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**Title of Paper:** Sampling disturbance effects in the Bothkennar laminated facies

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## **Synopsis**

Sample disturbance effects in the laminated facies at the Bothkennar soft clay research site are examined by comparing the results of laboratory tests on specimens obtained from three fixed piston tube samplers. A significant feature of the results is that the sampling process associated with the conventional piston tube used in the UK and Ireland appears to increase the post yield stiffness and the CAUC triaxial undrained strength, reduce the preconsolidation stress, the pore pressure coefficient at failure and induce a strong tendency for dilatant behaviour post peak when compared to tests on specimens from a sampler with a modified (sharper) cutting edge angle. It is reasoned that these findings are caused by material destructuration during the sampling process with the conventional tubes. Increased densification of these specimens caused both by sampling and during anisotropic consolidation may also contribute to these effects. The results are supported by reference to recent analytical work and data for three other soils. It is recommended that the use of these conventional thin walled tubes with a crude cutting edge is abandoned and that some with improved cutting edge geometry replaces them.

## **Introduction**

The need to assess the degree of sample disturbance prior to interpretation of parameters derived from laboratory tests on soils is now well accepted. There are many studies reported in the literature on sample disturbance effects on soft to firm homogeneous compressible clays. Some examples are the classic papers of Lacasse et al.<sup>1</sup> and Lunne et al.<sup>2</sup> on Norwegian clays and Tanaka et al.<sup>3</sup> on Japanese clays. Hight et al.<sup>4</sup> described a similar study on the Bothkennar clay from the UK. Their focus was on the relatively uniform bedded and mottled facies at this site. There are very few examples of similar studies on sample disturbance effects on soft laminated clays.

In some recent theoretical work, Clayton et al.<sup>5</sup> and Clayton and Siddique<sup>6</sup> studied some different sampler geometries, which were meant to represent, amongst others, the standard open drive “U100” tubes and the ELE 100 mm fixed piston sampler which are both commonly used in the UK. The results of this work suggested that, if the ELE tube cutting edge angle was reduced from the standard 30° to 5°, axial compressive strains due to the sampling process would be much reduced and tensile strains would be eliminated completely.

Hight and Leroueil<sup>7</sup> and Hight et al.<sup>8</sup> further studied these effects by comparing laboratory test results for parallel samples for Bothkennar clay (not the laminated facies) and a site at Port Said in Egypt. In the case of the Bothkennar clay, the modified tube performed as well as the high quality Sherbrooke block sampler. For the Port Said site, significantly higher quality samples were also obtained from the modified ELE sampler and it was possible to justify more optimistic design parameters which ultimately led to cost savings in the project.

Non-homogeneous “mixed” deposits are frequently encountered in the UK, Ireland and elsewhere. The main objective of this work is to extend the experience mentioned above for relatively uniform soils to the Bothkennar laminated facies. This is achieved by comparing the results of laboratory tests on samples recovered using the standard 100 mm diameter ELE fixed piston sampler (30° cutting edge angle), the modified ELE sampler (5° angle) and a specially constructed large (210 mm) diameter fixed piston sampler.

### **Geological background**

Work at the UK’s Science and Engineering Research Council (now Engineering and Physical Sciences Research Council) soft clay test site at Bothkennar in Scotland is well documented, particularly in *Geotechnique*, Volume 42 from 1992. Hight et al.<sup>9</sup> identified three principal units at Bothkennar, namely the bedded, mottled and laminated facies. Nash et al.<sup>10</sup>, mostly using the results of piezocone penetration tests, showed that the laminated facies, which they described as a highly laminated silty clay, was mostly confined to the south-eastern corner of the site and extended to a maximum depth of about 7 m (-4.3 mOD). Hight et al.<sup>9</sup> and Paul et al.<sup>11</sup> summarise the depositional environment as being in relatively sheltered and, therefore, quiet, saline or brackish water, between 7 m and 20 m deep. A local more energetic environment, perhaps associated with a subtidal channel in water depths of a few metres, would have been associated with the laminated facies. It consists of individual beds of silt / clay, separated on their bedding surfaces by silt laminae or partings and dustings of silt.

No attempt was made in this earlier work to separate the individual layers for geotechnical testing. Material properties, as measured on bulk samples from the

laminated facies, are summarized on Table 1. A feature of these data is the relatively high values of both undrained and effective stress shear strength, which perhaps reflect the relatively high angular silt content and the absence of true clay mineralogy, i.e. “clay” sized particles are frequently finely ground “rock flour”.

### **Drilling and sampling techniques**

Four boreholes were drilled, in the south-east part of the site at the locations shown on Figure 1 during July 2001. These were immediately adjacent to some boreholes and piezocone tests performed in 1986. Samples were taken, more or less continuously, with the conventional ELE 100 mm diameter fixed piston sampler (30° cutting edge) in BH1 and the same sampler with a sharpened 5° cutting edge in BH3. In BH2 and BH2A attempts were made to obtain samples with a specially manufactured large diameter (210 mm) sampler. Except for the diameter and the sampler wall thickness the design and operation of the sampler was similar to the conventional 100 mm sampler. Details of all three samplers are given on Table 2. It proved difficult to obtain samples with the large diameter sampler. Due to the size of the sample and the laminated nature of the material, many of the samples were lost. Generally the boreholes were terminated at about 6.0 m at the bottom of the laminated zone.

In all cases the hole was advanced using percussive means (conventional shell and auger drilling) within a fully lined 200 mm or 250 mm diameter borehole. Possible disturbance at the base of the borehole was an obvious concern and the borehole was maintained full of water to approximately 0.5 m above ground level in order to minimise these effects. No difficulties were encountered with holding the piston fixed. Except for

the large diameter samples, recovery was generally 100%. The drilling crew, from Norwest Holst Soil Engineering Ltd., had recent experience of using the equipment.

### **Laboratory testing techniques**

As well as routine index and classification testing, it was decided that the principal means of comparing the quality of specimens obtained from the different samplers would be by means of maintained load oedometer (MSL) and anisotropically consolidated undrained triaxial tests (CAUC). It was intended to carry out sets of these tests at three different depth intervals.

#### *Oedometer tests*

These were conventional maintained stage load tests (MSL), commencing at  $0.25 \sigma'_{a0}$ , where  $\sigma'_{a0}$  is the in situ effective vertical stress, with a load increment ratio of 1.0. Generally each increment was terminated when at least 90% of the primary consolidation was completed, as observed from the time / compression curves using the Taylor construction<sup>14</sup>. This allowed about four increments to be completed each day, with the disadvantage that only limited information was obtained on the secondary compression characteristics. Otherwise the procedures used were broadly those adopted as standard at the Norwegian Geotechnical Institute, NGI (Sandbækken et al.<sup>14</sup>). The 101.4 mm piston tube specimens were extruded directly into 100 mm diameter and 20 mm high oedometer rings. Large diameter specimens were trimmed, using a thin piano wire, slightly greater than 100 mm diameter prior to slowly pushing in a lubricated oedometer ring.

