:** Lecturer, Department of Civil Engineering,  
University College Dublin, Earlsfort Terrace, Dublin 2, Ireland

**Contact address:** Michael Long, Department of Civil Engineering, University  
College Dublin, Earlsfort Terrace, Dublin 2, Ireland.

**Phone:** +353-1-7167333

**Fax:** +353-1-7167399

**e-mail:** Mike.Long@ucd.ie

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by Michael Long, UCD.

**Synopsis:** Practicing engineers designing civil engineering works on soft clay usually assume that laboratory tests on normal piston tube sampling will at worst give conservative design parameters. Indeed most research into sampling disturbance effects on soft clays has proven that use of poor quality tube samplers ultimately leads to lower undrained strength, stiffness and preconsolidation stress than actually exist in situ. There is some evidence to suggest that this may not hold true for “intermediate” clay / silts or laminated soils. These issues were investigated for the Athlone laminated clay / silt and it was found that tube sampling disturbance leads to increase in stiffness and undrained strength and induces a strong tendency for dilatant behaviour post peak. These findings were made by comparing tube sample data with that from high quality Sherbrooke block sampling and full scale field trials. From the results of this investigation and from comparisons with other soils, it is concluded that undrained tube sampling strains have only a minor influence and that the behaviour of these medium plasticity clay / silts is mainly due to partially drained tube insertion process. Engineers dealing with soft “intermediate” or laminated soils need to carefully assess the laboratory derived parameters, especially when the clay content is less than about 40% and the plasticity index is less than 20%.

## 1. INTRODUCTION

There are many studies reported in the literature on sample disturbance effects on soft structured plastic clays. Some examples are the classic papers of La Rochelle and Lefebvre<sup>1</sup> on Canadian Champlain clay, Lacasse *et al.*<sup>2</sup> and Lunne *et al.*<sup>3</sup> on Norwegian clays, Hight *et al.*<sup>4</sup> on Bothkennar clay from the UK and Tanaka *et al.*<sup>5</sup> on Japanese clays. These studies confirmed that poor quality piston tube sampling causes destructuration of the soils leading to lower preconsolidation stress, strength and stiffness when compared to values from high quality samples. If these parameters were subsequently used in design, the net result would be a conservative solution.

It is also well known that piston tube sampling can densify loose silts and sands (Hight and Leroueil<sup>6</sup>). Testing of the subsequent samples can lead to higher strength and stiffness values than exist in situ. However designers are generally aware of these phenomena and in these cases mostly rely on the results of in situ testing.

Clearly there exists a body of “intermediate” soils, e.g. low to medium plasticity clay / silt where sampling induced destructuration and densification effects occur simultaneously. If the densification effects should dominate, poor quality sampling could lead to unsafe designs.

### 1.1 Examples of “intermediate” soil behaviour

Some examples of this “intermediate” soil behaviour are shown on Fig. 1 and a summary of pertinent soil parameters is given on Table 1. Long<sup>7</sup> reports on work carried out on samples of the laminated facies from the UK soft clay research site at Bothkennar. The ground conditions in this area of the site were described by Nash *et al.*<sup>8</sup>. This facies has a slightly lower clay content and plasticity index than the more well known bedded or mottled facies at the site (Table 1). Results of CAUC triaxial tests (anisotropically consolidated undrained compression tests) on samples recovered

using regular British, 1m long, 100 mm diameter ELE type piston tubes with the standard (30°) and modified (5°) cutting edge are shown in Figure 1(a). The stress paths are plotted in  $s' = (\sigma'_a + \sigma'_r)/2$ ,  $t' = (\sigma'_a - \sigma'_r)/2$  space. The 30° specimen is somewhat denser (initial density 1.738 Mg/m<sup>3</sup> compared to 1.638 Mg/m<sup>3</sup>), is clearly of inferior quality when compared to the 5° specimen and it shows dilative behaviour on shearing. In contrast, the 5° specimen shows contractive behaviour following the same pattern as that of high quality block samples of the same material (Hight *et al.*<sup>4</sup>). The difference in behaviour is due to the inferior cutting shoe geometry of the 30° tubes. This outcome is supported by the volume change required to consolidate the samples to in situ stress, which were 2.8% and 9.5% for the 5° and 30° tubes respectively.

Similar behaviour, i.e. the apparent reversal of the stress path caused by sampling induced disturbance, was found by NGI during a study of the very silty Eidsvold clay (Karlsrud<sup>9</sup>, Lunne *et al.*<sup>3</sup>). Eidsvold silty clay has very similar basic parameters to Athlone brown laminated clay, which is the subject of this paper. Its water content is 25 – 33%, plasticity index 13 – 19%, clay content 37 – 48% and sensitivity 2 – 5. CAUC tests on Sherbrooke block samples of the clay were compared with those on 54 mm diameter piston samples (composite type). Stress path plots (from Karlsrud<sup>9</sup>) for typical block and 54 mm tube specimens are shown in Figure 1(b). In this case also, the difference in behaviour was attributed to differing sample disturbance with to different volume changes during reconsolidation (1% for block samples compared to 3% for piston samples).

NGI (Lunne *et al.*<sup>3</sup>) report than similar behaviour can occur with 54 mm diameter (composite) samples of “lean” Drammen clay. This material is typically recovered

form depths greater than about 10 m, has a plasticity index of between 10 and 20%, clay content of about 40%, and field vane sensitivity of 5 to 7.

Seierstad<sup>10</sup> studied another Norwegian marine clay, in this case quick clay from Kvenild near Tiller, just south of Trondheim, and made similar findings. Kvenild clay has a water content of about 40%, plasticity index 6 - 8%, clay content 42% and sensitivity of about 70. Some stress paths for CIU (isotropically consolidated) tests on specimens recovered from about 8.5 m using 54 mm and 75 mm thin walled piston tube samples are shown in Figure 1(c). In this case the 54 mm samples were simple thin walled steel tubes and thus should produce specimens of higher quality than those mentioned above for Eidsvold which were of the composite type with an inner plastic liner. The 75 mm specimen is slightly denser ( $1.906 \text{ Mg/m}^3$  compared to  $1.876 \text{ Mg/m}^3$ ) and exhibited a greater volume change during consolidation (6.3% compared to 4.5%). During shearing the 75 mm specimen exhibits dilative behaviour, whereas the 54 mm specimen contracts. Seierstad<sup>9</sup> attributes this behaviour to disturbance caused by inferior cutting shoe geometry in the 75 mm tube and additional disturbance during extrusion.

Randolph *et al.*<sup>11</sup> also proposed a similar hypothesis in order to explain unusual stress paths for soft calcareous sediments but did not give any detailed stress – strain or stress path plots. Santagata and Germaine<sup>12</sup> used the “ideal sampling approach” (ISA) to study the effects of tube sampling on the undrained behaviour of resedimented Boston blue clay. This involved subjecting the specimen to strain paths, which mimicked the theoretical tube sampling strains, prior to shearing the samples. It was shown that the increasing amplitude of strain imposed during disturbance is associated with a change from a contractive to an increasingly dilative effective stress path.

## **1.2 Objectives of this work**

The overall objective of the paper will be to give guidance to designers who need to interpret laboratory tests on these “intermediate” soils and to attempt to distinguish soils where destructuration dominates, even with very poor samples, from those where densification may be most important. Little, if any, similar guidance exists in the literature probably because there have been few studies where poor and high quality samples of such a material have been studied.

These objectives are achieved by a detailed case study of soil sampling effects for very soft clay / silt from a site at Athlone in Ireland. Comparisons are made between specimens obtained from four different samplers ranging from very poor to high quality. Laboratory derived parameters are compared with the in situ behaviour of the material measured during embankment construction. Comparisons are made between the behaviour of the Athlone soils and some other well characterised materials.

## **2. THE SITE**

Athlone is located midway between Dublin and Galway in the Republic of Ireland. The Athlone Bypass, which passes to the north of the town, was constructed between 1982 and 1991. Part of the Bypass crosses an area underlain by up to 12 m of very soft clays on embankments up to 8.6 m high. Details of the site together with an examination of the field behaviour of the very soft soils are given by Long and O’Riordan<sup>13</sup>.

## **3. DRILLING AND SAMPLING TECHNIQUES**

Sampling was initially carried out using the 1 m long ELE 100 mm diameter fixed piston sampler, which has a 1.7 mm wall thickness. This is conventionally used in the UK and Ireland to obtain high quality samples of soft compressible material. However, some recent studies (e.g. Hight<sup>14</sup> and Long<sup>7</sup>) have shown that a sharpened

cutting edge can produce significantly better samples. Therefore samples were subsequently taken with a modified version of this sampler, in which the sample tube cutting edge was sharpened from the normal 30° to 5°. In both cases the hole was 200 mm in diameter. It was advanced using conventional shell and auger drilling and was maintained full of water.

Continuous soil samples, of 65 mm diameter, were obtained using a MOSTAP<sup>®</sup> soil sampler. A thin walled (2 mm) sampling tube (or liner) acts as a guide for a piston during sampling and distributes the stocking uniformly around the sample. The purpose of the stocking is to minimise friction. Together with the liner it serves to effectively transport and store the sample. For this technique no borehole is required. The sampler has a poor area ratio of approximately 105%, compared to about 7% for the ELE samplers. Thus it was expected to yield relatively poor specimens

The Canadian Sherbrooke block sampler (Lefebvre and Poulin<sup>15</sup>) was also employed. Previous researchers (e.g. Lacasse *et al.*<sup>2</sup>, Lunne *et al.*<sup>3</sup> and Hight *et al.*<sup>4</sup>) have shown that high quality samples can be obtained using this technique. Samples were 250 mm in diameter and up to 350 mm high and extracted from within a 450 mm diameter borehole, which was stabilised by water. Sherbrooke samples had never previously been recovered from ground as soft as that encountered at Athlone.

