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**Manuscript title:** Sample disturbances due to removal of confining pressure in laminated clay

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## Abstract

Sample disturbances in laminated soils may be caused by several factors including water movement between the clay and sand layers upon removal of overburden pressures. The research reported in this article examines the impact of this water movement on various geotechnical parameters. Samples of kaolin with laminations were formed and subjected to isotropic consolidation and subsequently sheared under undrained conditions. Further tests were carried out in which the samples were isotropically unloaded after consolidation and isotropically reloaded under undrained conditions and this was then followed by undrained shearing. Tests were also carried out to examine the impact of unloading/reloading on the yield stress and small strain stiffness ($G_{max}$). The results have shown that the isotropic unloading/reloading process under undrained conditions leads to reduction in undrained shear strength, small strain stiffness ($G_{max}$) and yield stresses. Comparative tests carried out on unlaminated samples showed that the unloading/reloading process has a marginal impact on the above mentioned geotechnical properties.

**Keywords**: Clays; sampling; stiffness

## INTRODUCTION

Laminated clay is formed by sedimentation of alternate layers of clay and silt or fine sand in still lakes. Usually, the clay thickness is greater than the silt/sand laminations, which may vary in thickness from 1 mm to 10 mm. However the thickness of silt/sand layers can be larger when deposits are close to a glacial source (Hvorslev, 1949). Various studies (Saxena *et al.,* 1978; Giraud *et al.*, 1991; Bell and Coulthard, 1997; Bell, 1998) suggest that the presence of alternate layers of very different materials may induce significant anisotropic behaviour, also due to sampling disturbances and this makes the estimation of reliable geotechnical parameters difficult.

Numerous deposits of laminated clay are found in the United Kingdom (Hight *et al.*, 1992; Nash *et al.,* 1992; Barras and Paul 1999; Long 2003; Cummings *et al.,* 2003). One of the deepest (37m thick) deposits of laminated clay was found in Northern Ireland when ground investigations were carried for Swann's Bridge over River Roe, Limavady. Laboratory investigations were carried out and it was found that the undrained shear strengths were significantly lower than *in-situ* measurements which also agreed with significantly lower preconsolidation pressures measured in the laboratory compared with the *in-situ* effective overburden pressures (Cummings *et al.,* 2003). However overestimation of undrained strength is also possible if the samples are reconsolidated to *in-situ* stresses in the laboratory environment prior to undrained compression (Ladd, 1991; Germaine and Ladd, 1988). Additional observations in relation to underestimation of undrained shear strength are shown in Figure 1, which plots the stress-strain relationship of several Belfast Boulder Clay samples subjected to unconsolidated undrained compression tests. Belfast Boulder Clay is clay-rich material and it is a firm to stiff, overconsolidated red-brown clay which is heavily laminated particularly near the base of the deposit. The clay is described as intermediate to high plasticity clay. On this occasion the samples were recovered from 24-33 m below the ground surface and the intensity of laminations varied significantly with depth. As shown in Figure 1, the heavily laminated samples yielded a significantly lower deviator stress than the unlaminated samples. The reason for this reduced strength of the laminated samples is believed to be due to sample disturbances.

Sample disturbances in soils are caused by several factors, including the area ratio of the sampler, lack of proper use of a fixed piston and friction between the sampling tube and the soil during recovery (Clayton *et al.*, 1995; Ladd and DeGroot, 2003; Long, 2003; Hight and

Leroueil, 2003 and Ferreira *et al.,* 2011; Tan *et al.,* 2011: Clayton, 2011; Karlsrud and Hernandez-Matinez, 2013). Other forms of sample disturbances can emerge due to the laminated nature of the deposits. In principle, the sampling is regarded as an undrained process whereby there is no water movement into or out of the sample during recovery. However the removal of overburden pressure generates negative pore water pressure within the recovered sample (Doran *et al.,* 2000). In laminated deposits, particularly when the water-table is high, an influx of water into the sampling location may take place. Some of the water in the sand/silt layers may also drain out upon recovery of the sample to the surface as these layers may not be able to sustain water under negative pressure. However the clay layers can sustain negative pore water pressure and consequently there may be some water movement from the sand/silt layers to the clay layers (Donohue and Long, 2009). This water movement could also activate remoulding of clay layers, particularly in the presence of stiff sand/silt layers. The purpose of this article is to examine if the presence of laminations has an effect on sample quality during the removal of the overburden pressure, albeit that the other factors mentioned above also contribute to severe sample disturbances.

## EXPERIMENTAL PROGRAMME

In the vast majority of geotechnical testing for design, the recovered samples are cut and trimmed to size and then subjected to unconsolidated undrained compression without pore water pressure measurements (BS1377:1990 7/8). It is also possible to reconsolidate the samples to in situ stress conditions (i.e. under $K_0$ loading conditions) and subsequently subject the sample to undrained compression (Ladd and Lambe, 1963). However performing $K_0$ loading on laminated soil is not particularly straightforward in laboratory. Typically $K_0$ loading condition is achieved by restricting lateral deformation of the soil by manipulating the vertical and lateral stresses applied to the sample with the aid of a lateral strain gauge (Sivakumar *et al.,* 2015). However, in laminated soils, the stiffness properties of the sand/silt and clay layers are different and therefore they respond differently to the external loading and consequently true $K_0$ conditions cannot be achieved.  More evidence of this is reported later in this article. Since the aim of the article is to assess if the water movement between clay and sand/silt layers leads to sample disturbances, as a qualitative indicator, the tests were carried out on isotropically compressed laminated samples prepared in the laboratory.

## Sampling Method

Tests were carried out on artificially prepared laminated samples. Tests were also carried out on unlaminated samples for the purpose of comparison. The samples were prepared using previously consolidated kaolin clay (Liquid Limit 71% and Plastic Limit 31%). The kaolin was mixed at 1.5 × Liquid Limit and consolidated to 200 kPa of vertical stress in a one-dimensional consolidation chamber (100 mm diameter). The following procedure was adopted when forming laminated samples.