#### *Triaxial tests*

Testing comprised anisotropically consolidated undrained compression (CAUC) tests. Again the procedures used were broadly those adopted as standard by NGI<sup>15</sup>. The

specimen, of diameter as extruded for the 101.4 mm piston samples or trimmed to 100 mm for the large diameter samples, was trimmed to a diameter height ratio of between 1.8 and 2.0. A cell pressure of  $0.5 \sigma_{a0}$ , where  $\sigma_{a0}$  is the total in situ vertical stress, was applied and the initial effective stress ( $p'_i$ ) was measured.  $K_0$  was assumed to equal 0.7 from Hight et al.<sup>9</sup>. Initially an isotropic stress of about 60% of  $\sigma'_{r0}$  (in situ effective horizontal stress) was applied and then final stress was applied gradually under computer control. A diagrammatic representation of the consolidation stress path is given together with the test results on Figure 8. 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.

### **Laminated nature of material**

Some split and dried samples of the material from various depths are shown on Figure 2. Visually the laminations are typically 1 mm to 2 mm thick and occasionally up to 5 mm. The thicker layers appear to contain a higher clay fraction. Mostly the material is made up of silt with some fine sand. However each layer is not entirely uniform and instead appears to gradually grade into the adjacent layer. This gradation and the small thickness of the layers made separation of individual layers for testing impossible.

In an attempt to further assess the laminated nature of the material, moisture content tests were carried out on sub-specimens taken at 10 mm intervals and the results are plotted on Figure 3. This plot reveals clearly the existence of individual zones, typically 30 mm to 40 mm but up to 80 mm thick. Those individual zones which have higher moisture content also appear, by visual inspection, to contain a greater proportion of clayey material. A similar exercise was carried out with loss on ignition (LOI) at 440°C

test results. Values of between 6% and 10% were recorded (similar to those reported by Nash et al.<sup>10</sup>) with no apparent variation with depth.

Piezocone penetration tests were initially used to delineate the Bothkennar laminated facies. A typical test result (Test F2, see Figure 1) in the form of pore pressure versus depth and pore pressure ratio versus depth is shown on Figure 4. The laminated facies is clearly evident between depths of about 2.2 m and 6.1 m, with the much more homogenous mottled deposits present below this. In this case it can be seen that the individual layer thickness is between 125 mm and 165 mm. However it should be noted that piezocone readings were being taken at 20 mm intervals.

In summary then it would appear that the Bothkennar laminated facies is not similar to the classic Canadian varved clays (e.g. as reported by DeLory<sup>16</sup>) which are made up of a consistent set of silt and clay varves, corresponding to summer and winter lake bed deposition. Instead it comprises a series of overlapping zones of gradually increasing thickness, with each zone made up of a series of coarser and finer layers. This pattern is consistent with the shallow tidal depositional environment.

### **Sample disturbance effects on basic parameters**

#### *Effects of sampling on laminations*

Mechanical disturbance effects caused by the conventional (30°) and modified (5°) sample tubes can be seen dramatically on Figure 2. Severe distortion of the individual layers is evident in the specimens from the conventional samples. In particular significant layer distortion is apparent at the edge of the tubes with visually estimated shear strains of 25% and greater. However layer distortion is evident throughout the specimen. In

contrast the layers in the specimens from the modified sampler appear unaffected with little departure from the original horizontal pattern.

#### *Variation in basic index parameters*

Values of moisture content for specimens taken from the end of the sampling tubes immediately after sampling are shown on Figure 5a. They vary generally between 50% and 60% with no apparent pattern with depth. These values are similar to those reported by Nash et al.<sup>10</sup> (for Borehole D2, see Figure 1), albeit being slightly lower in the 2.5 m to 3.5 m depth range.

Values of moisture content and bulk density for “bulk” samples (i.e. from oedometer or triaxial tests) are plotted on Figures 5b and 5c. From these plots it can be seen that on average moisture content and bulk density values from the conventional (30°) samples are respectively lower and higher than those from the modified tubes. Moisture content is about 3% lower and bulk density is about 4% higher. Only limited data are available for the large diameter samples but they are similar to those of the modified sampler.

Internal tube sample pore water migration both from the outer sheared perimeter to the interior and between silt layers to adjacent clay layers is a well known phenomenon for soft normally consolidated to lightly overconsolidated clays<sup>7</sup>. However an increase in bulk density and a reduction in moisture content due to the tube sampling would require overall drainage of the sample to the exterior. It is possible that the excess pore pressures induced directly in front of the tube during sampling are at least partially dissipated through the silt lenses prior to the material entering the tube, thus causing the sampling process to be partially drained. The poorer cutting edge geometry of the conventional

tube would make this process more significant than for the modified or large diameter tubes.

### **Effects on 1D consolidation parameters**

#### *Stress - strain behaviour*

A summary of all of the oedometer tests is given on Table 3. Comparison of  $e$ - $\log p$  curves, for the three depth ranges under consideration are shown on Figure 6. 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. Each of the conventional sample tests shows a rounded nature with no clear definition of yield. Only the modified tube test from depth interval 2.6 m to 2.8 m (and arguably from 3.4 m to 3.5 m) and the large diameter test give sharper curves and allow the yield point (or preconsolidation pressure,  $\sigma'_p$ ) to be estimated with some degree of confidence.

In Norway, and elsewhere, use is made of plots of constrained or tangent modulus ( $M$ ) versus stress for settlement calculations (Janbu<sup>17, 18</sup>). For 1D compression, such as for an oedometer test,  $M$  is simply given by the change in stress over the change in strain for the increment, i.e.:

$$M = \frac{\delta\sigma_a}{\delta\varepsilon_a} \quad (1)$$

However  $M$  varies with both the current stress level and the stress history. Before reaching  $\sigma'_p$ ,  $M$  values are high and then gradually reduce on following yielding before increasing again in the normally consolidated zone. The yield point (or  $\sigma'_p$ ) can be identified as just before the minimum  $M$  value.

Test results are also presented in this form on Figure 6. In this case the superiority of the modified samples can easily be seen as they exhibit much higher initial stiffness values and a much clearer yield point. There would seem to be some significant advantages in using constrained modulus plots for the analysis of oedometer test results.