Boreholes for 30° piston tube, Sherbrooke block and MOSTAP<sup>®</sup> specimens were all drilled within a few meters of one another (Location called Profile D by Long and O’Riordan<sup>13</sup>). Cone penetration, T-Bar and vane testing was also carried out at this location. Unfortunately the 5° piston tube borehole was drilled at Profile C, some 110 m west of Profile D. This has implications for comparing the 30° and 5° piston tube samples as will be detailed later. These investigations were carried out in 1997 / 1998.

## 4. LABORATORY TESTING

The principal means of studying the difference in shearing behaviour of the material from the block and tube samples was by means of CAUC triaxial tests in which the specimens are anisotropically consolidated to the best estimate of the in situ stress. Maintained load oedometer (MSL) were performed to study any sampling induced effects on compressibility parameters.

### 4.1 Triaxial tests

The procedures used were broadly those adopted as standard by the Norwegian Geotechnical Institute (NGI) as described by Berre<sup>16</sup>. The specimen, of diameter as extruded for the piston samples or trimmed to 100 mm and 50 mm for the block and MOSTAP<sup>®</sup> specimens respectively, was trimmed to a height diameter ratio of about 1.8. A cell pressure of  $0.5\sigma_{v0}$  (total in situ vertical stress) was applied and the initial effective stress or suction ( $u_r$ ) was measured. Initially some isotropic consolidation was carried out at an effective cell pressure of  $0.6 \sigma'_{h0}$  before slowly applying the in situ stress.  $K_0$  was assumed to be equal to 0.6 from Brooker and Ireland<sup>17</sup>. The final consolidation stresses are kept constant until the rate of volumetric strain is less than 0.0001% per minute. Shearing was carried out at the slow rate of 4.5% per day. Corrections were applied for the restraining effects of the membrane and filter paper.

### 4.2 Oedometer tests

In order to attempt to accurately define the preconsolidation stress, “gentle” load increments to  $0.25\sigma'_{v0}$  (the in situ vertical effective stress),  $0.5\sigma'_{v0}$ ,  $0.75\sigma'_{v0}$ , and  $1.0\sigma'_{v0}$  were initially used. Twenty-four hour maintained load stages were employed. Otherwise the procedures used were again broadly those adopted as standard by NGI (Sandbækken *et al.*<sup>18</sup>). Piston tube specimens were extruded directly into 100 mm

diameter oedometer rings. Block and MOSTAP<sup>®</sup> specimens were trimmed, using a thin piano wire, slightly greater than 100 mm and 50 mm diameter respectively prior to slowly pushing in a lubricated oedometer ring.

## **5. SITE CHARACTERISATION**

### **5.1 Geology and ground conditions**

The soft soils at Athlone are glacial lake deposits, which were laid down during the retreat of the glaciers at the end of the last ice age some 10,000 to 20,000 years B.P. Two distinct strata were formed, as can be seen on Fig. 2. The lower soils are very soft brown horizontally laminated (varved) clays and silts with clearly visible partings typically 1 mm to 2 mm thick (see Fig. 3). These deposits are the subject of this paper and are referred to as the brown laminated clay. The varving is not always as clear as shown on Fig. 3. Occasionally, and particularly towards the top of the stratum, the clay has a more homogeneous appearance.

As the climate became warmer, the depositional environment changed and the upper soils show only some signs of varving and have an increasing organic content. The material deposited under these conditions is homogenous grey organic clay and silt. These glacial lake bed clays are overlain by thin layers of calcareous marl and peat. The water table is located close to ground level.

The stratigraphy of the site is also confirmed by the results of two piezocone (CPTU) tests carried out adjacent to the block sampling (Figure 2). In the brown laminated clay CPTU  $q_{net}$  values are very low at about 0.20 MPa with a gradual increase with depth to about 0.6 MPa, particularly below 10.5 m.

### **5.2 Basic material parameters**

Basic material properties, from the Sherbrooke block samples only, are shown on Fig. 2. The brown laminated clay has average moisture content of 40% and bulk

density of about  $1.9 \text{ Mg/m}^3$ . Clay content and total fines content are about 35% and 95% respectively. It has average liquid limit ( $w_L$ ) and plasticity index ( $I_p$ ) of about 45% and 18% respectively, thus placing it close to but above the “A” line and within the classification “clay of medium plasticity” on a standard plasticity chart. Values of  $w_L$  are often close to the natural water content and the average value of the liquidity index is about 1.0.

As described above, unfortunately the 5° samples were recovered from a location 110 m west of all the other sampling and testing. This location is further away from the lake centre and thus the deposits are slightly coarser having average clay content of about 25% and average  $I_p$  of 12% (Long and O’Riordan<sup>13</sup>)

The basic material parameters presented on Fig. 2 were measured on bulk triaxial or oedometer specimens and the scatter is due to the varved nature of the material. However, the material is relatively uniform on a macroscopic scale, as evidenced by the CPTU tests. Nonetheless, in order to minimise any effects of natural material variability, laboratory tests specimens were chosen to be as large as possible (e.g. 100 mm diameter for triaxial testing).

### **5.3 Undrained strength**

Vane strength data at the location of the block sampling and CPTU testing are plotted on Fig. 2. Data were obtained from a 150 mm by 75 mm Farnell field vane (tests carried out during shell and auger drilling), a 38 mm diameter hand Torvane at the base of piston samples and by using a 26 mm by 13 mm lab (“motor”) vane on piston samples. In all three cases the rate of rotation was between 5° / min. and 9° / min with only a short delay between insertion and testing. All gave similar undrained strength results ( $s_u$ ) of about 5 kPa, values which are well below the typical strength of  $0.3\sigma'_{v0}$  for normally consolidated clays. It was felt that these low values may have

been due to borehole base instability and some field penetration vane tests, where no borehole was necessary, were carried out at another location on the site (Long and O’Riordan<sup>12</sup>). Again similar results were obtained and it was concluded that the low values were due to vane insertion disturbance effects. In contrast CAUC triaxial strength data fall on or close to the  $0.3\sigma'_{v0}$  line.

#### **5.4 Hydraulic conductivity / permeability**

The degree of anisotropy of permeability of varved clays has a strong influence of their behaviour. Horizontal permeability ( $k_h$ ) measured from in-situ constant head and rising head permeability tests, where the length to diameter ratio of the permeable response zone was about 3, gave values in the range 1 to  $4 \times 10^{-9}$  m/s. Triaxial permeability tests on specimens orientated both horizontally and vertically, together with results from oedometer tests suggest the material exhibits a small anisotropy ratio ( $r_k = k_h / k_v$ ) of perhaps 1.5. Given the visibly varved nature of the material this value appears surprisingly low. However it is consistent with the findings of other researchers, e.g. Leroueil *et al.*<sup>19</sup>, who found that the Bothkennar clay had  $r_k$  values in the range 1 to 3 but more typically 1 to 1.3, despite the presence of laminated zones.

#### **5.5 Sensitivity and structure**

According to Hight *et al.*<sup>4</sup>, the degree to which a natural clay is structured can be characterised in terms of state, by comparing void ratios of the natural clay and the reconstituted clay under the same stress, or by strength, by comparing the strength of intact or remoulded soils, e.g. by sensitivity  $S_t$ . Some 1D oedometer tests for a block and 30° tube sample of Athlone clay are compared with the intrinsic compression curve on Figure 4. This latter curve was obtained using the procedure of Burland<sup>20</sup> by reconstituting the material at  $1.5w_L$ . Also shown on the plot are similar data for Norwegian Onsøy clay (tests carried out by the author and reported in Lunne *et al.*<sup>21</sup>).

In both cases it can be seen that the plot for the block sample lies above the intrinsic compression curve but that the tube sampling has destructured the material causing the plot to lie closer to and eventually converge with the intrinsic compression curve.

Field vane and cyclic T-bar testing (Long and O’Riordan<sup>13</sup>, Long and Gudjonsson<sup>22</sup>) suggest that the Athlone material has  $S_t$  in the range 2.0 to 2.5. However these authors argue that disturbance due to insertion of the device gives intact strength, which is too low, thus leading to reduced  $S_t$  values. Correlation with liquidity index suggests  $S_t$  should be in the range 4 to 10. Similar values are obtained from piezocone friction readings. Nevertheless despite uncertainty in the actual value of  $S_t$ , the material is clearly structured, albeit to a lower degree than Onsøy clay, which has field vane  $S_t$  in the range 6 to 8. Thus both materials are susceptible to destructureation by tube sampling as can be seen in Figure 4.

## **6. ANALYSIS OF TRIAXIAL TEST RESULTS**

Three sets of CAUC tests were carried out as follows:

- Set 1: Thirteen tests to examine effect of sampling (4 on block, 4 on 30° tubes, 3 on 5° tubes and 2 MOSTAP<sup>®</sup>). Results of these tests are summarised on Table 2.
- Set 2: Three additional tests on block samples to examine effects of increasing tube sampling strains (i.e. ISA approach from Santagata and Germaine<sup>12</sup>), Table 3.
- Set 3: Five additional tests on 30° tubes to examine the effects of rate of sampling tube insertion (Table 4).

