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Clay structure and K_0 measurements

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ABSTRACT: This paper discusses the importance of adopting consolidation procedures in triaxial and direct shear tests that do not alter the 'in-situ' mean effective stress of structured clays to enable a correct assessment of the strength and stiffness responses of these clays. Following the extensive studies on 'structure' of clays (fabric and bonding) carried out in the 1990s, the discussion highlights the importance of testing high quality samples, and the risks associated to procedures that could adversely affect intact structure of the material, focusing on the correlation between clay structure and earth pressure at rest (K0). It concludes that the preservation of the intact structure of the clay is essential for the correct assessment of K0.

KEYWORDS: Structure, strength, stiffness, strains, K_0, stiff clays.

1 INTRODUCTION

The structure of soils, intended as a combination of particle arrangement (fabric) and interparticle forces (bonding), develops from both depositional and post-depositional processes and reflects the cumulative effects of the geological history of a soil.

Natural deposits are in an 'intact state of structure' (Leroueil and Vaughan, 1990), and, under large strains, this can degrade to a 'destructured state'. If the soil structure has also developed through post-depositional processes, the soil can reach 'structure-permitted' stresses higher than its pre-consolidation stresses (i.e. the maximum stress reached by the soil during its geological history).

However, after yield (i.e. the onset of larger volumetric changes) the compression curves of soils with meta-stable structure would tend to converge towards the curve of the reconstituted material as the intact structure of the soil degrades; the compression curves of soils with stable structure, instead, would tend to move along a compression line that remains parallel to the normal compression line of the reconstituted material as the destructuration of these materials is typically limited to degradation of bonding and the soil fabric remains unaffected by the applied strains (Baudet and Stallebrass, 2004).

Cotecchia and Chandler (2000) show that samples of a stiff depositional clay (Pappadacia clay) sheared after compression to stresses higher than the gross yield define a failure surface that plots below the failure surface of the samples sheared from stresses similar to their in situ stresses due to the damage occurred to the soil structure by the large strains experienced during compression.

On the contrary, structurally complex clays including clay shales and glacial till could have lower strength than the reconstituted material as their macro-fabric includes planes of weakness. This 'negative' effect of intact structure can also be removed by the application of large strains (Fearon and Coop, 2000), so that the strength measured after consolidation paths involving large strains would be higher than the in-situ strength of these materials. A comprehensive summary of the effects of soil structure on the compression and shearing behaviour of soils is provided by Jardine et al. (2004).

The characterisation of natural deposits requires tests to be carried out on samples that are representative of the deposit in its intact state of structure. As well as adopting sampling techniques that minimise disturbance to the soil structure during the sampling process, it is important to adopt test procedures that avoid uncontrolled disturbance to the sample prior to the application of the intended loads.

Gasparre et al. (2008) showed that the development of plastic strains during the consolidation paths affects the stiffness response of London Clay to the stress history imposed during the consolidation process.

This paper discusses the stiffness and strength response of stiff, high plasticity clay samples that have experienced different levels of strains during their consolidation path prior to shearing.

2 MATERIALS AND TEST DETAILS

2.1 *Samples tested*

High quality samples obtained from 23-25m at a location in West London were used for the tests discussed in this study. The samples were retrieved using triple barrel rotary corer with polymer foam lubrication. Immediately after sampling, the outer 5mm of the sample shafts, wet from the drilling fluid, were removed to minimize changing to the in-situ water content and swelling of the samples due to free water around them. The samples were then wrapped in cling film and wax for storage until testing. Table 1 summarises the initial properties of the samples used in this study.

Table 1. Sample properties

Test name	Sample depth [m]	Initial specific volume	Plasticity Index [%]
t33-22.6gUC	22.75-22.95	1.72	44
t25-23.7aUC	23.6-23.8	1.67	43
t26-23.6iUC	23.4-23.6	1.69	43
t37-24.3gkUC	24.3-24.5	1.68	40
t44-22.6ikUC	22.4-22.6	1.73	44

2.2 *Assessment of K_0 and in-situ stresses*

Given the close proximity of the samples to each other, they were assumed to have the same nominal in-situ stress state. Their coefficient of earth pressure at rest (K_0) was determined from the suction measured on thin wall samples obtained from the same location (Hight et al., 2003); these were higher than the suction measured on rotary core samples obtained from the same location but were considered more representative of the in-situ mean effective stress (p'_0) of the clay because the rotary core samples were in contact with the drilling fluid that could have reduced their original suction.