#### *Normalised void ratio change to initial vertical effective stress*

Lunne et al.<sup>2</sup> proposed using the normalised void ratio change ( $\Delta e/e_0$ ) to the to the in situ vertical effective stress ( $\sigma'_{a0}$ ) as a guide to sample quality. As the data are normalised by the measured in-situ void ratio ( $e_0$ ), natural material variability effects are minimised. Data for the Bothkennar laminated facies are summarized on Table 3. It can be noted that the 5° specimens are best (average 0.085), followed by the large diameter specimens (0.109) and the conventional tube specimens (0.126). Lunne et al.<sup>2</sup> also give a general classification scheme which ranges between “very good to excellent” to “very poor” depending on the  $\Delta e/e_0$  value. However as these categories were originally intended for uniform marine clays, it is not appropriate to apply them here.

#### *Comparison of measured parameters*

Table 3 summarises the more important parameters which can be derived from the oedometer tests. Of these perhaps the preconsolidation stress ( $\sigma'_p$ ) is the most important as it is a critical parameter for reliable prediction of soft ground behaviour. These values have been derived using the Janbu<sup>17, 18</sup> technique only and are shown on Figure 7. Generally it was not possible to determine  $\sigma'_p$  using the traditional Casagrande<sup>19</sup> approach due to the rounded nature of the curves plotted in  $e$ - $\log p'$  space. In each case the modified tubes gave higher values than the conventional tubes corresponding to an overconsolidation ratio of about 2.0 compared to 1.5. The large diameter sampler gave

similar results to the conventional sampler. This finding has been reported previously by many researchers,<sup>1, 2, 3 & 4</sup> and can be attributed to loss in structure of the conventional samples when compared to those from the modified sampler.

Initial modulus ( $M_i$ ) and compression coefficient ( $C_c/1+e_0$ ) values were also higher on average for the specimens from the modified sampler compared to those from the conventional sampler. Once again values for the large diameter sampler were similar to those of the conventional sampler. The implication of this result is that sample disturbance effects will reduce the initial stiffness and increase the stiffness in the normally consolidated range. These effects can be attributed to sampling induced destructuration and densification.

A study was also made of other parameters such as coefficient of consolidation ( $c_v$ ) and coefficient of secondary compression ( $C_{sec}$ ). However there is insufficient data, in particular for  $C_{sec}$ , as most of the tests were terminated at the end of primary consolidation, and significant scatter in the results preventing any definitive conclusions being made.

### **Analysis of triaxial test results**

Results for all of the triaxial tests are summarized on Table 4.

#### *Residual (or initial) effective stress*

The ability of a soil sample to sustain suction, i.e. to retain a positive effective stress, at this stage is essential to the process of sampling. If the imposed suction cannot be sustained, the soil will lose coherence and water will drain from the sample. From Table 4, it can be seen that the values of the residual effective stress,  $p'_i$ , recorded in this study are generally very low. It is possible to explain these results by reference to the material's

laminated nature. During tube sampling the silt seams give up water to the surrounding clay and desaturate leading to low values of  $p'_i$ . (Note that B values for all the samples were close to 1.0). There is evidence of slightly lower values being recorded in the conventional tube samples, possibly due to increased loss of structure in these samples.

#### *Void ratio change during consolidation*

As for the oedometer tests, the normalised void ratio change ( $\Delta e/e_0$ ) required to reconsolidate the sample anisotropically to the initial effective stress ( $\sigma'_{a0}$ ,  $\sigma'_{r0}$ ), can be used to assess sample quality, see Table 4. Once again this assessment suggests that the modified samples are best, with the conventional and large diameter specimens being of similar quality.

#### *Undrained stress strain behaviour and stress paths*

Deviator stress / strain and stress path plots for the tests from 2.6 m and from depth interval 4.5 m to 5.5 m are shown on Figures 8a and 8b respectively. Again it can be observed that there is a significant difference in behaviour between the conventional and modified tube samples. It can be seen that the  $5^\circ$  specimens appear more brittle with peak strengths occurring at 4% to 6% strain and with a moderate degree of strain softening post peak. Behaviour of the  $30^\circ$  specimens in contrast is ductile with stress gradually building up with strain.

Initially all of the tests show contractive behaviour. For two of the three modified tube samples, shown here, this contractive behaviour continues until critical state conditions are reached. However there is a marked difference in the behaviour of the conventional  $30^\circ$  tube specimens, in that, post peak there is a strong tendency for dilation. This effect can again be attributed to loss of structure and sampling induced densification.

It is likely also that the more disturbed specimens may “densify” to a greater extent during anisotropic consolidation and thereby exhibit greater strength.

Test results from 3.3 m depth are compared with those for a Sherbrooke block sample test as reported by Hight et al.<sup>4</sup>, on Figure 9. This specimen was taken from a different part of the site but was located in the laminated facies. In this case the test results are presented in normalized form. The block sample shows clear brittle behaviour with significant post peak strain softening. All of the other specimens show more ductile behaviour, with the behaviour of the 5° specimens being closest to that of the block.

According to Lunne et al.<sup>2</sup>, for a good quality specimen, pre-peak, in which there is minimum slippage between the particles, the stress path (plotted in  $t'$ ,  $s'$  space as here) slope will be 1 horizontal to 3 vertical. Only the block sample specimen exhibits this behaviour. Subsequently the block sample result is typical of normally consolidated clay. For all the tube samples there is a strong tendency for dilation post peak.

#### *Undrained strength*

Values of undrained shear strength are plotted against depth on Figure 10 for the different samplers. Torvane (small hand shear vane) and CAUC triaxial test results show similar values, with  $s_u / \sigma'_{a0}$  in the range 0.45 to 0.7, as also reported for previous work on the site<sup>10</sup>. The Torvane values for 5° specimens are on average the highest, due possibly to the higher suctions being retained by these specimens. In contrast the CAUC strength results for these specimens are the lowest. This finding follows on from the discussion on stress / strain behaviour above, with the tendency for post peak dilation in the 30° specimens resulting in strength values which are consistently higher than those given by the 5° specimens. The average value for the modified sampler specimens are much closer

to the average value for the material of about  $0.5 \sigma'_{a0}$  reported by Hight et al.<sup>9</sup> and Nash et al.<sup>10</sup>. The single large diameter specimen gives similar results to the 5° specimens.

A plot of  $s_u / \sigma'_{a0}$  versus initial specimen density for all of the CAUC tests is given on Figure 11. Up to a density value of about  $1.72 \text{ Mg/m}^3$  the values are close to the  $0.5 \sigma'_{a0}$  value mentioned above. However at density values greater than this the values are higher than would be expected. It is also interesting to note that this value separates the specimens, which contracted and dilated on shearing.