### **6.1 Residual (or initial) effective stress (Sets 1 to 3)**

Many researchers (e.g. Ladd and Lambe<sup>23</sup> and Hight *et al.*<sup>4</sup>), have studied the residual effective stress ( $u_r$ ) in the specimens in order to assess sample quality. Values of  $u_r$  recorded in this study were generally very low (typically 2 kPa to 4 kPa), with an overall pattern of a decrease with depth and with some evidence of slightly higher

values being recorded in the block samples. These low values are consistent with occasional sample distortion and lack of coherence observed during specimen preparation in the laboratory. It is possible to explain these results by reference to the material's laminated nature in which the silt seams gave up water to the surrounding clay and desaturate leading to low values of  $u_r$ . In addition the relatively large silt content will mean that sustainable suction following stress relief will be low. (Note that B values for all the samples were close to 1.0).

## **6.2 Volumetric strain and normalised void ratio change during consolidation (Sets 1 to 3)**

Much recent research into sample quality has made use of either the volumetric strain ( $\Delta V/V_0$ ) or the normalised void ratio change ( $\Delta e/e_0$ ) required to reconsolidate the sample anisotropically to the in situ effective stress ( $\sigma'_{h0}$ ,  $\sigma'_{v0}$ ). Measured values can then be compared to published criteria, such as those of Kleven *et al.*<sup>24</sup> or Lunne *et al.*<sup>3</sup>, as shown on Figure 5. This technique and the corresponding criteria was developed for uniform marine clays and its application to laminated clays therefore needs to be treated with caution. However the following general trends can be inferred from these data:

- On average the block samples show the highest quality with average values of 4.3% and 0.09 respectively.
- The 5° tube specimens show similar quality (average values 4.0% and 0.1), followed by the 30° tube specimens (5.9%, 0.137).
- The MOSTAP<sup>®</sup> samples are worst (7.8%, 0.167).
- Some evidence that sample quality decreases with depth.

### 6.3 Undrained stress - strain behaviour – selected tests from Set 1

Normalised deviator stress / strain plots for four selected tests for which the basic material properties are similar are shown on Figure 6. There is a significant difference in behaviour between the tube samples and the block samples. It can be seen that the 30° and 5° specimens appear more ductile with peak strengths occurring at about 6% strain and with only a moderate degree of strain softening post peak. Behaviour of the block samples is quite brittle, with peak strength occurring at less than 1% strain and with considerable strain softening being evident. The MOSTAP<sup>®</sup> test result shows clear evidence of disturbance.

### 6.4 Undrained stress paths – tests Set 1

Normalised stress path plots for all the Set 1 tests are shown on Figure 7. (The data have been normalised by the in-situ mean effective stress  $s'_0 = (\sigma'_{h0} + \sigma'_{v0})/2$ ). According to Lunne *et al.*<sup>3</sup>, for a “perfect” specimen, pre-peak, in which there is minimum plastic volumetric strain, the initial stress path (plotted in  $s'$ ,  $t'$  space as here) slope will be 1 horizontal to 3 vertical. Most of the test results, in particular those of the block samples, initially follow his pattern and exhibit some slight structure.

Subsequently all of the tests show some evidence of contractive behaviour. For the block sample specimens this contractive behaviour continues until critical state conditions are reached and the result is typical of normally consolidated clay. However there is a marked difference in the behaviour of the tube specimens in that post-peak there is a strong tendency for dilative behaviour, with that for the 5° specimens being even more marked than for the 30° samples. The MOSTAP<sup>®</sup> test results are erratic.

A line representing a Mohr-Coulomb strength of  $\phi' = 36^\circ$  and  $c' = 0$  (critical state line for the block samples) has also been plotted on Figure 7. Stress paths for three of the four block sample tests ultimately fall on this line. Two of the four  $30^\circ$  tests and two of the three  $5^\circ$  tube tests show stress paths above this line, suggesting densification has taken place. Both MOSTAP<sup>®</sup> results show erratic behaviour. It would seem they have been severely destructured and loosened. This is possible with the MOSTAP<sup>®</sup> technique as the sample diameter is less than that of the protective plastic lining.

### **6.5 Other parameters measured in CAUC triaxial tests**

Average values for various other parameters measured in all of the triaxial tests are summarised on Table 5. The difference between strain to peak deviator stress ( $\varepsilon_f$ ) for the block samples and the others is striking. Average (CAUC)  $\varepsilon_f$  for the block sample specimens is only about 1.7% (and for three of the tests is less than 1%), with all of the other tests showing an average of more than 6%.

Average secant stiffness values ( $E_{sec}$ ) at 0.01% strain show considerable variability, with the block samples show the lowest average stiffness. Stiffness values were determined using local strain measurements with Hall effect gauges. Any errors resulting from the measurement system are significantly less than the differences in results from the various sampler types.

Average values of normalised undrained shear strength ( $s_u/\sigma'_{v0}$ ) for the block samples are lower than those determined from other specimens.

Skempton's pore pressure coefficient  $A_f$  (i.e. at peak deviator stress) for block samples are higher than those determined by the other techniques. On average a value of 0.9 was recorded for the block samples. According to Head<sup>25</sup>, this value is typical for sensitive clay.

## **6.6 Conclusions from CAUC tests Set 1**

From the results of the CAUC tests presented above it was concluded that both destructuration and densification effects had occurred during the tube sampling. Because of the laminated nature of the material, it is possible that sample tube insertion is a partially drained process. This would result in drainage of excess pore pressure from the silt layers during tube insertion, causing a contraction of these layers with a corresponding densification of the material. It was subsequently decided to investigate these effects by two further series of tests as follows:

## **6.7 Investigation of the effect of undrained tube sampling strains (Set 2)**

Theoretical work at the University of Surrey (Clayton and Siddique<sup>26</sup>) showed that strain induced during tube sampling is very sensitive to the sampler geometry, in particular the cutting edge angle. For conventional ELE type piston tube samplers, with no inside clearance, there are no extension strains induced as the sample enters and moves up inside the tube. Maximum compression strains were estimated to be about 0.6% for tubes with a sharpened 5° edge and more than 1% for the more usual tube with a 30° edge.

In this study the “ideal sampling approach” (ISA) was used to study the effects of tube sampling by initially imposing compressive axial strains (of 1%, 1.48% and 2.38% as measured using local transducers) on block sample specimens, and then subsequently reconsolidating and shearing them to failure. Details of the tests together with some results are given on Table 3. A typical result from the earlier study (cu100b26) is also given on the table for comparison.

Stress path plots for the initial compression and final shearing are shown on Figure 8. In the first instance it can be seen clearly that the contractive material behaviour in the new tests is as reported for the other block sample tests above. Also

it can be seen from Figure 8 and from Table 3 that the material behaviour in the final shearing is more or less identical to that during initial compression and that there is little effect on the measured parameters. Despite the stress state at the end of the initial compression corresponding to failure on the Mohr–Coulomb line, the reconsolidation process is sufficient to permit the sample to recover its original behaviour.

It may be concluded then that the difference in results between the block and tube samples is not mainly due to the effect of undrained tube sample strains.

### **6.8 Investigation of rate of insertion of tubes (Set 3)**

If the tube insertion process is partially drained, then the rate at which the tube is inserted should influence the quality and state of the specimens. In order to investigate the tube insertion rate effects, a further exercise was carried out in May 2001, in which conventional ELE piston tubes (with 30° cutting edge angles) were pushed into the stratum at different rates. The same drilling crew and technique was used in this study as in the earlier work and the borehole was drilled within 5 m of the Sherbrooke block sample hole. Tubes, 100 cm long, were pushed in at rates varying between 2.1 cm/min and 53.3 cm/min. These rates were the minimum and maximum it was possible to achieve. In conventional practice, and in the previous sampling exercise, tubes are inserted at rates close to the higher value achieved here.

Subsequently simple hand calculations using radial drainage theory, with a  $c_h$  value of about 100 m<sup>2</sup>/year for the silt lenses ( $k_h \approx 1 \times 10^{-8}$  m/s and  $M \approx 2000$  kPa), suggests that the degree of consolidation would be 30%, 50% and 70% after about 2, 5 and 11 minutes respectively. It is likely then that the range of tube insertion rates achieved on site was not sufficiently varied to permit significant difference in the response of the specimens. However this additional work provided a check on

whether the behaviour of the tube sample specimens noted in the first study was repeatable.

Stress path plots for these tests are shown in Figure 9 and a summary of the test results is given in Table 4. In the first instance it can be seen that all the stress paths extend above the characteristic Mohr-Coulomb failure line, of  $\phi' = 36^\circ$  and  $c' = 0$ , exhibited by the block samples, suggesting some densification has occurred in each case. However not all of the tests show post-peak dilatant behaviour. Tests 2 (the best test in terms of volumetric strain during consolidation) and 3 show contractant behaviour while the rest (including the worst 2 tests) show dilative behaviour. Inspection of Table 3 shows that the results are not related to rate of tube insertion but to whether the material contracted or dilated.