The intention of the sampling process was to form laminated samples with alternating layers of clay (9 mm thick) and fine sand (3 mm thick). Figure 2 shows the construction of laminated samples. Forty acrylic discs of 3 mm thickness and 99 mm diameter were used to assist the formation of laminated samples. The extruded sample from the one-dimensional consolidation chamber was placed in a split mould and trimmed to 200 mm height. The acrylic discs were then layered into another 200 mm high closed mould. Three acrylic disks were removed from the closed mould and located under the split mould to protrude the clay by 9 mm. This clay layer was carefully trimmed and placed on top of the acrylic discs in the closed mould (Figure 2a). A further acrylic disc from this mould was removed from the bottom and the space generated at the top (3 mm in thickness) was backfilled with fine dry sand which was passed through a 0.300 mm sieve but was retained on a 0.212 mm sieve. This was then followed by removal of a further 3 acrylic discs from the closed mould and placing them in the split mould to form a further clay layer. The procedure was repeated until a sample height of approximately 200 mm was achieved. Water movements during removal of overburden pressure and the consequences on geotechnical properties are thought to be somewhat limited in unlaminated soils and therefore parallel tests were also carried out to confirm this hypothesis. There is no direct comparison between the geotechnical characteristics of laminated and unlaminated samples, although the observed responses are used to draw some conclusions.

## Testing Procedure

Unlaminated and laminated samples of kaolin (100 mm diameter and 100 mm or 200 mm length, depending on the testing requirements) were assembled in the testing chamber and saturated until a saturation value B of 0.95 was achieved. The back pore water pressure at the end of the saturation process was 500 kPa. The samples were then taken through two testing programmes described as follows:

**Suction measurements:** The key aspect that may induce sample disturbances in laminated clays and consequently impact the stiffness and strength is the water movement between the clay and sand layers. This was initially examined using a newly developed testing chamber (Figure 3) instrumented with a high capacity tensiometer (Lynch *et al*., 2018), capable of measuring suction up to 1500 kPa. Unlaminated and laminated samples were isotropically consolidated to 800 kPa of mean effective stress (cell pressure 1300 kPa and back pore water pressure 500 kPa). Upon completion of the consolidation to 800 kPa of mean effective stress the cell pressure was reduced to zero under undrained conditions and re-applied after about 2-3 hours. During this process the suction in the sample was monitored.

**Undrained shear strength, yield stress and $G_{max}$**: In the main testing programme, a total of 28 tests were carried out on laminated and unlaminated samples including repeat tests (Table 1). The investigations were carried out at three effective consolidation pressures. In the case of undrained compression tests, 200 mm high, 100 mm diameter samples were prepared. In order to measure the yield stress and small strain stiffness ($G_{max}$), 100 mm high, 100 mm diameter samples were used. The average initial bulk densities ($\rho_s$) of the laminated and unlaminated samples were approximately 1612 ± 22 kg/m$^3$ and 1671 ± 35 kg/m$^3$, respectively. The bulk density of the laminated sample was slightly less due to the fact that it contained 25% of fine sand in a nearly dry state.

The saturated samples were consolidated isotropically to a mean effective stress (i.e. an effective confining pressure) of either 200 kPa, 400 kPa or 800 kPa (Table 1). The samples were then sheared under undrained conditions, at a strain rate of 2%/min (BS1377:1990 7/8) to measure the undrained shear strength. In parallel sets of tests, the relevant confining pressures (i.e. cell pressures) were removed after consolidation, under undrained conditions and reapplied after 1 hr. The samples were then sheared undrained without further consolidation as per BS1377:1990 7/8. The authors, however, accept the fact that in reality the duration between the sampling (*in-situ*) and testing in the laboratory can be several days if not weeks (Kirkpatrick and Khan, 1984; Graham and Lau, 1988). Nevertheless, as discussed later in this article, the pore water pressure in the sample upon unloading generally stabilised within an hour for both laminated and unlaminated samples.

The shear wave velocities of unlaminated and laminated samples were measured using bender elements. Samples (100 mm height and 100 mm length) were isotropically consolidated to a mean effective stress of either 200 kPa, 400 kPa or 800 kPa. At the end of consolidation at the selected pressures (Table 1) a transmitting wave at a frequency of 15Hz was sent from the base of the sample. The bender element for detecting the receiving wave was located at the top of the sample. In parallel sets of tests, the relevant confining pressures (i.e. cell pressures) were removed after consolidation (under undrained conditions) and reapplied after 1 hr. At this stage the shear wave velocity was measured.

The samples used for measuring shear wave velocities were utilised for assessing the yield stresses. The samples that had gone through the initial isotropic consolidation and subsequent unloading/reloading under undrained conditions (i.e. the shear wave velocities were measured at this stage) were then subsequently reconsolidated isotropically at low mean effective stresses. Then the mean effective stresses were increased up to 1100 kPa in stages.

## RESULTS

### Pore water pressure responses during unloading and reloading

Figure 4 shows the pore water pressure response during isotropic unloading and reloading under undrained conditions. The magnitude of the pore water pressure and the cell pressure prior to the unloading process were 500 kPa and 1300 kPa respectively and the initial pore water pressure is indicated by Point A in Figure 4. Upon completion of consolidation, the cell pressure was removed under undrained conditions and, as a consequence, the pore water pressure in the unlaminated sample immediately dropped to a lower value (-787 kPa, indicated by Point $B_{(NL)}$) where the pore water pressure in the laminated kaolin was about -40 kPa, which is indicated by $B_{(L)}$. The pore water pressures came to steady value within about 60 minutes and the final values of pore water pressure were -272 kPa and -20 kPa in the unlaminated and laminated samples respectively (the relevant points are indicated by Points $C_{(NL)}$ and $C_{(L)}$ in Figure 4). The reduction in the negative pore water pressure in the unlaminated sample was largely due to the absorption of the free water available in the top porous disc and the relevant drainage lines. However the massive reduction in the negative pore water pressure in the laminated sample was due to the free water available in the sand layers, the porous disc and the drainage lines.