Therefore as two of the 5° specimens had density lower than  $1.72 \text{ Mg/m}^3$  they contracted, whereas the remaining specimens had density greater than this and dilated. On average the 5° specimens had an initial density of  $1.687 \text{ Mg/m}^3$  compared to  $1.755 \text{ Mg/m}^3$  for the 30° tube specimens. It is likely then that the tube insertion process densified the material due to partial drainage through the silt lenses resulting in the response seen above.

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

Average values for various other parameters measured in all of the triaxial tests are summarised on Table 4. The modified tube samples show the lowest average undrained secant stiffness values ( $E_{\text{sec}}$ ) at 0.01% strain. (Sample strain measurements were made using an external LVDT.) This finding is consistent with the oedometer  $C_c/(1+e_0)$  values being highest for these samples. Skempton's pore pressure coefficient  $A_{\text{peak}}$  strength for (i.e. at peak deviator stress) for the modified samples are higher than those determined on the other samples. On average a value of 0.7 was recorded for these samples.

## **Discussion on role of natural material variability**

In the discussion above it is argued that a major reason for the differences in the behaviour of the modified and conventional tube samples is the increased loss of structure caused by the cruder cutting edge geometry of the conventional sample tubes. It is possible also that partial drainage from the sample to the exterior results in densification of the soil. However it could also be argued that the results could be explained simply by natural material variability. In the opinion of the author the effects are due to destructuration and possible densification because observations of the distorted shape of the laminations in the conventional tubes are consistent with the:

- increased density,
- reduced moisture content,
- poorer specimen quality,
- lower preconsolidation stress,
- greater post yield stiffness,
- dilatant behaviour on shearing,

of the conventional tube specimens when compared to those from the modified one.

In addition to this Long<sup>20</sup> reports very similar behaviour for of Athlone laminated clay when comparing tube and high quality Sherbrooke block samples. He also presents data for two Norwegian silty soils, which exhibited dilatant behaviour on shearing as a result of sampling disturbance induced phenomena.

Recent research by Santagata and Germaine<sup>21</sup> on resedimented Boston blue clay also supports the findings made here. In this work theoretically calculated “tube sampling strains” were first imposed on triaxial samples. The samples were subsequently sheared

and it was found that as the “tube sampling strains” were increased, there was a change from a contractant to an increasingly dilatant effective stress path.

## **Conclusions**

1. The Bothkennar laminated facies comprises a series of overlapping zones of gradually increasing thickness, with each zone made up of a series of coarser and finer layers. It bears little resemblance to the classical varved clays.
2. Because of its cruder 30° cutting edge angle the conventional sample tubes cause severe distortion of the laminations and more significant loss in structure when compared to the modified sampler, which has a 5° cutting edge angle.
3. It is also possible that the presences of the silt lenses results in partial drainage from the sample to the exterior during the sampling process. This results in an increase in the density of the material by about 4% with a corresponding reduction in moisture content in the conventional samples when compared to the modified ones.
4. The more significant loss in structure in the conventional samples results in
  - a reduction in preconsolidation stress ( $\sigma'_p$ ),
  - a reduction in initial stiffness ( $M_i$ ),
  - an increase in post yield stiffness ( $C_c/(1+e_0)$  and  $E_{sec/0.01\%}$ ),
  - lower initial effective stress (suction),
  - lower undrained strength ( $s_u$ ) by simple methods (Torvane),Similar findings have been reported many times in the literature.
5. However the sample disturbance effects also produced some unusual results for example:
  - an increase the CAUC triaxial undrained strength,

- a reduction in the pore pressure coefficient,  $A_{\text{peak}}$ ,
- and a strong tendency for dilatant behaviour post peak.

These findings are irregular as usually sample disturbance effects tend to decrease strength and stiffness and shrink the soil's yield envelope.

6. It is likely that this unexpected behaviour is caused by material destructuration during the sampling process with the conventional tubes and also by increased densification caused both by sampling and during anisotropic consolidation.
7. Although obtaining good quality samples of “mixed” and laminated soils is inherently difficult, in view of their frequent occurrence in the UK and Ireland, the practice of using thin walled piston tubes with a  $30^\circ$  cutting edge angle should be abandoned and tubes with a sharper cutting edge angle used instead.

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### **Notation**

- $A_{\text{peak}}$  Skempton's pore pressure coefficient (at peak deviator stress) related to change in deviator stress
- $B$  Skempton's pore pressure coefficient related to change in isotropic stress
- $c_v$  coefficient of consolidation
- $C_c$  compression index
- $C_{\text{sec}}$  coefficient of secondary compression

$e / e_0$  void ratio / initial void ratio  
 $E_{sec}$  secant Young's modulus  
 $K_0$  ratio of horizontal to vertical initial effective stress  $\sigma'_{h0} / \sigma'_{v0}$   
 $M / M_i$  constrained modulus / initial stiffness in oedometer test  
 $p'_i$  initial or residual effective stress  
 $q_t$  corrected piezocone cone end resistance  
 $s'$  mean stress =  $(\sigma'_a + \sigma'_r) / 2$   
 $s_u$  undrained shear strength  
 $t'$  shear stress =  $(\sigma'_a - \sigma'_r) / 2$   
 $w / w_i$  moisture content / natural moisture content  
 $\epsilon_a$  axial strain  
 $\phi'$  effective friction angle  
 $\rho_i$  initial bulk density  
 $\sigma'_a$  axial effective stress  
 $\sigma'_p$  preconsolidation stress  
 $\sigma'_r$  radial effective stress  
 $\Delta e$  change in initial void ratio

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## LIST OF FIGURES

Fig. No.	Caption	File Name*
1	Location of boreholes	Laptop/Labtests/Bothkennar/siteplan.grf+siteplan.xls
2	Split and dried samples showing sampling induced distortion of layers	Desktop/Bothkennar/Laminations.doc
3	Assessment of laminated nature	Laptop/Labtests/Bothkennar/varving.grf+laminated.xls
4	Piezocone test results	Desktop/Bothkennar/Piezocone.doc
5	Moisture content and bulk density	Laptop/Labtests/Bothkennar/Moisturecon.grf+Moisturecon.xls
6	Oedometer test results	Laptop/Labtests/Bothkennar/Oedsum.grf+Oedsum.xls
7	Preconsolidation stress	Laptop/Labtests/Bothkennar/Preconsolstress.grf+preconsolstress.xls
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10	Undrained shear strength	Laptop/Labtests/Bothkennar/su.grf+su.xls
11	Undrained shear strength versus density	Laptop/Labtests/Bothkennar/sudensity.grf+su.xls