## **7. Analysis of oedometer test results**

Long<sup>23</sup> reports twenty MSL oedometer tests carried out on the brown laminated clay, i.e. five each from specimens from the four sampler types from the 1997 / 1998 works. In addition three extra tests were carried out on 30° sample tube specimens from the 2001 sampling exercise. For each sampler type the results were very similar and representative test results only are presented here.

### **7.1 Stress - strain behaviour**

A comparison of oedometer test  $\log \sigma'_{v0}$  – strain curves, for each of the sampler types are shown on Figure 10. The block sample stress – strain curve is of characteristic shape for a slightly structured material and allows a relatively easily definition of yield (or preconsolidation stress,  $p'_c$ ). Although  $p'_c$  is not as well defined as for the block, the 30° tube sample test shows similar behaviour. It is recognised that as oedometer tests are on thin specimens, then variations in material type will strongly affect the results. In particular silty soils will give flatter curves.

Nevertheless, the curves from both other sample types are consistently flatter (i.e. higher stiffness both pre-yield and post-yield and it is difficult to determine  $p'_c$ ). Similarly the plots of constrained modulus,  $M$ , confirm that the block sample specimen gives the lowest stiffness value. This result for the MSL tests is consistent with average triaxial secant stiffness values ( $E_{sec}$ ) at 0.01% strain being lowest for the block samples.

## 7.2 Comparison with in situ behaviour

The block sample test result, presented above, is compared with some field compressibility data on Figure 11. These data were derived from magnetic extensometers placed at the top, middle and bottom of the laminated clay stratum. Only those data where a piezometer was also available to allow calculation of vertical effective stress are shown in the plot (Long and O'Riordan<sup>13</sup>, Long<sup>27</sup>). Post-yield stiffness for each of these data is very close to that given by the block sample specimen. It seems that tube sampling effects can densify the material thus leading to higher measured stiffness values.

## 8. Relationship between disturbance and measured parameters

The thesis presented in this paper is that tube sampling in medium plasticity silt / clay can increase triaxial  $E_{sec}$  (at small strain), oedometer  $M$ ,  $s_u$  and  $\varepsilon_f$  and reverse the undrained stress path. If these findings are truly due to sampling effects and not due to other influences such as natural material variability, then there should be a systematic variation between the degree of disturbance and the parameters measured. It is difficult to quantify disturbance and the dangers in using a parameter such as  $\Delta e/e_0$  have been discussed above. Nonetheless this parameter can be easily determined and in the absence of another more reliable parameter it is used in the following study.

Plots of  $s_u$ ,  $\varepsilon_f$  and  $C_c/1+e_0$  against disturbance, characterised as  $\Delta e/e_0$ , are shown on Figure 12. There is a tendency of increasing  $s_u$  and  $\varepsilon_f$  with increasing disturbance.  $C_c/1+e_0$  values seem to decrease with increasing  $\Delta e/e_0$ , i.e. trend of increasing stiffness. Despite the scatter there seems to be a systematic relationship between disturbance and these parameters, suggesting that the tube insertion process altered the initial state of the soil by densification due to partial drainage through the silt lenses.

## **9. Quality of 30° and 5° piston tube samples**

It is evident from the data presented above and especially from Figures 6 and 10, that contrary to expectations, the quality of the 5° piston tube samples is probably worse than the 30° specimens. This would be a very surprising result if destructurement effects only were relevant. However here densification effects are probably dominating over destructurement effects. As the material at the location of the 5° sampling (lower  $I_p$  and clay content than at the main trial area) is more susceptible to densification then these samples are of poorer quality.

## **10. Comparison with other soils**

A summary of pertinent soil parameters for the Athlone soils, the other “intermediate” soils, which were discussed in Section 1.1, and a number of other well characterised clays is given on Table 1. The soils have been subdivided into those which can show dilative behaviour on shearing and those which are contractive even if poor samples were (deliberately) obtained. Examples of the latter are open drive Shelby tubes in the case of Ariake clay and 54 mm tube samples with an inner plastic liner in the case of Onsøy clay.

All of these soils possess structure to some degree and some, in both categories, are very sensitive or quick. It would seem then that the main cause of the dilative behaviour is densification rather than destructuration. A comparison of the two sets of soils confirms that dilative behaviour occurs for the soils with lowest clay content and  $I_p$ . It is tentatively suggested that if the clay content is less than about 40% or  $I_p$  is less than about 20%, poor quality sampling may induce densification effects and subsequently give unconservative design parameters. Permeability also clearly plays a role, especially when the soil is anisotropic.

## 11. Conclusions

1. This work confirms that poor quality tube sampling does not necessarily yield parameters which lead to conservative designs. It was found that tube sampling in a laminated clay / silt, can cause material densification and destructuration, resulting in higher strength and stiffness values than those in situ. This work confirms the findings of a small number of others who showed similar effects in silty or laminated soils.
2. Careful assessment needs to be made of laboratory tests on tube samples in soils where the clay content is less than 40% or the  $I_p$  is less than 20%.
3. In particular it was found that for the natural Athlone laminated clay, which was the subject of this study, tube sampling disturbance leads to:
  - an increase in small strain stiffness ( $M$ , and  $E_{sec/0.01\%}$ ), see Table 5
  - an increase in the undrained strength and the strain to peak,
  - a reduction in the pore pressure coefficient,  $A_f$ ,
  - and a strong tendency for dilatant behaviour post peak.
3. Results of tests in which theoretical tube sampling strains were imposed on block samples (ISA approach), together with the finding that a piston sampler with a  $5^\circ$

cutting edge in a slightly siltier soil gave poorer samples than those from a sampler with a 30° angle, showed that undrained tube sampling strains have only a minor influence. It is likely then that the behaviour is mostly caused by densification during a partially drained sampling process.

4. Care needs to be taken when using well established criteria for assessing sample disturbance in clays, such as  $\Delta V/V_0$  or  $\Delta e/e_0$  during reconsolidation to in situ stress, in laminated or silty soils. They may give information on general trends but should not be used in isolation.

## **Acknowledgments**

The author is grateful to Mr. Tom Lunne of NGI for assistance with both field and laboratory work associated with the Sherbrooke block samples and to Dr. David Hight of Geotechnical Consulting Group, London who reviewed the data and provided some useful insights. George Cosgrave of UCD assisted with the laboratory testing.

## **Notation**

- $A_f$  Skempton's pore pressure coefficient (at peak deviator stress) related to change in deviator stress
- $B$  Skempton's pore pressure parameter related to change in isotropic stress
- $c_v$  coefficient of consolidation (h / v refer to horizontal and vertical directions)
- $e_0$  initial void ratio
- $E_{sec}$  secant Young's modulus
- $I_p$  plasticity index
- $k$  coefficient of permeability (h / v refer to horizontal and vertical directions)
- $K_0$  ratio of horizontal to vertical in situ effective stress  $\sigma'_{h0} / \sigma'_{v0}$

M	constrained modulus in oedometer test
$p'_c$	preconsolidation pressure
$q_c$	piezocone cone end resistance
$q_{net}$	piezocone net end resistance = $q_t - \sigma_{v0}$
$q_t$	corrected piezocone end resistance
$r_k$	anisotropy of permeability = $k_h / k_v$
$s'$	mean effective stress = $(\sigma'_a + \sigma'_r) / 2$
$s'_0$	in situ mean effective stress = $(\sigma'_{h0} + \sigma'_{v0}) / 2$
$s_u$	undrained shear strength
$t'$	shear stress = $(\sigma'_a - \sigma'_r) / 2$
$u_r$	initial (or residual) effective stress
$V_0$	initial volume
w	natural moisture content
$w_L$	liquid limit
$\epsilon_f$	strain at peak in triaxial test
$\phi'$	effective friction angle
$\gamma_b$	bulk unit weight
$\rho_b$	bulk density
$\sigma'_a$	axial effective stress in triaxial test
$\sigma'_{h0}$	in situ horizontal effective stress
$\sigma'_r$	radial effective stress in triaxial test
$\sigma_{v0}$	in situ vertical total stress
$\sigma'_{v0}$	in situ vertical effective stress
$\Delta e_0$	change in initial void ratio

$\Delta V_0$  change in initial volume

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**Table 1.** Summary of soils considered

Soil	Clay (%)	Silt (%)	$I_p$ (%)	$S_t$ (Fall cone)	Permeability (m/s)	Reference
<u>Soil which can show dilative behaviour on shearing</u>						
Athlone – Main trial	35	60	18	Section 5.5	$k_h: 1-4 \times 10^{-9}$ $k_h/k_v: \approx 1.5$	13, 22, 27
Athlone – C (5° samples)	25	65	12	Section 5.5	$k_h: 1-4 \times 10^{-9}$ $k_h/k_v: \approx 1.5$	13, 27
Bothkennar laminated	15-30	60-75	20-40	9.5 - 15	$k_h: 2 \times 10^{-9}$ $k_h/k_v: \text{up to } 5$	7, 8
Eidsvold	37-48	47-58	13-19	2-5		9
Kvenild	42		6-10	70		10
“lean” Drammen	40	60	10-20	5 - 7		3
<u>Soils which always show contractive behaviour on shearing</u>						
Bothkennar bedded	19-30	65-76	30-50	8	$k_h: 1.6 \times 10^{-9}$ $k_h/k_v: 1.2$	4, 8
Onsøy	60	40	30-50	4-6	$1 \times 10^{-9}$	2, 3, 21
Louiseville	75-80	20-25	40	> 20	$k_h: 1.4 \times 10^{-9}$ $k_h/k_v: 1.2$	1, 6, 15
Ariake	58	42	50-70	25		5