On the reapplication of the confining pressure (1300 kPa) the pore water pressure in the sample initially increased to 952 kPa in the case of the unlaminated sample and that for the laminated sample was 990 kPa. These pressures gradually reduced to 590 kPa and 935 kPa in the unlaminated and laminated samples respectively. The corresponding mean effective stresses in the unlaminated and laminated samples were 710 kPa and 356 kPa respectively and the latter value is significantly lower than the initial effective stress applied to the sample (i.e. 800 kPa). The drop in pore water pressure was largely due to refilling of the previously emptied drainage lines and the voids in the porous disc in the case of the unlaminated sample. However, in the case of the laminated sample, the removal of cell pressure may have left a large amount of air in the sand layers due to cavitation (Hight and Leroueil, 2003; Ewy, 2015) and this would not necessarily all get dissolved in the water or compressed upon the reapplication of the cell pressure. That only means a higher pore water pressure in the sample. It clearly indicates water movement between the clay and sand layers. It was not the intention of the work to re-establish the B value close to 1, since it is not in normal practice to check this aspect in BS1377:1990 7/8. The final assessment of the void ratio of the clay layers in the laminated sample (after removing from the testing chamber and scarifying the sand) revealed that it had a value of 1.35 which was significantly higher than the unlaminated clay which had a value of approximately 1.09. The increased void ratio of the kaolin layers may therefore be due to a significant water movement from the sand layers to the clay layers. The increased void ratio may also be caused by other factors which are discussed later in this article.

## Undrained Shear Strength

Figure 5 shows the typical stress-strain curves for laminated and unlaminated samples (initially consolidated to a mean effective stress of 400 kPa) which were subjected to undrained compression either without isotropic undrained unloading or after isotropic undrained unloading/reloading. The differences in the stress-strain responses are quite pronounced, particularly when the samples were unloaded and reloaded before undrained shearing. Although it is a qualitative observation, the stiffnesses of the samples which had undergone unloading/reloading are noticeably less than those of the samples which were not unloaded before shearing under undrained conditions (more on this is discussed in the small strain responses). The undrained shear strengths obtained on each sample initially consolidated to 200 kPa of effective confining pressure (Table 1) were 55 kPa, 50 kPa, 48 kPa and 47 kPa respectively for clay which was laminated (not isotropically unloaded), laminated (isotropically unloaded and reloaded under undrained conditions), unlaminated (not isotropically unloaded) and unlaminated (isotropically unloaded and reloaded under undrained conditions), Figure 6. The removal of overburden pressure resulted in a reduction of approximately 10% in the undrained shear strength of the laminated clay and around 2%

for the unlaminated clay. The tests carried out on laminated samples at other consolidation pressures (i.e. 400 kPa and 800 kPa) exhibited a much greater reduction in undrained shear strength when compared to unlaminated samples (Figure 6). The differences in the undrained shear strength between the conditions “after initial isotropic consolidation” and “isotropic unload and reload under undrained conditions” prior to shearing are quite prominent in laminated samples, with an average of 15% strength reduction caused by the removal of overburden pressure whereas the equivalent reduction for unlaminated samples is not significant (Figure 6b). These observations also agree with a significant increase in pore water pressure after unloading and reloading under undrained conditions in laminated soils, as discussed before, based on the observations shown in Figure 4.

Figure 7 shows the relationship between the void ratio and the consolidation pressure for samples initially isotropically consolidated to 800 kPa of effective confining pressure for both laminated and unlaminated samples. The filled circular data point refers to the initial stress state of the sample prior to unloading under undrained conditions and the open circular data point refers to the approximate yield stress upon reconsolidation. The approximate value of the yield stresses (estimated using the method by Casagrande) are 315 kPa and 620 kPa for laminated and unlaminated samples, respectively. In the case of the laminated sample, the reduction in the yield stress (with an initial consolidation pressure of 800 kPa) is significant. The value of the yield stress ratio (ratio between yield stress $p'_Y$ and the previous consolidation pressure $p'_o$) is approximately 0.40 for the laminated sample and that for the unlaminated sample is approximately 0.87, but it is accepted that determining the yield stress is not a clear-cut process. These ratios for other initial consolidation pressures are summarised in Figure 8.

$G_{max}$ was measured on samples that were consolidated to required effective consolidation pressures (mean effective stresses) and isotropically unloaded and reloaded under undrained conditions to the original consolidation pressures (Table 1). The shear wave velocity ($V_s$) and bulk density ($\rho_s$) prior to introducing the shear wave were calculated carefully in order to determine $G_{max}$ ($=\rho_s V_s^2$). Figure 9 shows $G_{max}$ plotted against consolidation pressure for loaded and unloaded/reloaded samples in the case of unlaminated and laminated samples. The reduction in the small strain stiffness upon isotropic unloading and reloading in the case of laminated soils is significant and reasonably consistent at all stress levels. However for unlaminated samples the difference is not significant and these values agree with existing data in literature (Jovcic, 1997; Landon *et al.,* 2007; Ferreira *et al.,* 2011; Donohue and Long, 2010; Vardanega and Bolton 2013).

## DISCUSSION

As outlined earlier, other factors during the *in-situ* sampling process not investigated in the present investigation could have generated further reductions in the relevant geotechnical properties. The apparent reduction in performance within the context of the present investigation may therefore be largely attributed to the water movement from sand layers to clay layers during the unloading process and this process is not completely reversible upon re-application of external loading as highlighted in Figure 4.