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

**Table 1. Summary of principal material properties on bulk samples**

Parameter	Units	Value	Comment / source of data	Reference
Natural moisture content (w)	%	50 - 70	Tests on "bulk" samples	10
Bulk density	Mg/m <sup>3</sup>	1.55 – 1.65		10
Clay content	%	15 – 30		9
Liquid limit	%	50 - 75		9
Plastic limit	%	20 – 25		9
Plasticity index	%	20 - 40		9
Liquidity index	-	0.9 – 1.1		9 / 10
Activity	-	1.34		10
Specific gravity	-	2.65		9
Yield stress ratio	-	1.5	By 1 D oedometer testing	10
K <sub>0</sub>	-	0.7	From self boring pressuremeter and spade cells	9
Sensitivity (field vane)	-	5	Fall cone shoes slightly higher values	9 / 10
Vertical permeability	m/s	2x10 <sup>-9</sup>	Horizontal value up to 5 times higher	12 / 13
s <sub>u</sub> / σ'v0	-	0.45 – 0.7	Field vane	10
φ'	Deg.	45°	In triaxial compression. Values particularly high for laminated facies	10

**Table 2. Details of samplers**

Sampler	Length	Cutting edge angle	Inside diameter	Wall thickness	Area ratio <sup>1</sup>	Inside clearance
	mm	deg.	mm	mm	%	%
ELE 100	1000	30	101.4	1.7	6.8	0
ELE 100 (modified)	1000	5	101.4	1.7	6.8	0
Large diameter	640	25	210.0	4.0	7.8	0

1. Area ratio =  $(D_{\text{external}}^2 - D_{\text{internal}}^2) / D_{\text{internal}}^2$

**Table 3. Summary of oedometer test results**

Test	Depth: m	Sample diameter: mm	Cutting angle: deg.	$\sigma'_{a0}$ : kPa	$w_i$ : %	$\rho_i$ : Mg/m <sup>3</sup>	$M_i$ : MPa	$C_c/1+e_0$	$\sigma'_p$ *: (Janbu) kPa	$\varepsilon_a$ at $\sigma'_{a0}$ †: %	$\Delta e/e_0$ †
B1	2.6	100	30°	29	69	1.707	985	0.173	44	7.5	0.120
B2	3.5	100	30°	36	47	1.790	1400	0.133	51	5.8	0.108
B3	5.0	100	30°	44	47	1.732	1690	0.109	88	8.4	0.149
B4	2.8	100	5°	30	63	1.576	1300	0.220	60	6.1	0.096
B5	3.4	100	5°	32	51	1.728	1200	0.100	57	3.5	0.061
B6	4.6	100	5°	38	58	1.606	1100	0.204	77	5.3	0.085
B7	5.6	100	5°	44	54	1.683	3040	0.110	88	5.8	0.097
B8	3.4	210	25°	32	64	1.583	780	0.123	39	7.7	0.121
B9	3.4	210	25°	32	60	1.636	830	0.125	60	5.1	0.082
B10	3.1	210	25°	31	57	1.621	900	0.123	46	7.7	0.126
B11	3.2	210	25°	31	61	1.579	700	0.153	63	6.9	0.108

\* preconsolidation stress from Janbu (Refs. 16 & 18) technique.

† strain to in situ stress and normalized void ratio change to in situ stress respectively for purpose of estimating sample quality after Lunne et al. (Ref. 2)

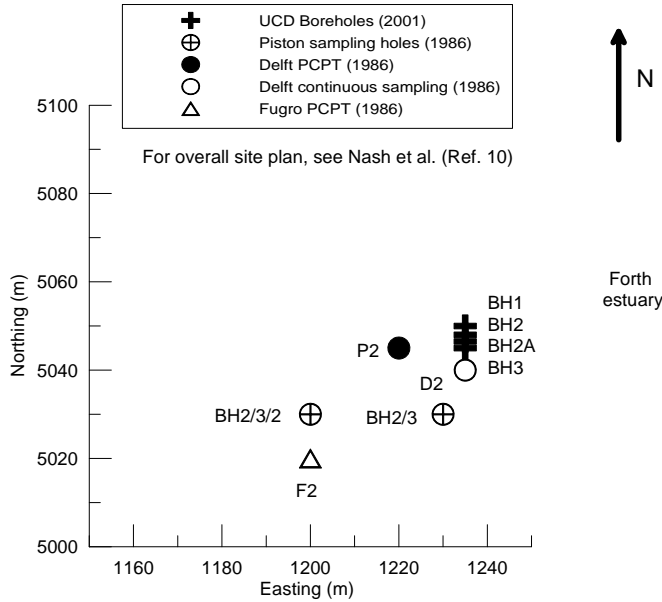
**Table 4. Summary of CAUC triaxial tests**

Test	Depth: m	Sample diameter: mm	Cutting angle: deg.	$\sigma'_{a0}$ : kPa	$w_i$ : %	$\rho_i$ : Mg/m <sup>3</sup>	$p'_i$ : kPa	$\Delta e/e_0^\dagger$	$s_u$ : kPa	$s_u / \sigma'_{a0}$ :	$\varepsilon_{peak}$ : %	$A_{peak}$ :	$E_{sec/0.01\%}$ : MPa
B1	2.6	100	30°	29	59	1.738	1	0.160	15.8	0.55	12.5	0.55	100
B2	3.2	100	30°	36	47	1.836	1	0.199	23.5	0.65	13.1	0.41	120
B3	4.8	100	30°	44	50	1.737	0	0.175	25.5	0.58	17.2	0.51	80
B4	2.6	100	5°	26	61	1.638	3	0.045	14.9	0.50	4.4	0.74	22
B5	3.2	100	5°	29	49	1.820	3	0.108	21.4	0.63	12.2	0.53	55
B6	4.5	100	5°	32	51	1.738	2	0.094	19.3	0.51	6.5	0.74	-
B7	5.5	100	5°	37	52	1.705	3	0.081	23.3	0.53	4.1	0.65	60
B8	3.2	210	25°	34	59	1.742	0	0.173	19.4	0.57	13.1	0.52	-

† normalized void ratio change to in situ stress for purpose of estimating sample quality after Lunne et al. (Ref. 2).