**Table 2.** CAUC triaxial tests to examine effect of different samplers (Set 1)

Test number	Depth (m)	$w_i$ (%)	$\rho_{bi}$ (Mg/m <sup>3</sup> )	$\Delta V/V_0^*$ (%)	$\varepsilon_f$ (%)†	$E_{sec}$ ( $\varepsilon$ =0.01%)	$s_u/\sigma'_{v0}$	$A_f$ †
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									(MPa)
<b><u>Block</u></b>									
cu100b26	6.9	31	1.945	3	0.7	100	0.44	1	
cu100b27	7.8	42	1.903	5	5	135	0.35	0.8	
cu100b28	8.5	54	1.814	3.6	0.3	80	0.36	1.1	
cb100b1	6.9	31	2.035	1.7	0.6	70	0.39	0.6	
<b><u>30° tube</u></b>									
cu100b3	8.3	34	1.946	7.0	5.3	190	0.39	1.2	
cu100b20	9.5	25	2.068	5.2	5.4	140	0.36	1.5	
cu100b21	9.5	27	2.099	5.8	6.5	220	0.44	0.9	
cu100b25	7.2	29	2.008	2.7	5.8	300	0.53	0.3	
<b><u>5° tube</u></b>									
cu100b22	11.2	32	2.044	5.6	8.3	250	0.52	0.3	
cu100b23	11.0	31	2.180	3.7	5.8	350	0.39	0.6	
cu100b24	9.65	25	2.072	2.7	6.3	128	0.58	0.4	
<b><u>MOSTAP®</u></b>									
cu50b1	9	28	1.985	7.3	9.0	288	0.93	-0.63	
cu50b2	8	36	1.798	8.2	4.2	225	0.36	0.55	

\* volumetric strain during consolidation

†f refers to peak deviator stress

**Table 3.** CAUC tests used to investigate effect of tube sampling strains (ISA approach) – Set 2

Test	First	Depth	$w_i$	$\rho_{bi}$	$\Delta V/V_0^*$	$\varepsilon_f (\%)^\dagger$	$E_{sec} (\varepsilon)$	$s_u/\sigma'_{v0}$	$A_f^\dagger$
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number	strain (%)	(m)	(%)	(Mg/m <sup>3</sup> )	(%)		=0.01%)		
							(MPa)		
Cu100b26	0	6.9	31	1.945	3	0.7	100	0.44	1
Cb100b1	1	6.9	31	2.035	1.7	0.6	70	0.39	0.6
Cb100b4	2.38	7.3	48	1.843	2.6	1.0	50	0.49	0.8
Cb100b5	1.48	7.3	48	1.892	4.5	0.8	17	0.38	0.7

\* volumetric strain during first consolidation

†f refers to peak deviator stress during final shearing

**Table 4.** CAUC tests used to investigate tube insertion rates – Set 3

Test number	Insertion rate (cm/min)	Depth (m)	w <sub>i</sub> (%)	ρ <sub>bi</sub> (Mg/m <sup>3</sup> )	ΔV/V <sub>0</sub> * (%)	ε <sub>f</sub> (%) <sup>†</sup>	E <sub>sec</sub> (ε =0.01%) (MPa)	s <sub>u</sub> /σ'v0	A <sub>f</sub> <sup>†</sup>
Brown1	5.33	9.4	33	2.026	6	8.7	70	0.44	0.7
Brown2	53.33	8	32	1.943	2.6	1.4	50	0.37	1.0
Brown3	4.0	10.7	36	1.818	6.2	0.7	90	0.33	1.2
Brown4	2.1	12.1	29	2.014	6.8	8.2	100	0.42	0.7
Brown5	53.33	7.5	31	2.099	7.4	12.9	100	0.75	0.2

\* volumetric strain during consolidation

†f refers to peak deviator stress during final shearing

**Table 5.** Average measured values in CAUC triaxial tests

Property	30° tubes	5° tubes	MOSTAP <sup>®</sup>	Block
ε <sub>f</sub> (%)*	5.8	6.8	6.6	1.7

$E_{sec}$ ( $\varepsilon$ =0.01%) (MPa)	213	243	257	96
$s_u/\sigma'_{v0}$	0.43	0.50	0.65	0.39
$A_f^*$	1.0	0.4	-0.04	0.9

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\*f refers to peak deviator stress

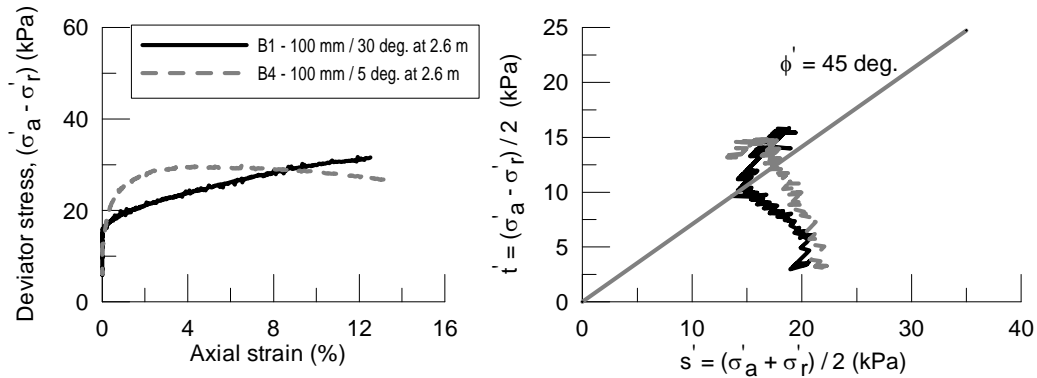
#### LIST OF FIGURES

Fig. No.	Caption	File Name*
1	Triaxial test results for various "intermediate" soils	D(S)/ICEGeoJnl/Bothkennaretc.xls+grf
2	Basic material properties	D(C)/Porto04/AthChar.grf+Athbasics,

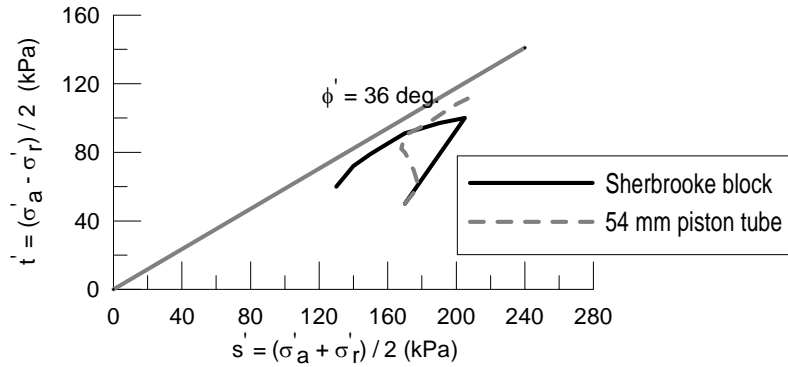
		Athsu,Athcptu.xls
3	Profile of brown laminated clay showing varving	C:/papers/geo/laminatedfig1.ppt
4	1D compression behaviour of Athlone and Onsøy clay	D(S)/ICEGeoJnl/Intrinsic.grf+.xls
5	Assessment of sample quality – triaxial tests	D(S)/ICEGeoJnl/Dele0triax.grf+.xls
6	Deviator stress – strain curves – CAUC tests Set 1	D(S)/ICEGeoJnl/Devstressstrain.grf+.xls
7	Stress path plots – CAUC tests Set1	D(S)/ICEGeoJnl/Stresspaths.grf+.xls
8	Stress paths for ISA tests (Set 2)	D(S)/ICEGeoJnl/isatests.grf+.xls
9	Stress paths for further tube samples (Set 3)	D(S)/ICEGeoJnl/ratestressps.grf+.xls
10	MSL oedometer test results	D(S)/ICEGeoJnl/oedcomp.grf+.xls
11	In-situ compressibility	D(S)/ICEGeoJnl/insitucomp.grf+oedcomp+.xls
12	Effect of disturbance on triaxial and oedometer test parameters	D(S)/ICEGeoJnl/Effectdisturbance.xls+Effectonsuandoedstiff.grf

\* Microsoft EXCEL<sup>®</sup>, POWERPOINT<sup>®</sup>, WORD<sup>®</sup> and Golden Software GRAPHER<sup>®</sup> used throughout.