The reduced strength and stiffness of the laminated soils upon unloading and reloading under undrained conditions also could have been caused by other factors, for example the remoulding of clay layers due to interfacial shearing. In essence the sand layers act as horizontal reinforcements to the clay layers. When an isotropic loading is applied on a laminated sample, the clay and sand layers experience generally similar vertical stresses. However due to the difference in the stiffness and frictional properties of sand and clay (the friction angle of kaolin is $21^0$ and that for sand is $33^0$) the sand layers carry more loading than the clay layers in the lateral direction, at least closer to the flexible lateral boundaries. Therefore, the loading in the clay and sand layers is no longer under isotropic stress conditions. It is possible that the clay layers may have experienced lower consolidation pressures in the lateral direction than in the vertical direction, largely caused by internal shear stresses along the interfaces between sand and clay layers, as illustrated in Figure 10. This aspect is further validated by some qualitative observations which are described below.

Clay samples subjected to isotropic consolidation would undergo lateral and axial compressions in equal magnitudes, provided the stress-strain characteristics of the samples are isotropic. However, under laboratory testing conditions, the samples generally exhibit necking (where lateral strains at the drainage boundaries are much smaller than those along the sample), due to friction between the sample and the filter disks. A similar situation prevails in laminated samples where the stiffer frictional material (in the present case, sand) is sandwiched between the clay layers, totalling 25% of the volume. One typical case is presented below to support this postulation.

Some approximate values of strains in vertical and horizontal directions are presented, which were obtained on a laminated sample subjected to 800 kPa of isotropic consolidation pressure. Figure 11a shows the image of a laminated sample which had an initial diameter of 100 mm and was then subjected to an effective isotropic consolidation pressure of 800 kPa (but had not yet undergone shearing). Figure 11b shows an identical dummy sample that has a diameter of 100 mm. The purpose of this dummy sample was to provide a control or baseline and therefore to avoid errors in approximate measurement of the diameter using images, these errors being caused by refraction when the sample was contained in a cylindrical cell filled with water. During isotropic consolidation, the laminated clay sample experienced 7.5% axial strain (based on an external displacement transducer, assuming the axial compression of the sand layers is not significant when compared with clay). The same sample expanded laterally by 5 mm in diameter, corresponding to 5% radial strain (approximately). Therefore, the net shear strain ($\varepsilon_s$) of the clay layer is approximately 8.3%, which is sufficient to take the clay closer to critical state although the boundary stresses were isotropic. The lateral stresses acting on the clay and sand layers are highly variable due to frictional resistance between the materials. It is possible that part of the sand layers may undergo passive loading as opposed to the clay layer undergoing active loading. When the laminated sample is then sheared under undrained conditions, the clay layers may offer remoulded strength to the overall shear strength of the laminated sample.

When the laminated sample is unloaded isotropically under undrained conditions, negative pore water pressure develops in the clay and sand layers (Figure 4). Since the sand layers cannot sustain negative pore water pressure, the effective stress in the sand reduces significantly. The clay layers can sustain negative pore water pressure but they also have access to the free water available in the sand layers. If the confining pressure is reapplied, it may not be possible to completely reverse the process making the sand layers fully saturated. This could in effect weaken the clay layers as discussed earlier. In addition the interfacial shearing between the clay and sand layers during the reapplication of confining pressure could further aid the remoulding of the clay layers, contributing to further loss of shear strength. These aspects could have determinant effects on undrained shear strength, stiffness and yield stresses. The authors wish to bring to the reader’s attention that the tests were carried out in a laboratory environment in a controlled fashion using a simple model. In natural soils the interface between clay and sand layers tends to be much more diffuse, with a band of interpenetration between materials, so the effects of water movement related to loading-unloading cycles are probably much more complex. As pointed out earlier, the sample disturbances may also be caused by several other factors (previous stress history, cutting-edge of the sampling tube, ground water level etc.) which were not considered in this investigation.

## CONCLUSIONS

Sample disturbances in laminated soils *in-situ* may be caused by several factors including water movement between the clay and sand layers upon removal of overburden pressures and physical processes (sampling methods). This article investigated the former factor in an idealised manner through laboratory investigations. A number of samples (laminated and unlaminated) were subjected to undrained shearing following isotropic compression to various consolidation pressures. The results have shown that the isotropic unloading/reloading process under undrained conditions leads to a significant reduction in undrained shear strength, shear modulus and yield stress ratio in the case of laminated samples. The reductions in such parameters are not significant in unlaminated samples. The reason for this is attributed to moisture movement from the sand to the clay layers during the removal of total stress under undrained conditions and due to a potential remoulding process during initial consolidation and the subsequent unloading/reloading process.

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Table 1 List of tests

| **Test No** | **Consolidation pressures kPa** | **Testing conditions** | **Test carried out** |
|---|---|---|---|
| Laminated | | | |
| 1,2,3 | 200,400,800 | Loaded | Undrained compression |
| 4,5,6 | 200,400,800 | Unloaded and reloaded | Undrained compression |
| 7,8,9 | 200,400,800 | Loaded | $G_{max}$ |
| 7*,8*,9* | 200,400,800 | Unloaded and reloaded | $G_{max}$ |
| 10,11,12 | 200,400,800 | Unloaded and reloaded | Yield stress |
| 13,14,15 | 200,400,800 (repeat) | Unloaded and reloaded | Undrained compression |
| 16 | 800 (repeat) | Loaded | Undrained compression |
| Unlaminated | | | |
| 17,18, 19 | 200,400,800 | Loaded | Undrained compression |
| 20,21,22 | 200,400,800 | Unloaded and reloaded | Undrained compression |
| 23,24,25 | 200,400,800 | Loaded | $G_{max}$ |
| 23*,24*,25* | 200,400,800 | Unloaded and reloaded | $G_{max}$ |
| 26,27,28 | 200,400,800 | Unloaded and reloaded | Yield stress |

* No separate sample required for measuring $G_{MAX}$ of isotropically unloaded/reloaded samples

**Figure captions**

Figure 1  Deviator stress vs axial strain during undrained compression of Belfast clay