**Figure 1.**

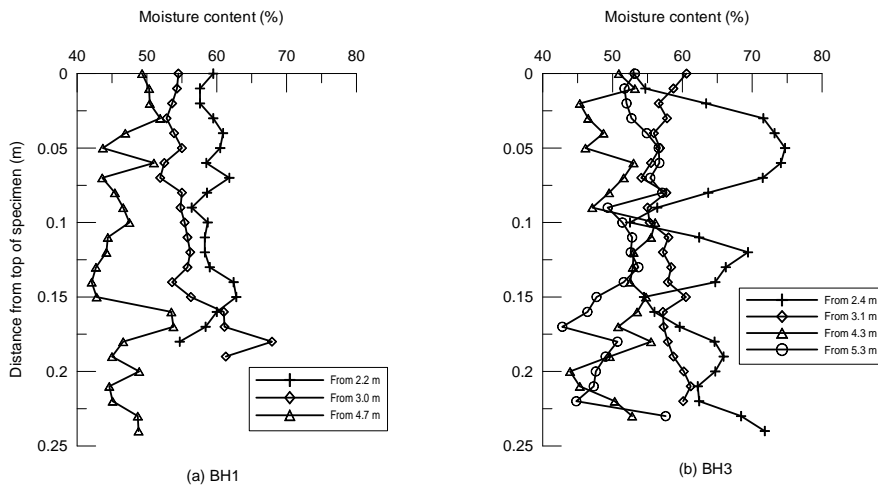
Laptop/Labtests/Bothkennar/siteplan.grf+siteplan.xls



**Fig. 1. Location of boreholes**

**Figure 3**

Laptop/Labtests/Bothkennar/varving.grf+laminated.xls



**Fig. 3. Assessment of laminated nature**

Figure 5

Laptop\Labtests\Bo\kennar\Moisturecon.grf+Moisturecon.xls

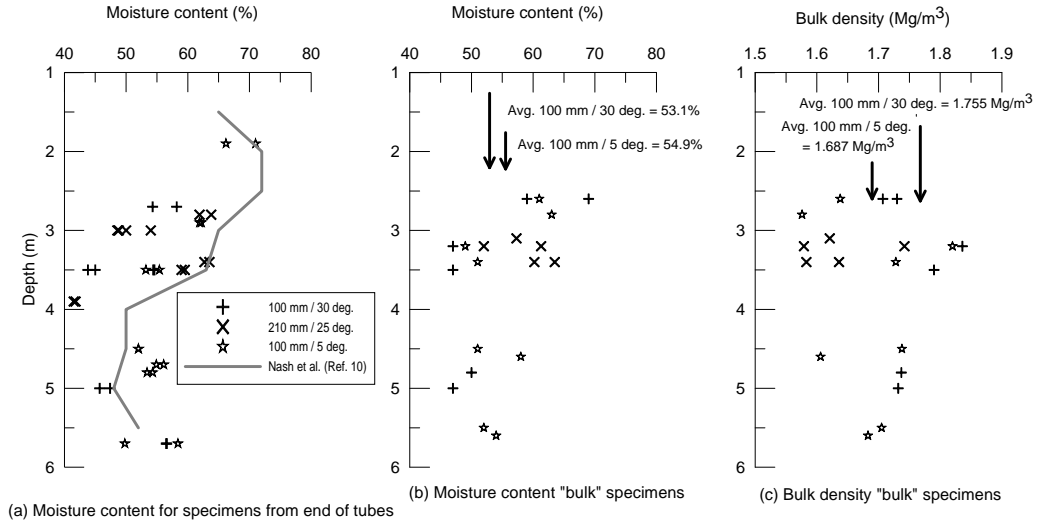


Fig. 5. Moisture content and bulk density

Figure 7

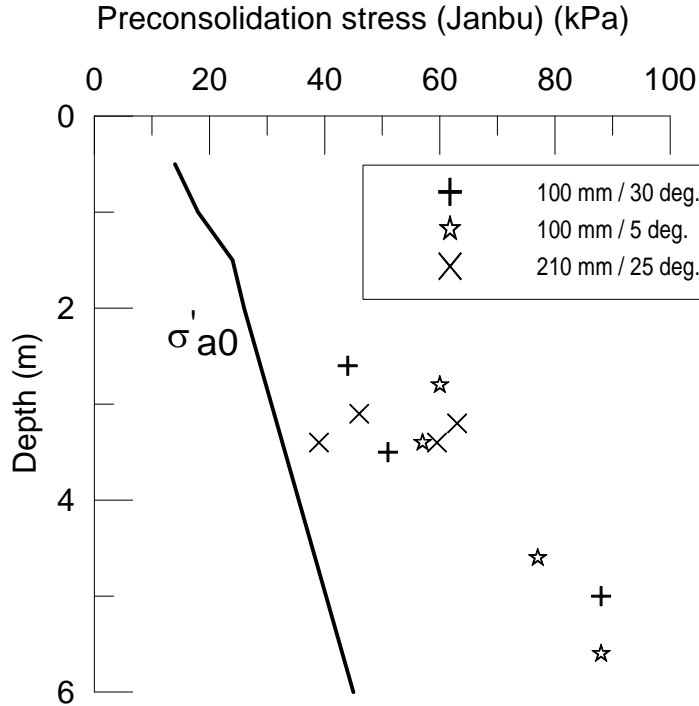
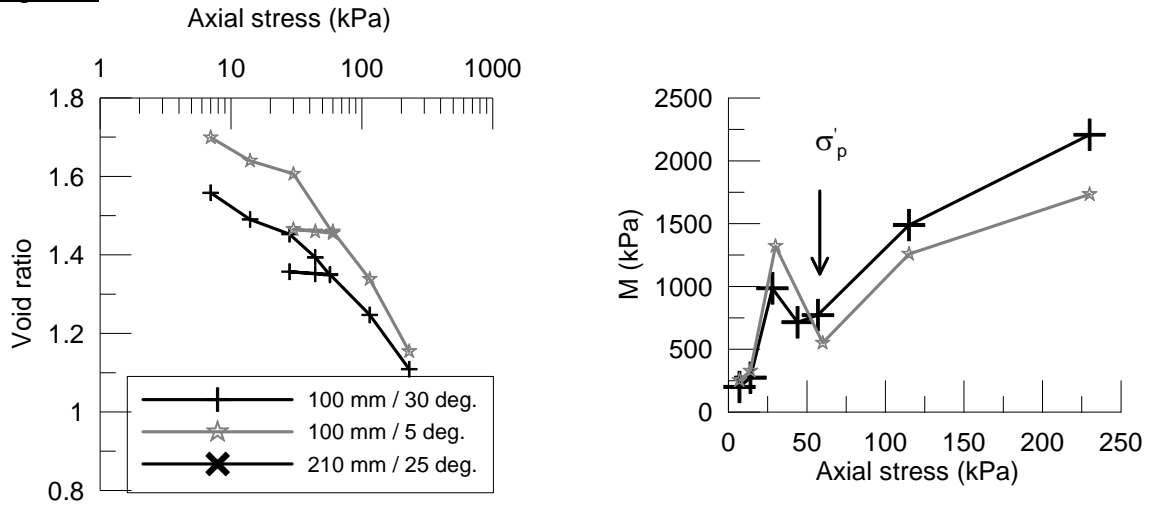
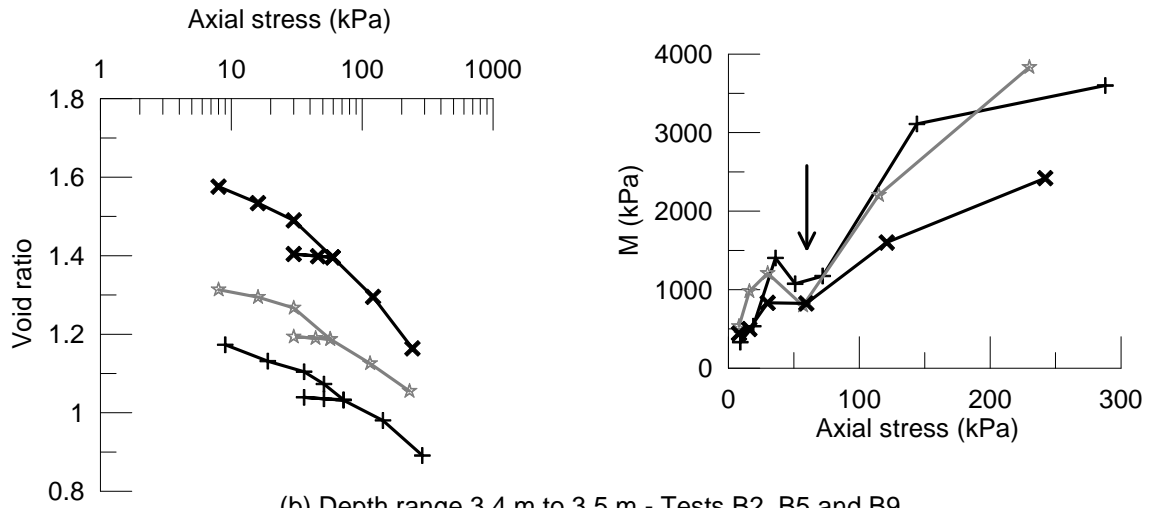