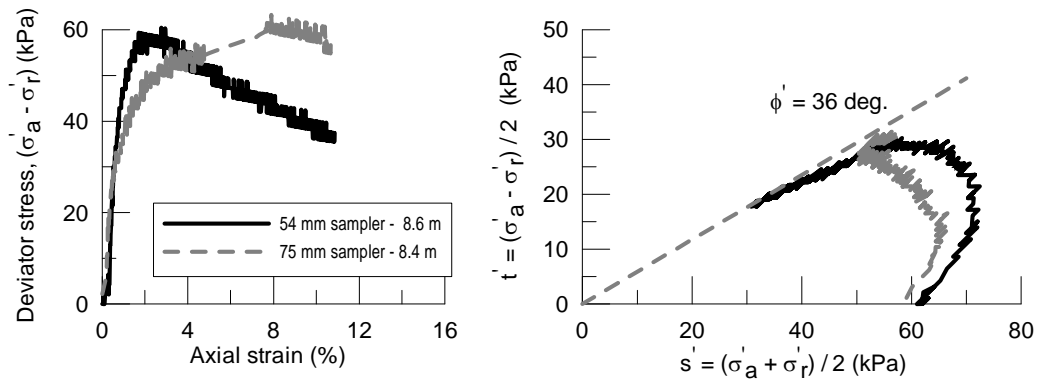
**Figures for paper:  
Sample disturbance effects on medium plasticity clay / silt by Michael Long, UCD.**



(a) Bothkennar laminated facies (Long 2003)



(b) Eidsvold clay (Karlsrud 1995 and Lunne et al. 1997)



(c) Kvenild quick clay (Seierstad 2000)

**Figure 1. Triaxial test results for various clays showing anomalous behaviour**

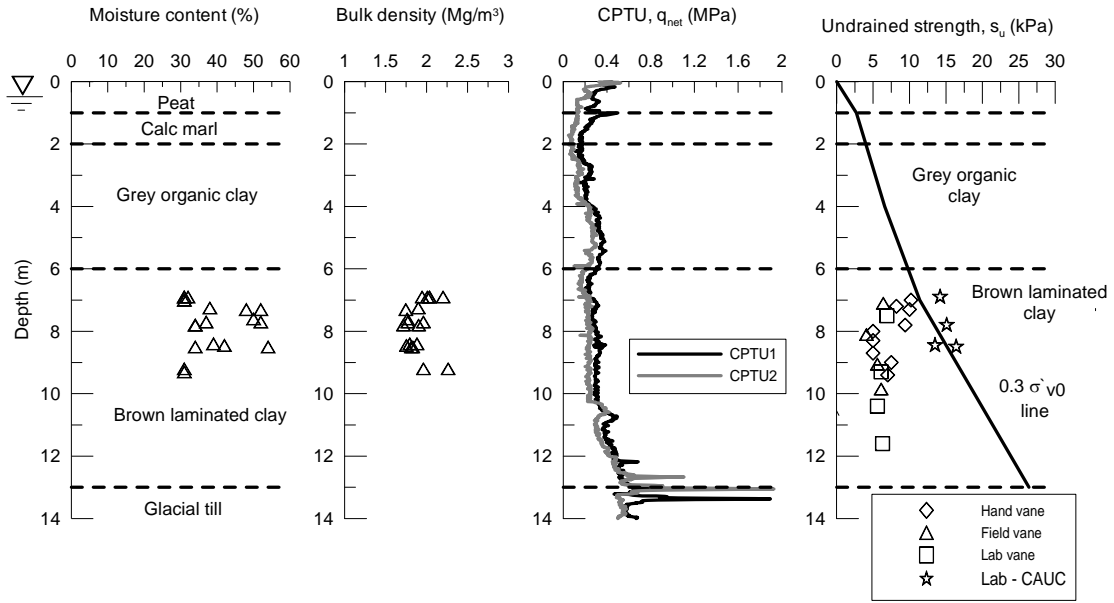
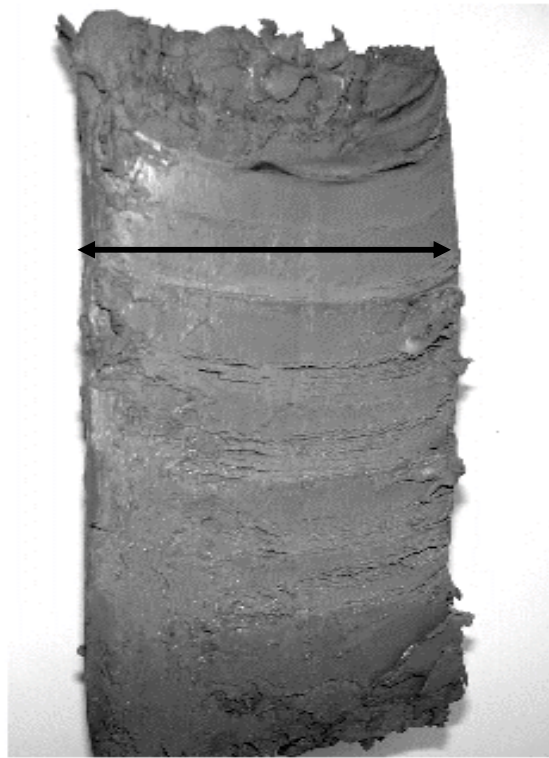
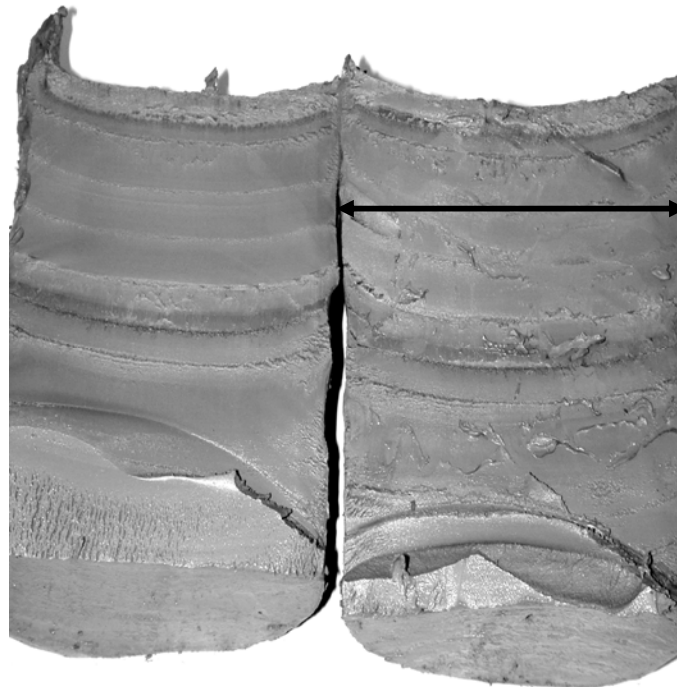