Figure 2  Construction of laminated samples

Figure 3 Suction measurements using high capacity tensiometer

Figure 4 Pore water pressure measurements during unloading-reloading process

Figure 5  Stress-strain curves for laminated and unlaminated samples consolidated to 400 kPa of mean effective stress (samples subjected to shearing after consolidation and isotropic unloaded/reloaded)

Figure 6  Undrained shear strength vs consolidation pressure

Figure 7  Void ratio vs  consolidation pressure (ln scale) for unlaminated and  laminated samples

Figure 8  Stress ratio vs initial consolidation pressure for laminated and unlaminated samples

Figure 9  $G_{max}$ vs  consolidation pressure for unlaminated  and laminated samples

Figure 10  Vertical and lateral stresses acting on  laminated sample

Figure 11  Physical observations of laminated sample with respect to axial and lateral deformation during consolidation

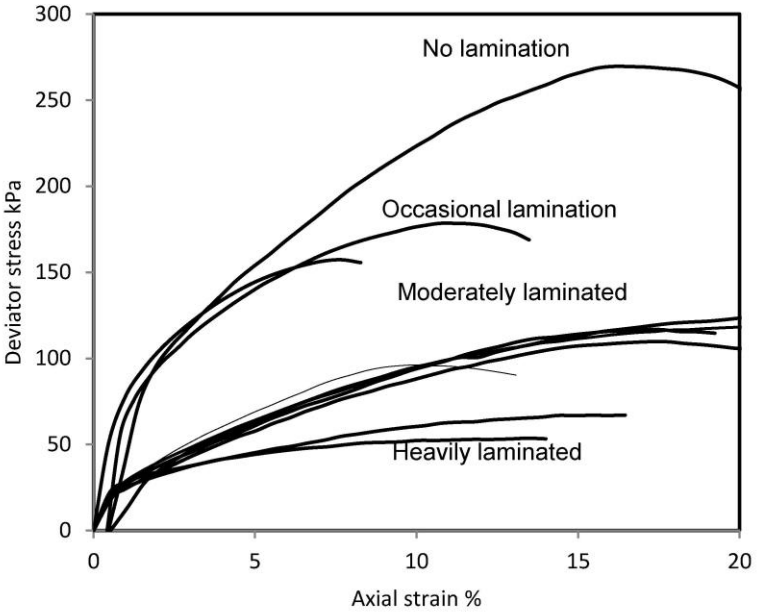
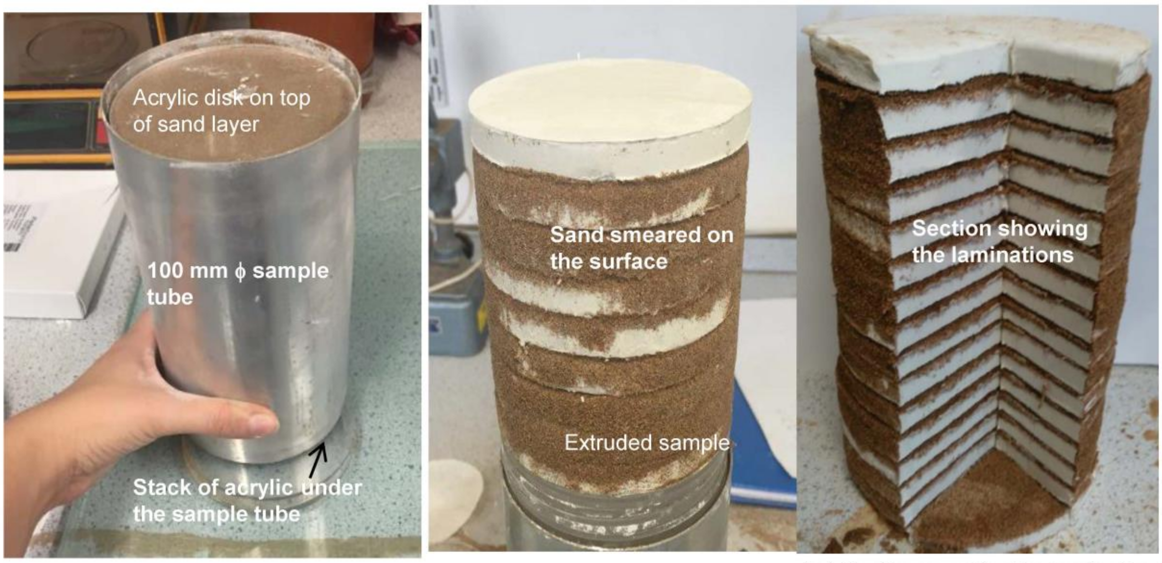

No lamination
Occasional lamination
Moderately laminated
Heavily laminated
Deviator stress kPa
Axial strain %
0
50
100
150
200
250
300
0
5
10
15
20

Figure 1



(a ) Formation of sample (b ) Extruded sample (c ) Section revealing the laminations