The K_0 and in-situ stresses were also estimated using the correlations proposed by Mayne & Kulhawy (1998). Considering that the geological history of the London Clay in the area involved depositional processes followed by erosion and deposition of Quaternary materials, a simplified 'three-phases' geological history was assumed, characterized by the following K_0 relationships:

Deposition of clay:

$$K_{0NC} = 1 - sin\varphi' \qquad (1)$$

Erosion of clay:

$$K_0 = (1 - sin\varphi')OCR^{sin\varphi'} \qquad (2)$$

Deposition of Quaternary deposits on the clay:

$$K_0 = K_{0NC}\left[\frac{OCR}{OCR_{max}^{1-sin\varphi'}} + \frac{3}{4}\left(1 - \frac{OCR}{OCR_{max}}\right)\right] \qquad (3)$$

where ϕ' is the critical state friction angle of the clay, taken as 20°; OCR is the Over Consolidation Ratio of the clay, obtained from the assumption that the erosion involved the removal of approximately 175m of clay (Skempton & Henkel, 1957; Chandler, 2000);

The in-situ K_0 derived from the above relationships was different from that calculated from the suction measurements (Hight et al. 2003), as shown in Table 2.

Table 2. Estimated K_0

Reference depth for calculations [m]	K0 assessed from suction measurements on thin wall samples (Hight et al. 2003)	K0 assessed from suction measurements on rotary core samples	K0 assessed from Mayne and Kulhawy (1982)
25m	1.5	1.05	1.14

The difference is believed to be due to the simplifications of the three-phases history, because, given the influence of the sea level changes during deposition and the presence of the lithological units, it is likely that the London Clay has undergone several cycles of deposition and erosion throughout its geological life before the final deposition of Quaternary Deposits. The calculations also neglect the development of bonding throughout the geological history of the clay.

Given the difficulty in simulating a more complex geological history, the geological path of the clay was assumed to be represented by the simplified "three phases" path 'shifted' so that the end of Quaternary deposition matched the stress point obtained from the suction measurements, as shown in Figure 1.

The re-loading stress path due to the deposition of the gravel is likely to reproduce quite realistically the last geological stress path on this site and was expected to have a more significant influence on the sample behaviour, therefore the simplified shift of the geological stress paths was considered adequate.

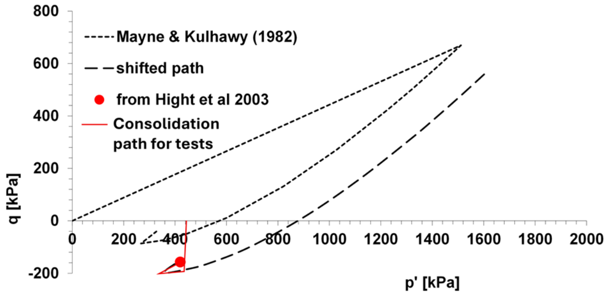


Figure 1. Compression curves of intact samples and reconstituted clay (Intrinsic compression line)

2.3 *Testing procedures*

Prior to starting the sample setting procedures, the triaxial apparatus was kept under pressure for 24h to ensure full saturation of the drainage system. During the sample-set-up process, which involved the application of local instrumentation, bender elements and mid-height probe, the samples were suspended on thin wires placed on the pedestal of the triaxial apparatus. This avoided direct contact between the drainage system and the sample at a stage where the suction in the sample was very high and could cavitate the drainage system of the triaxial cell. Contact between the sample and the drainage system occurred when the cell pressure was applied so that positive pore pressure could be measured. This enabled to obtain high saturation parameters (B>95%) for the samples in all cases, so that the p' measured in the triaxial apparatus coincided, with good approximation, to the suction of the samples after sampling and did not require 'saturation' procedures.