Figure 2. Material characterisation



View of perimeter  
of sample  
100 mm



100 mm

**View of sample cut  
and partially dried.  
Note distortions  
caused by tube  
sampling**

**Figure 3. Profile of laminated clay: BH 97/1 at 10.8 m**

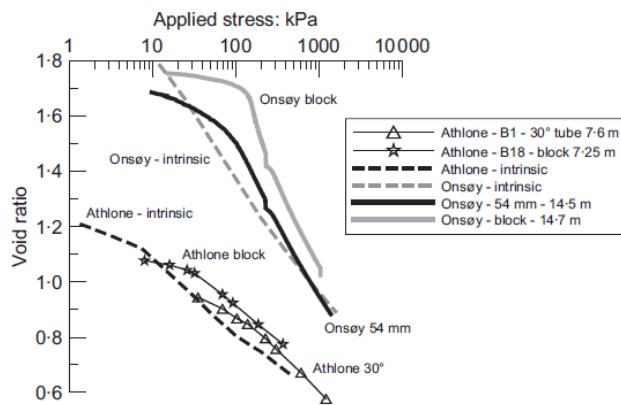


Figure 4. 1D compression behavior of Athlone and Onsøy clays

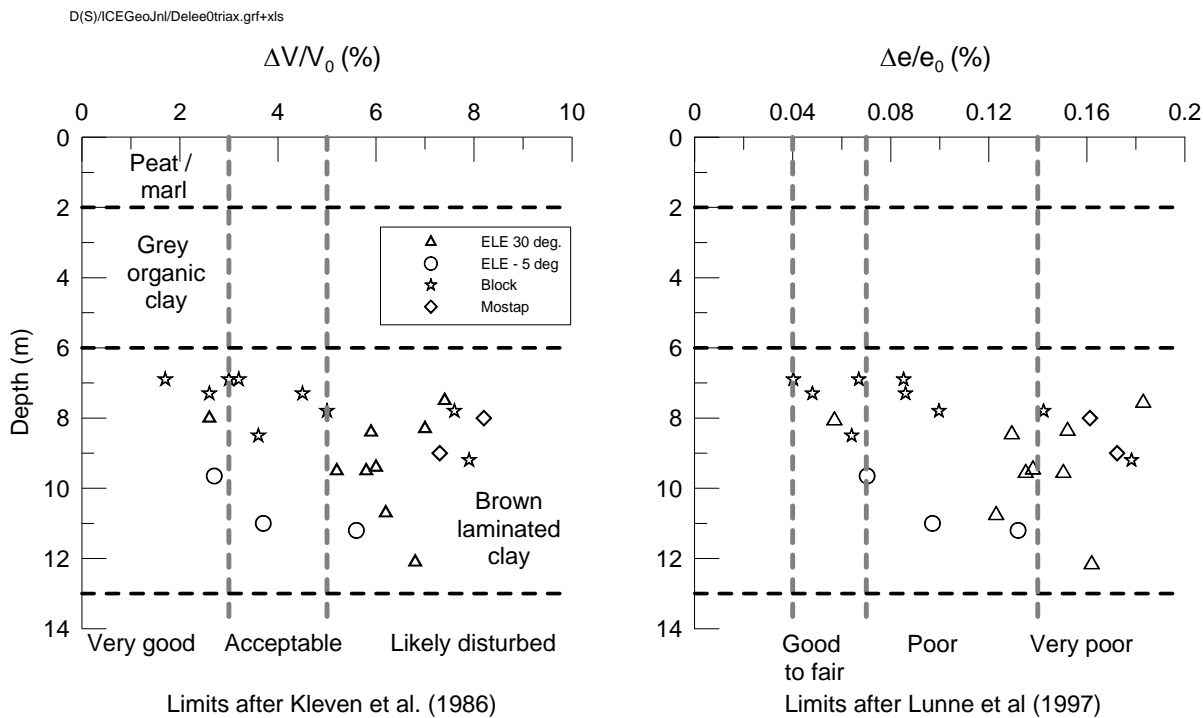


Figure 5. Assessment of sample quality for triaxial tests

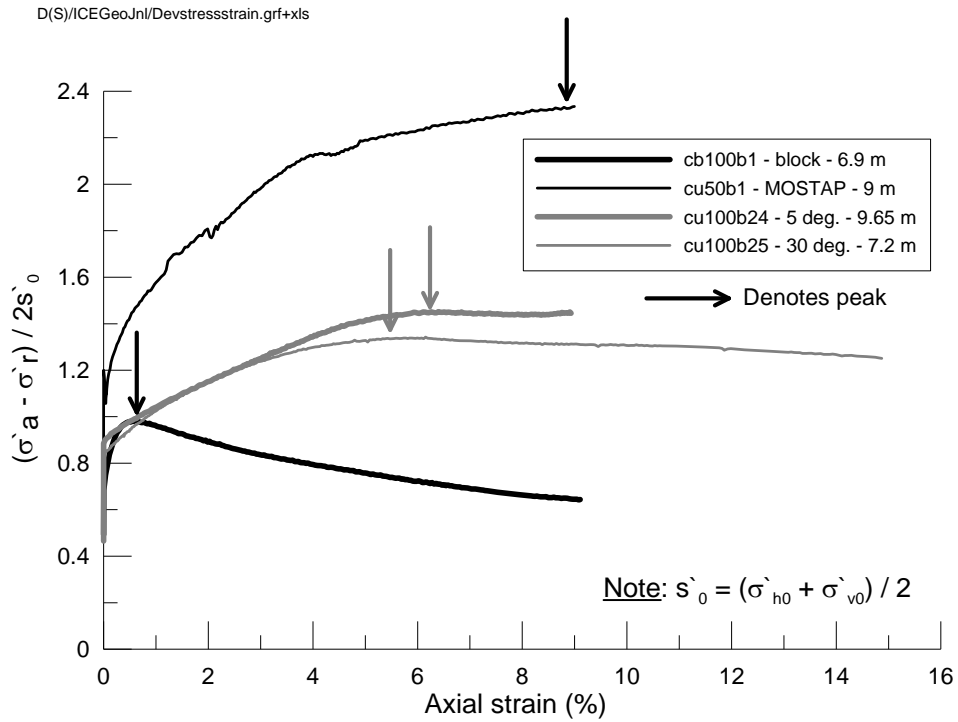


Figure 6. Deviator stress – strain curves – CAUC tests Set 1 |

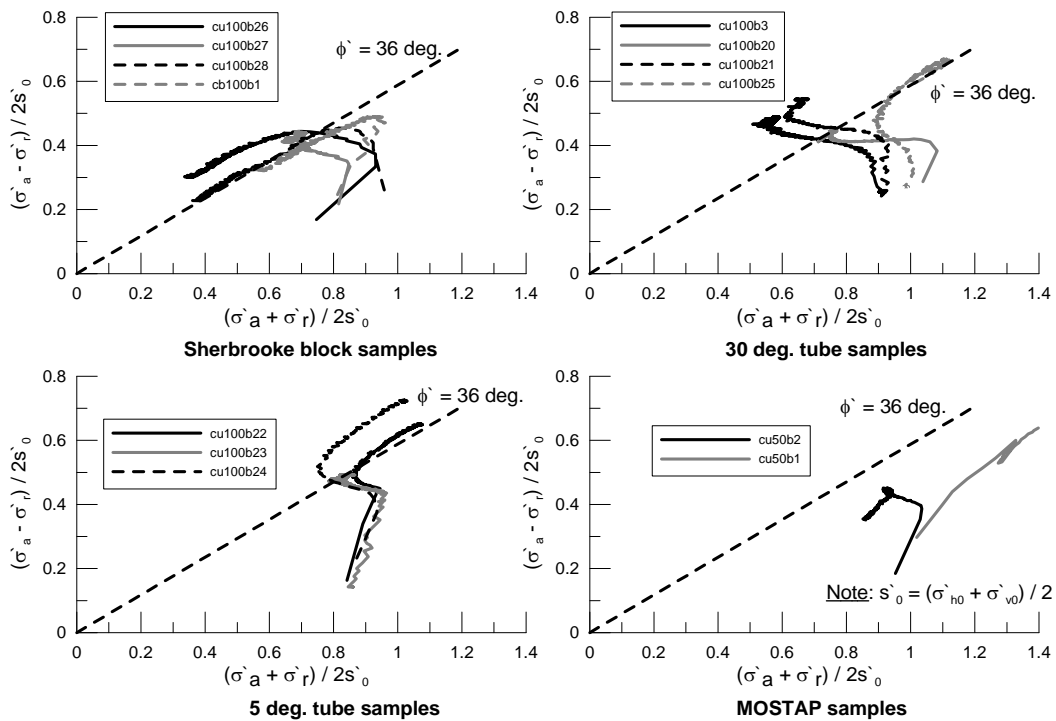
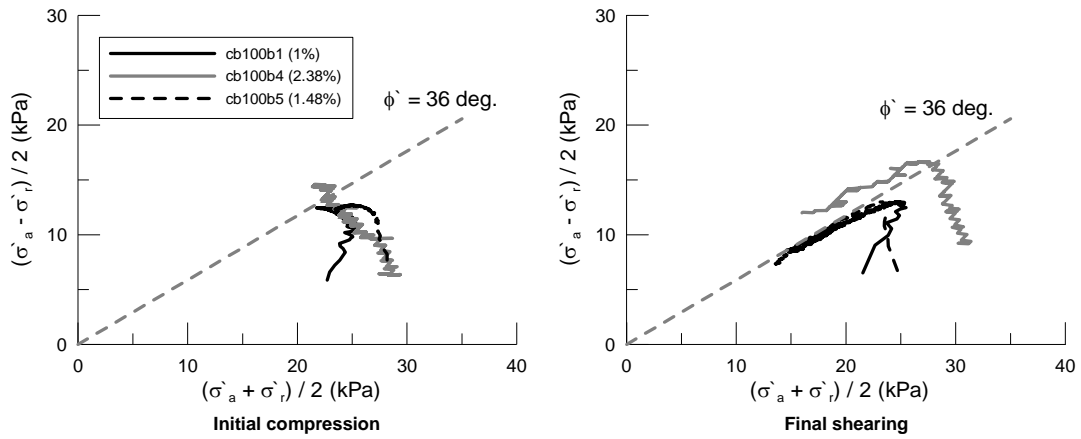


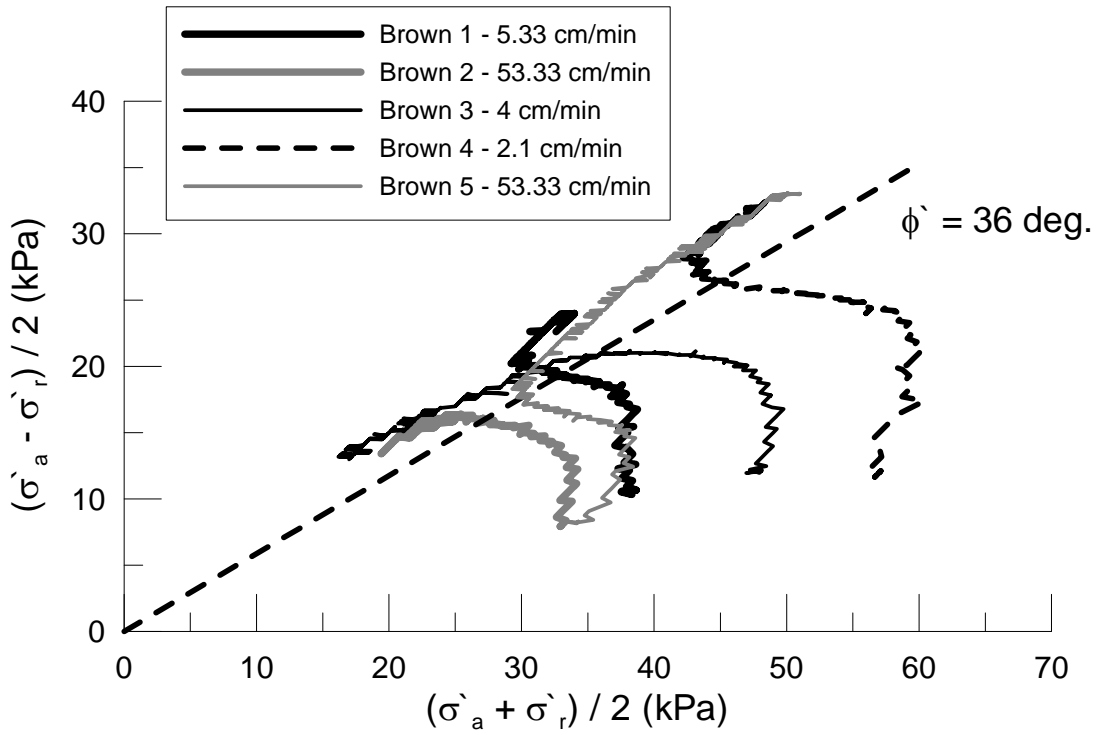
Figure 7. Stress path plots – CAUC tests Set 1