Figure 2

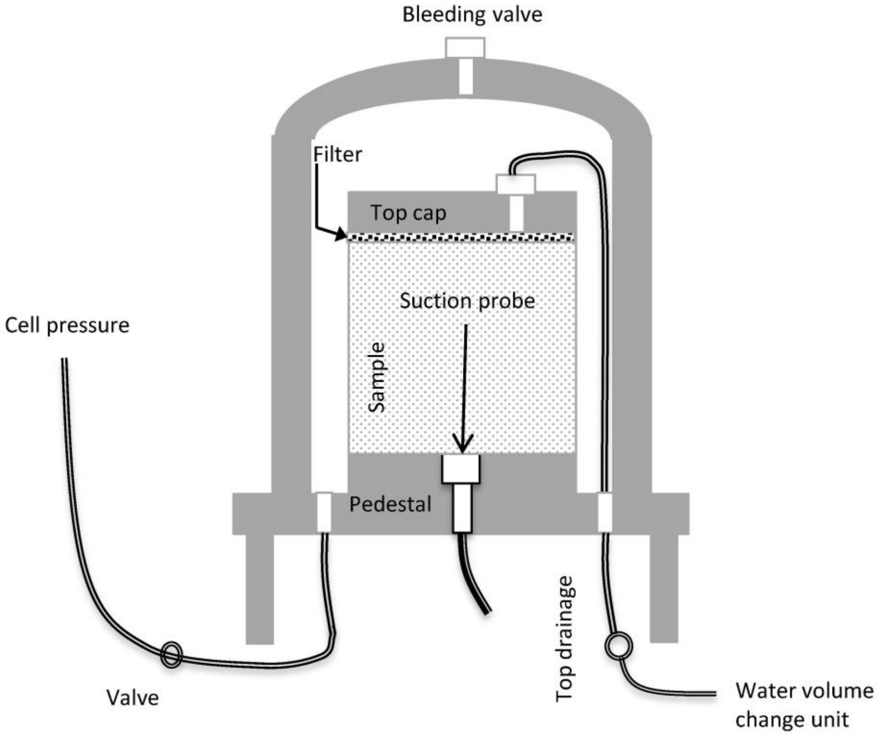

Bleeding valve
Filter
Top cap
Suction probe
Cell pressure
Sample
Pedestal
Top drainage
Valve
Water volume change unit

Figure 3

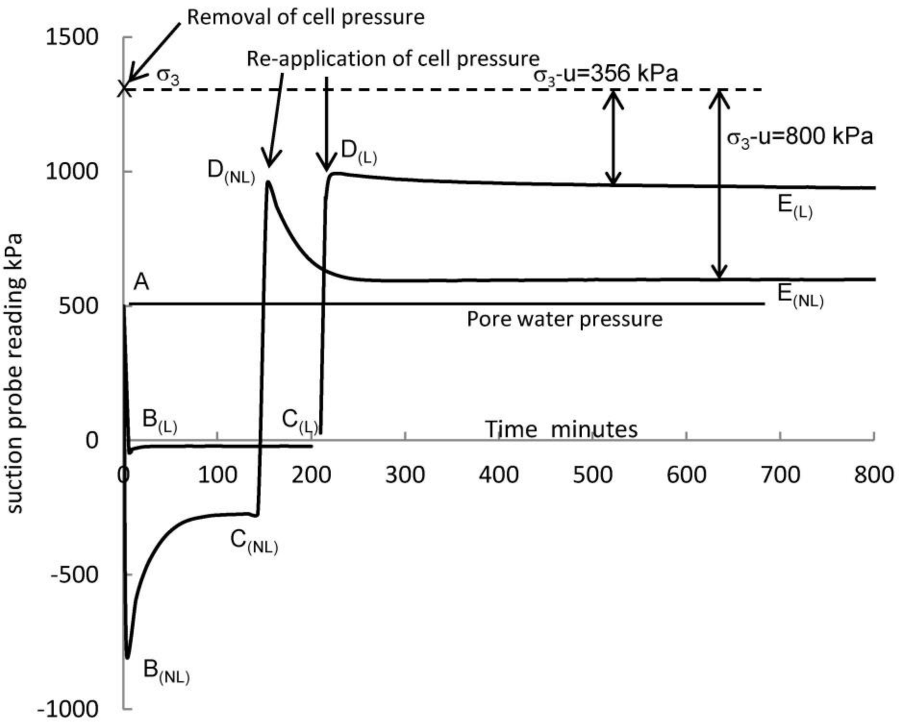

Removal of cell pressure
Re-application of cell pressure
$\sigma_3$
$\sigma_3$-u=356 kPa
$\sigma_3$-u=800 kPa
$D_{(NL)}$
$D_{(L)}$
$E_{(L)}$
$E_{(NL)}$
A
Pore water pressure
$B_{(L)}$
$C_{(L)}$
$C_{(NL)}$
$B_{(NL)}$
Time minutes
suction probe reading kPa
1500
1000
500
0
-500
-1000
0
100
200
300
400
500
600
700
800