Before being sheared undrained in compression, the samples were subject to different consolidation paths, as shown in Figure 2:

- Sample t33-22.6gUC was consolidated to the estimated in-situ stresses following a stress path that replicated only the last part of the assessed recent stress history of the clay: from the initial isotropic p' measured at sample set up, the deviatoric stress (q) was reduced to intercept the assumed geological unloading curve and then continue along the unloading and reloading sections (Figure 2). Through this consolidation path, the samples experienced volumetric strains of approximately 0.2% and axial strains of approximately 0.4%.
- Sample t25-23.7aUC followed a similar approach path to reach a different anisotropic state defined by K_0=1.05, which was derived from suction measured on rotary cored samples at the same depth. Through this approach path, the samples experienced approximately 1.1% volumetric strains and 0.6% axial strains.
- Sample t26-23.6iUC was consolidated isotropically to p'=1.3MPa, more than three times higher than the estimated in-situ p'_0 and experienced approximately 1.6% axial strains and 2.9% volumetric strains.
- Sample t37-24.3gkUC was first consolidated to its in-situ state following a stress path similar to that of sample t33-22.6gUC, and then compressed in one dimensional conditions (i.e. K_0 consolidation) by increasing the axial stress and automatically adjusting the radial stresses to ensure zero radial strains (Figure 2). This sample experienced approximately 2.4% and 2.5% axial and volumetric strains respectively.
- Sample t44-22.6ikUC was consolidated isotropically to p'_0 and then one-dimensionally (i.e. K_0 consolidation) to

860MPa, more than twice p'$_0$. This sample experienced more than 2.5% axial and volumetric strains during its consolidation path prior to shearing.

It should be noted that none of the tests reached the estimated pre-consolidation pressure of the clay and did not show any gross yield (Figure 3).

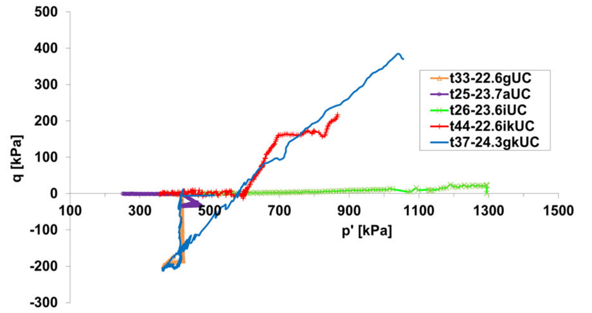


Figure 2. Stress paths followed by the samples prior to shearing.

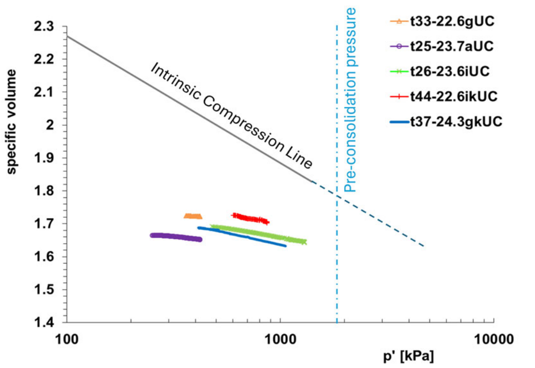


Figure 3. Compression curves of intact samples and curve of reconstituted material (Intrinsic Compression Line), with the estimated pre-consolidation pressure also marked-up.

3 STRENGTH AND STIFFNESS RESPONSE

Figure 4 shows the curves of deviatoric stress normalised by the mean effective stress (q/p') against axial strains (ε_a) for the samples in Table 1.