Fig. 7. Preconsolidation stress

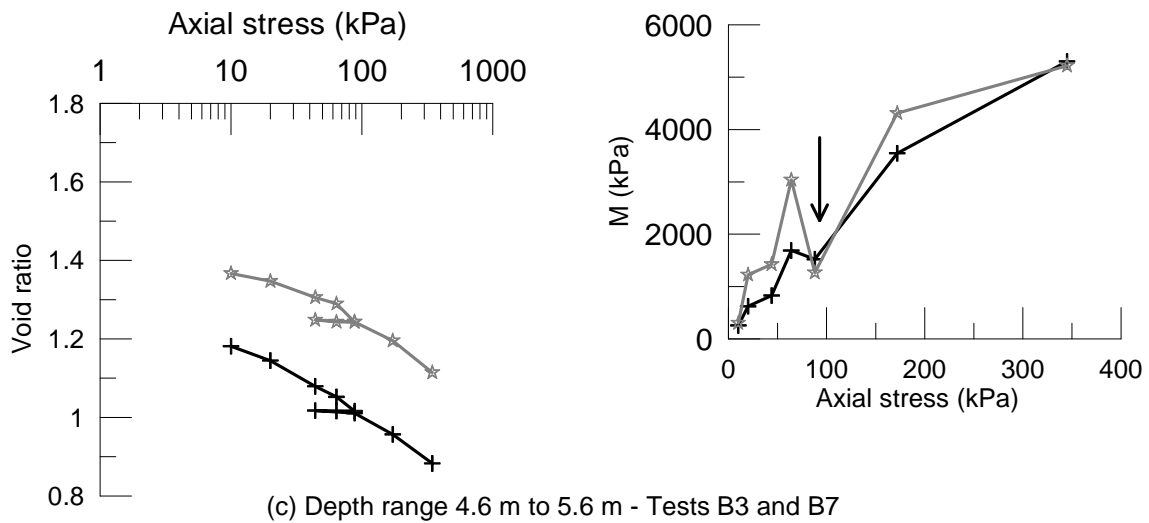
Figure 6



(a) Depth range 2.6 m to 2.8 m - Tests B1 and B4



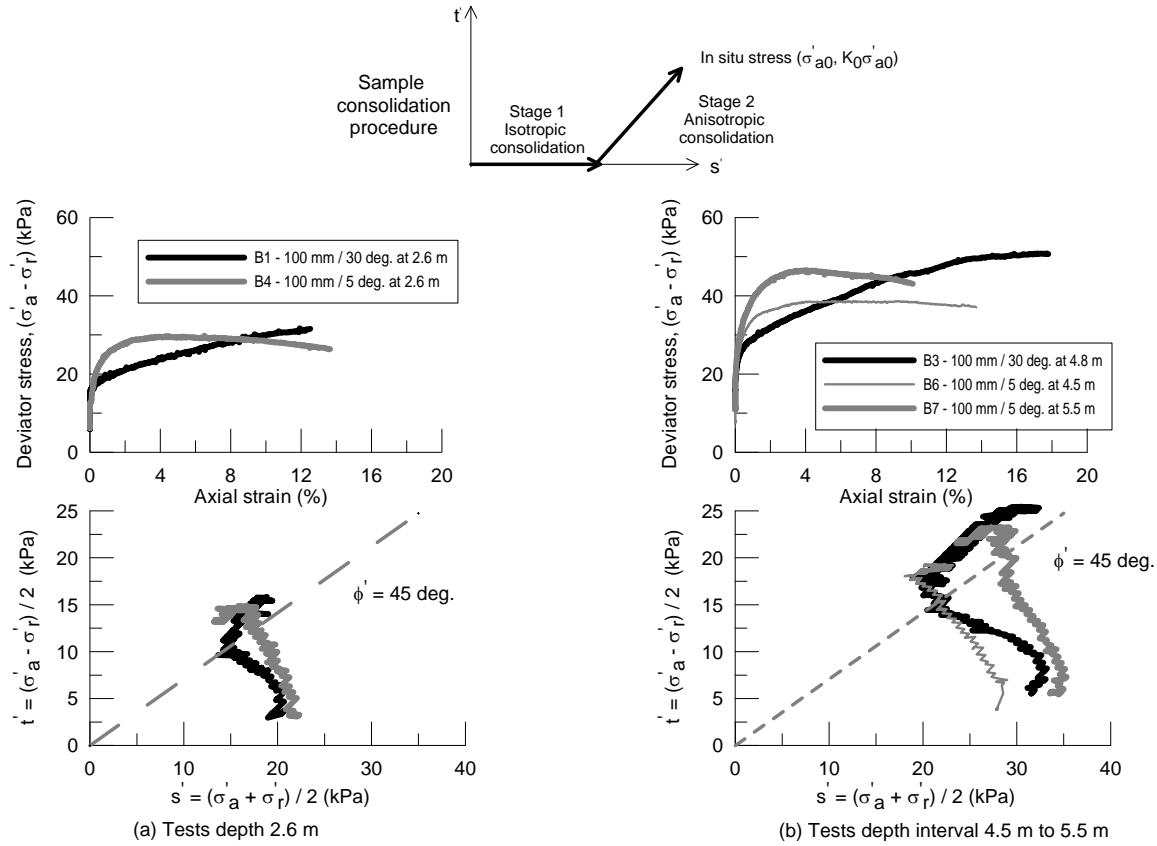
(b) Depth range 3.4 m to 3.5 m - Tests B2, B5 and B9