Fig



**Figure 8. Stress paths for ISA tests (Set 2)**

D(S)/ICEGeoJnl/ratestresspaths.xls+grf



**Figure 9. Stress paths for further tube samples (Set 3)**

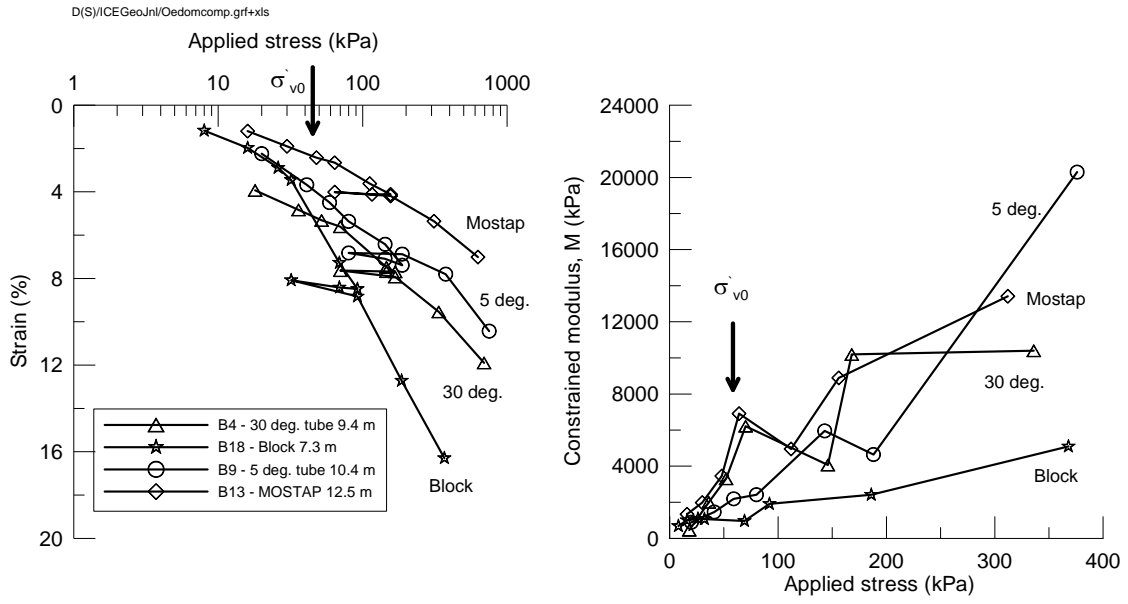


Figure 10. MSL oedometer test results

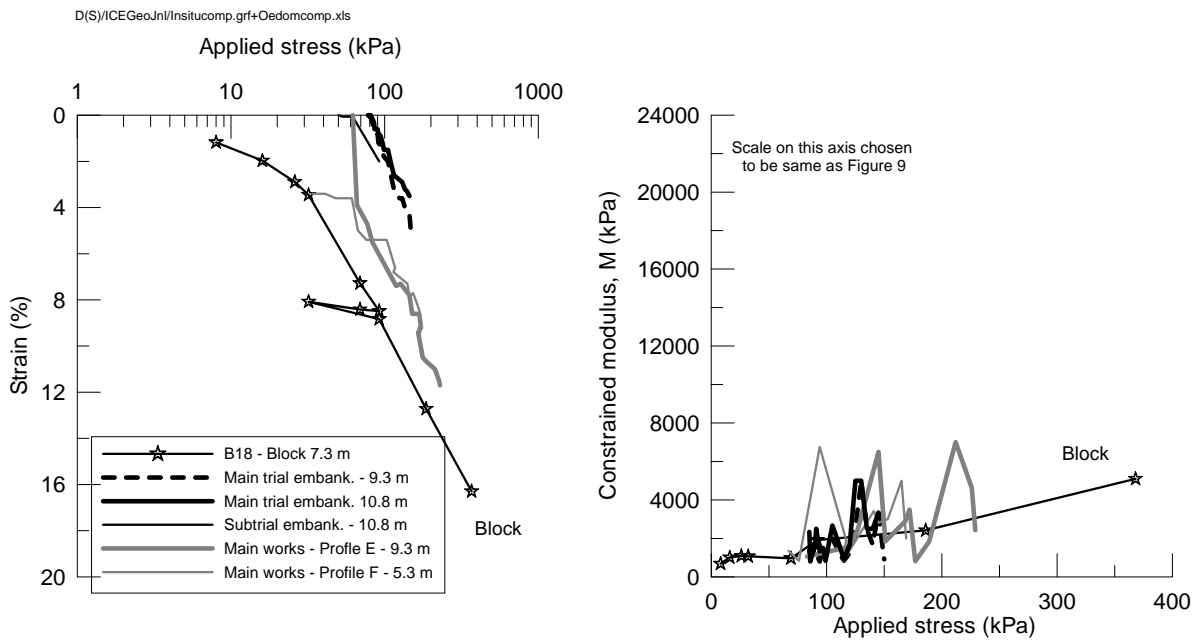
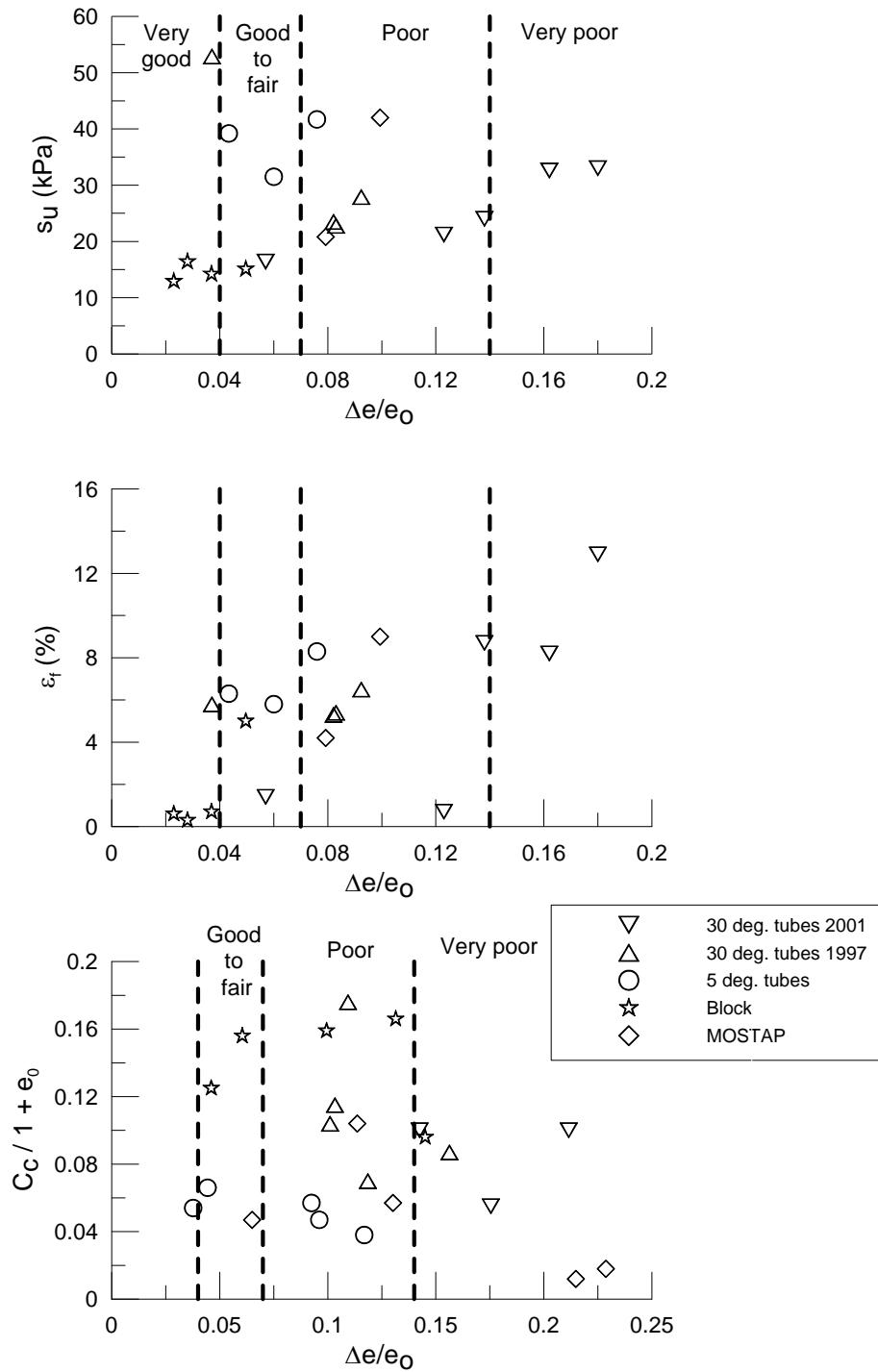


Figure 11. In situ compressibility



**Figure 12. Effect of disturbance on triaxial and oedometer test parameters (showing quality criteria of Lunne et al (1997))**