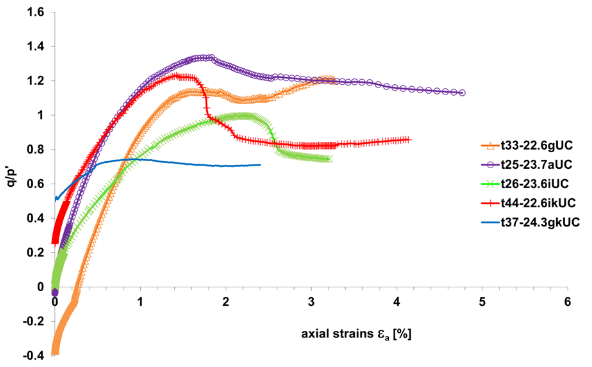


Figure 4. Normalised stress-strain curves against strains during shearing.

The samples that experienced large strains before shearing appear to converge towards a critical state that is lower than that defined by the intact samples, which experienced low strains before shearing. It should be noted that when the shearing of t33-22.6gUC reached approximately 0.2% axial strains, a leak of the drainage system occurred so that the sample was partially drained; this affected the development of its peak strength, but the results are representative at large strains.

At critical state, the q/p' ratio of the samples that experienced large strains before shearing is approximately 0.8 and coincides with the value defined for reconstituted samples from similar depths (Gasparre, 2005).

Figure 5 shows that the stiffness curves of the samples that experienced large strains during the approach path plot below the curves of the samples that experienced low strains; the stiffness reduction depends on the strains developed and is more significant when both axial and volumetric strains occur, as indicated in Figure 6.

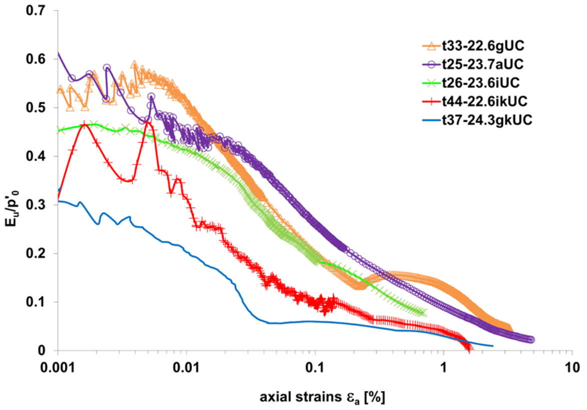


Figure 5. Curves of undrained stiffness (E_u) normalized by p' at the start of shearing (indicated as p'_0 , although it does not coincide with the in-situ stress for the samples consolidated to high stresses).

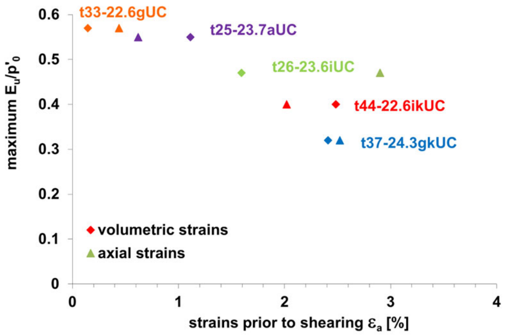


Figure 6. Variation of maximum Eu/p'o measured in shearing against the axial strains developed in the approach stress path prior to shearing.

4 K$_0$ COMPRESSION

Test t44 was compressed in a one-dimensional mode (i.e. along a K$_0$ line) from its estimated in situ stress state. The oedometric modulus (M) measured during this stage is shown in Figure 7. It appears to have an initial plateau up to axial strains of approximately 0.01% (equal to volumetric strains in this compression mode); beyond this value, it starts to reduce as the strains continue to increase, and the changes are more significant when the strains exceed approximately 0.2%.

The ratio of horizontal to vertical stresses (i.e. K$_0$) measured in this test shows a similar pattern: up to 0.01% strains, it remains constant at the value to which the sample was consolidated (i.e. 1.5) based on the suction measured on thin wall samples (see Section 2.2), which also broadly corresponds to the K$_0$ value obtained from the initial p' measured in the triaxial apparatus; as the axial and volumetric strains increase beyond 0.01%, K$_0$ starts to reduce (Figure 8a) and, at larger strains, it tends towards a constant value of approximately 0.75 (Figure 8b).