Figure 4

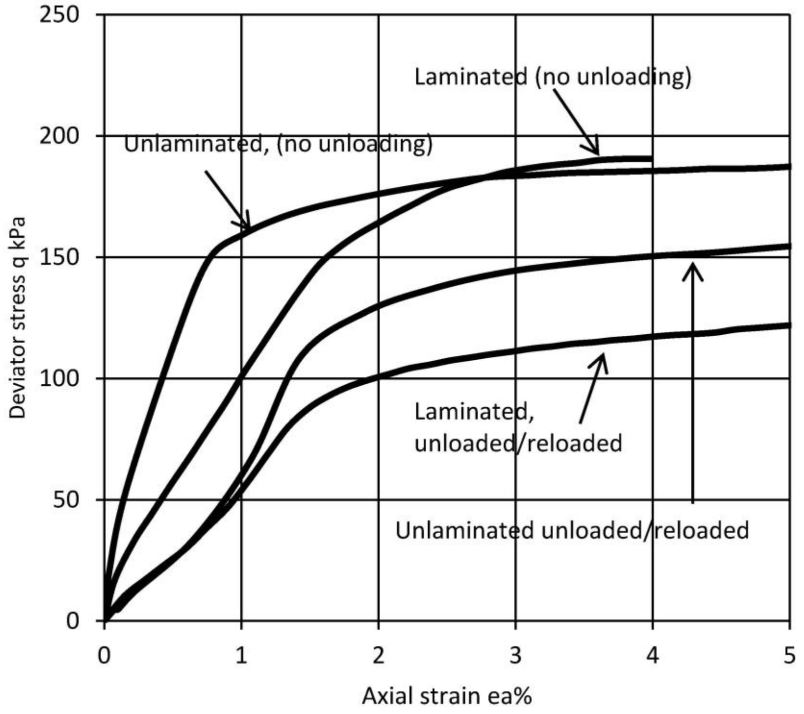
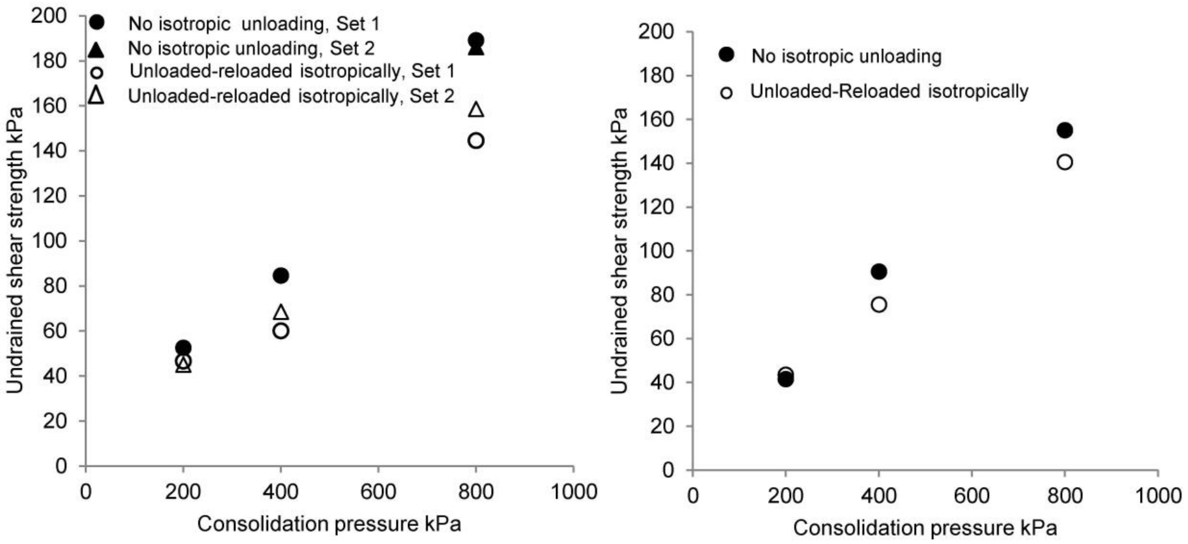

250
200
150
100
50
0
Deviator stress q kPa
0
1
2
3
4
5
Axial strain ea%
Laminated (no unloading)
Unlaminated, (no unloading)
Laminated,
unloaded/reloaded
Unlaminated unloaded/reloaded