(c) Depth range 4.6 m to 5.6 m - Tests B3 and B7

**Figure 8**

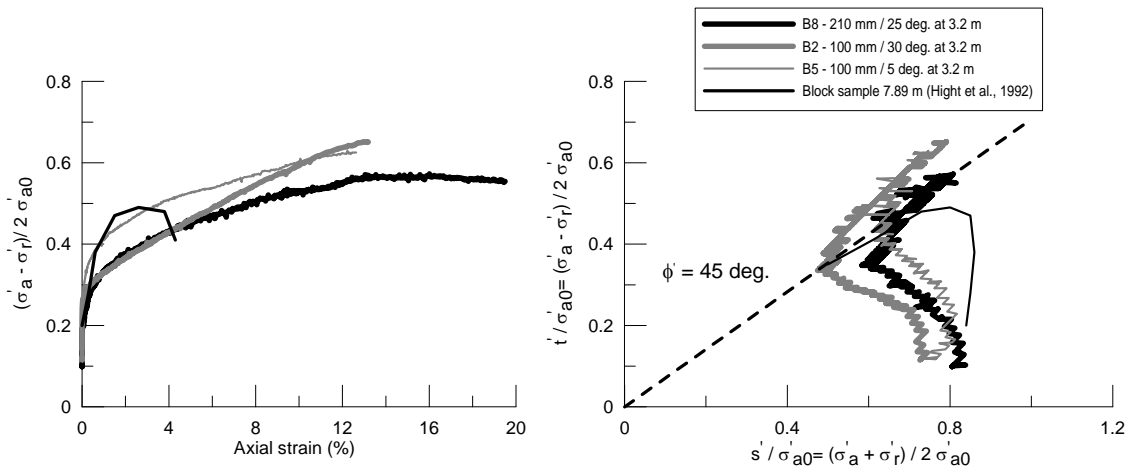
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**Fig. 8. CAUC test results**

**Figure 9**

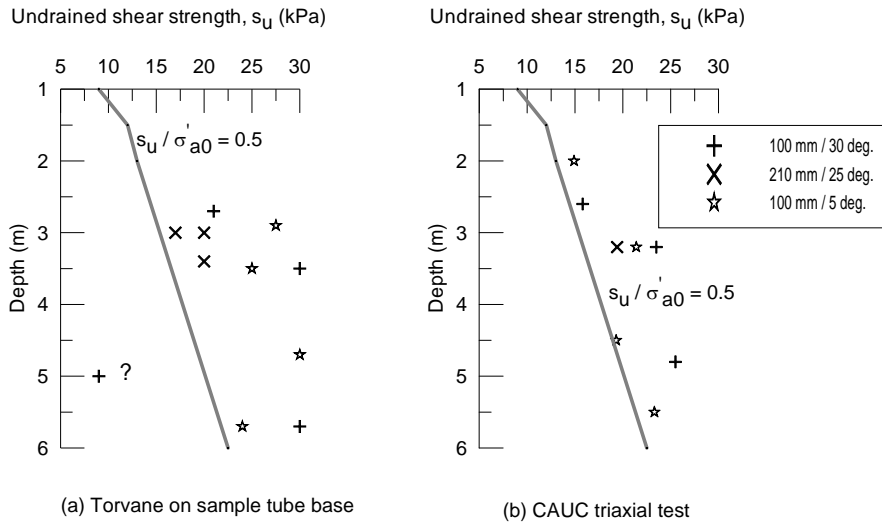
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**Fig. 9. CAUC tests on samples from 3.2 m**

**Figure 10**

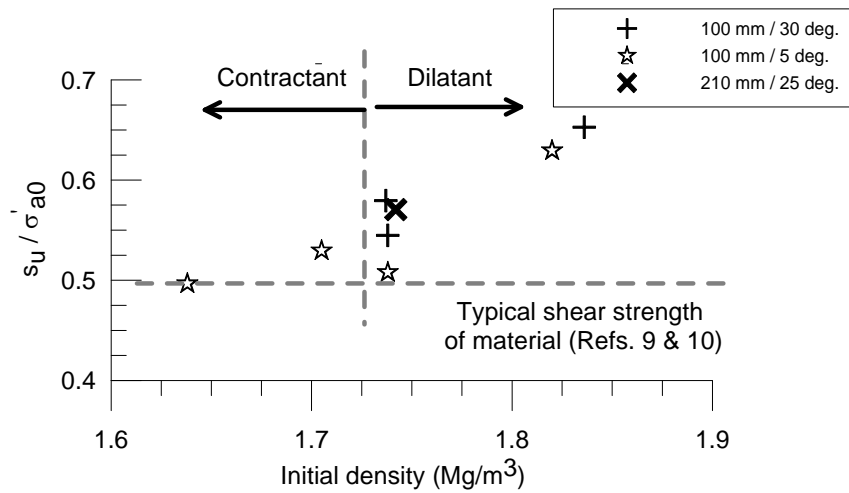
Laptop/Labtests/Bothkenna/su.grf+su.xls



**Fig. 10. Undrained shear strength**

**Figure 11**

Laptop/Labtests/Bothkenna/sudensity.grf+su.xls



**Fig. 11 Undrained shear strength versus density**