The consistency between the strain reduction of oedometer stiffness M and K_0 suggests that the K_0 measured up to 0.01% strains is to the true K_0 of the clay from the tested depth (25m), while its reduction is related to alterations of the natural structure of the material.

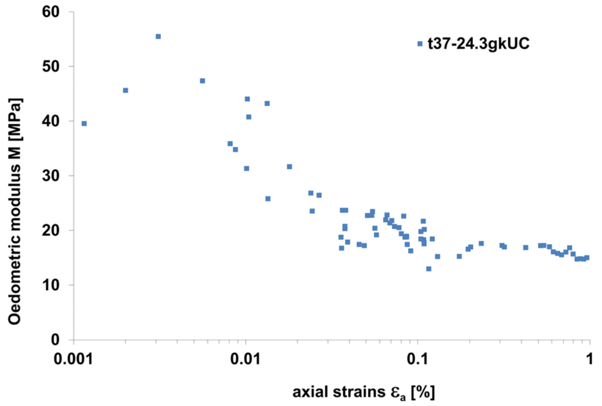
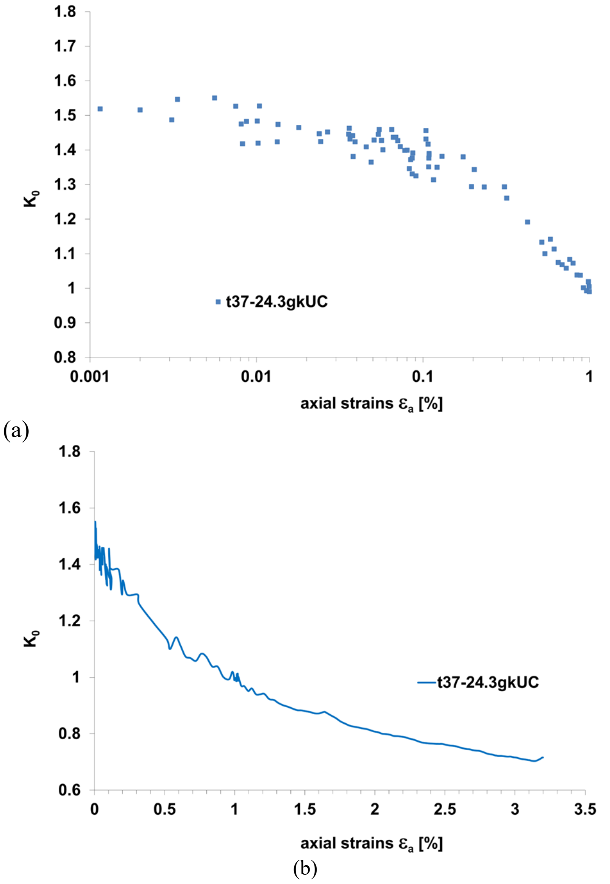


Figure 7. Modulus of oedometric compression (M) against volumetric (axial) strains



(a)

(b)

Figure 8. K0 against volumetric (axial) strains in the (a) small strain and (b) large strain range

5 CONCLUSIONS

Consolidation stress paths that involve large strains damage the intact structure of stiff, overconsolidated clays like London Clay, and adversely affect their strength and stiffness responses to shearing. Alterations to the intact structure of the clay start when the consolidation strains exceed approximately 0.2% and adverse effects on the true stiffness and strength response of the material are noticeable for consolidation strains that exceed approximately 1%.

The true K_0 of the clay degrades as the one-dimensional consolidation path proceed and strains exceed approximately 0.2%.

Damaging strains occur when the in-situ stresses of the clay are significantly changed, below reaching high stresses corresponding to the pre-consolidation pressure of the clay.

Tests aiming at the characterisation of the in-situ conditions of stiff deposits should therefore adopt testing procedure that preserve the intact state of the clay structure and avoid the occurrence of excessive strains prior to shearing. SHANSEP consolidation methods are therefore not appropriate on structured clays as the required stress changes and the associated unrecoverable strains are such that the strength and stiffness responses of the clay to shearing would be unrepresentative of the in-situ material.

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