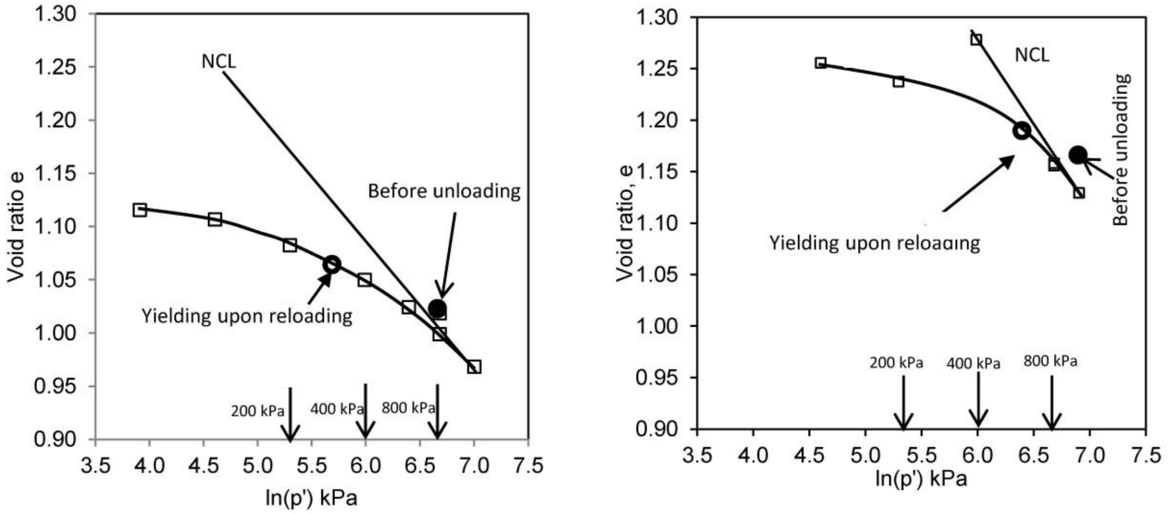
Figure 5



(a) Laminated clay

(b) Unlaminated clay

Figure 6



(a) Laminated

(b) Unlaminated

Figure 7

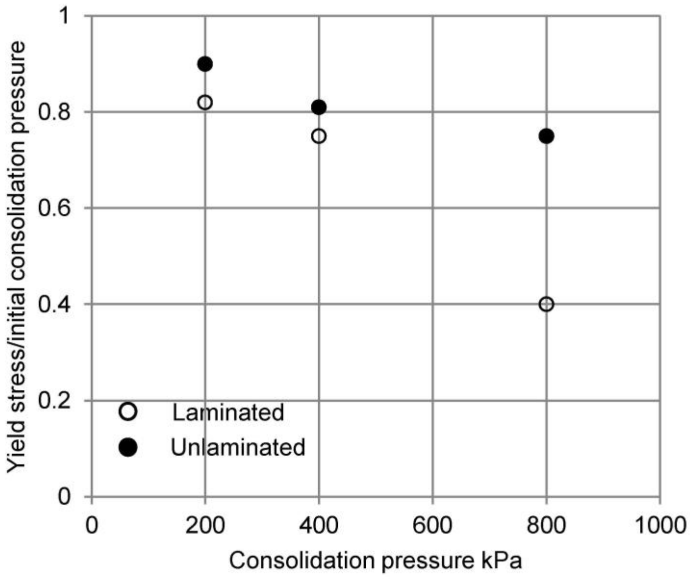
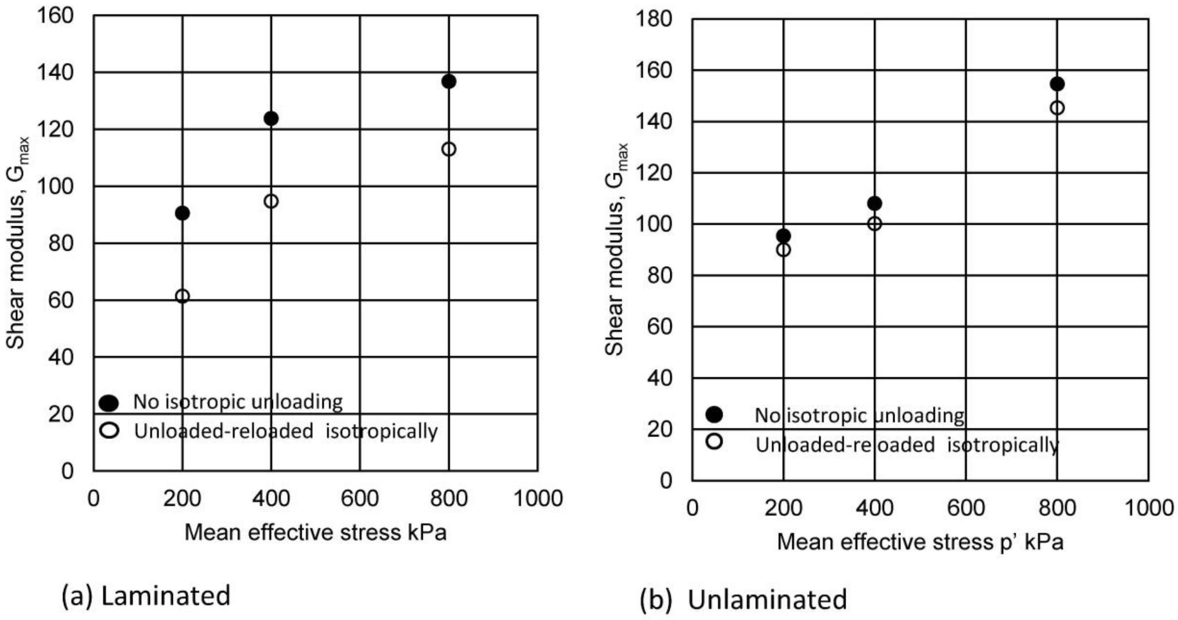

1
0.8
0.6
0.4
0.2
0
Yield stress/initial consolidation pressure
Laminated
Unlaminated
0
200
400
600
800
1000
Consolidation pressure kPa

Figure 8



(a) Laminated

(b) Unlaminated

Figure 9

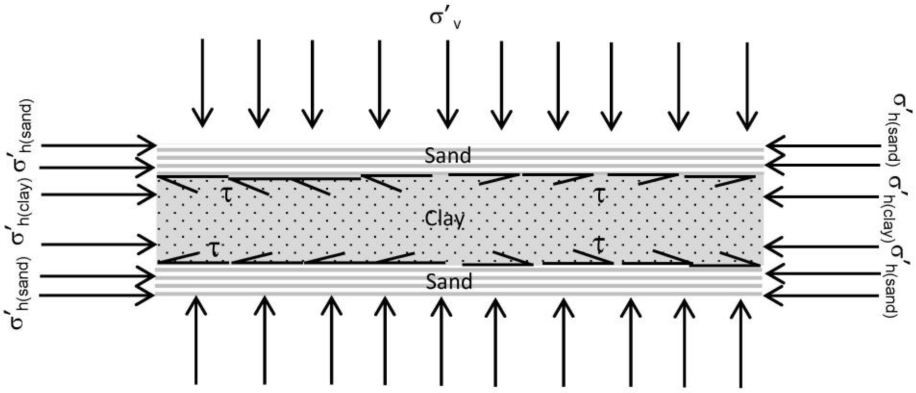
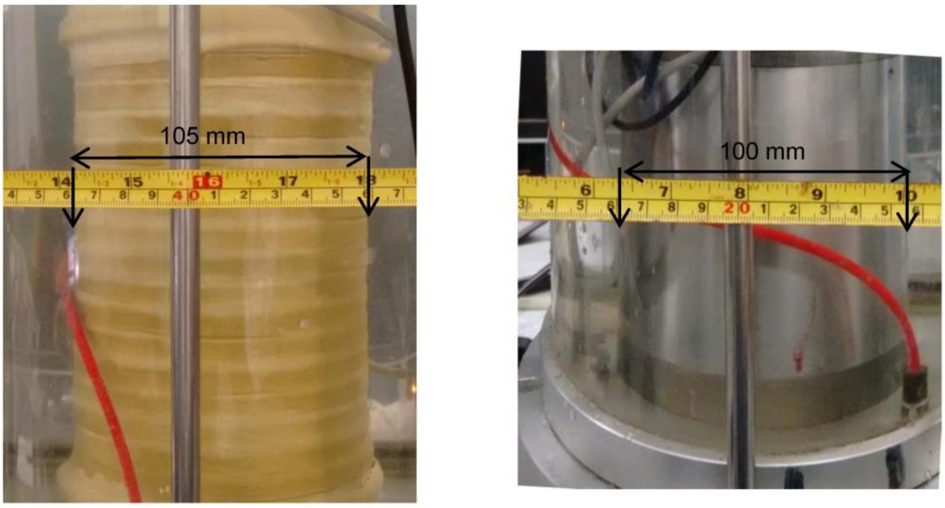

σ′v
σ′h(sand)
σ′h(clay)
σ′h(sand)
σ′h(sand)
σ′h(clay)
σ′h(sand)
Sand
Clay
Sand
τ
τ
τ
τ

Figure 10



(a) Image of the sample while in consolidation cell under 800 kPa of effective consolidation pressure

(b) Dummy sample

Figure 11