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Experimental Insight into the Small Strains Behaviour of Compacted Clay

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Abstract: This study presents the results of an experimental investigation into the stress-strain behaviour of re-compacted unsaturated clayey soil, with an emphasis on the behaviour at small strains levels. Series of triaxial tests were conducted in a hydraulic stress path controlled cell, on unconsolidated undrained samples. No measurement of pore water pressure was made; the results were interpreted in terms of total stresses. To account for the small strains behaviour of the soil, several strains measurement methods were used. Initially identical isotropicaly compressed specimens were subjected to triaxial compression following a variety of stress paths. The strains measurements, the stress path dependency and the effect of the initial isotropic confining pressure are discussed. For the interpretation of the results obtained, use was made of the method of strains energy contours.

Key words: Re-compacted clay, triaxial testing, small-strains, energy contours

INTRODUCTION

Typically the majority of soil mass influenced by construction projects including compacted soils are governed by the small strains behaviour; therefore, accounting for its effects during analysis offers potential improvements in accuracy. Research works have shown that at small strains levels, soils exhibit non-linear stiffness (Atkinson, 2000). This fact was put forward by many fundamental studies (Jardin *et al.*, 1986; Burland, 1989; Stallebrass, 1990; Messerklinger, 2006) and was a key topic in many geotechnical conferences. Therefore, investigating the small strains behaviour of compacted clayey soils remains an up-to-date issue. Quality experimental results involving small strains measurements are still required as they are still the only reliable way for full validation of proposed constitutive and numerical models.

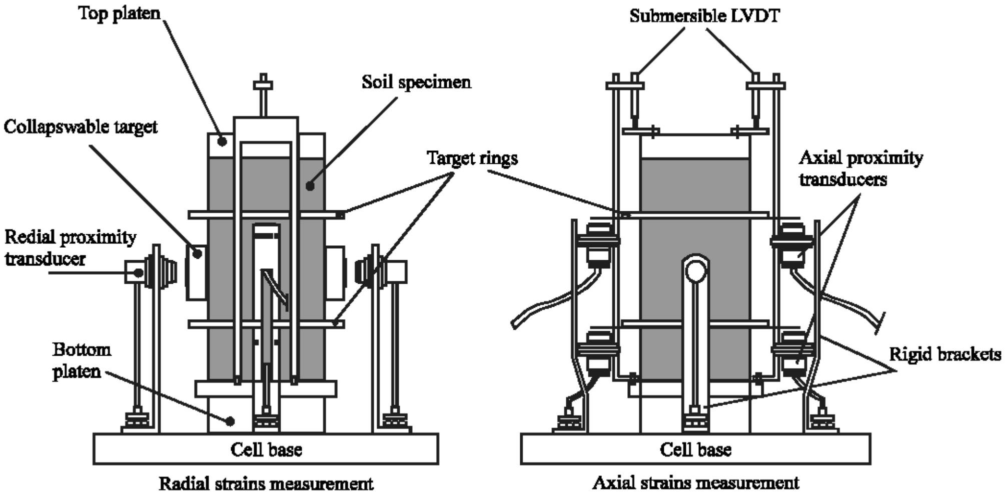
Conventional procedures for determining deformations during triaxial tests are generally based on measurements made externally to the cell. This practice is inadequate, particularly if the small strain stiffness of the soil is being investigated, because errors are introduced which limit the accuracy and resolution of the measurements. The errors can only be eliminated if axial strains are determined internally, within the cell and locally over the central one third of the specimen. Likewise, the radial dimensions should be monitored at specimen mid-height. The introduction of a diverse range of new small-strain measuring devices in the triaxial cell has been largely in response to recognition of the importance of achieving strain measurement accuracy of at least 1-3% for small-strain stiffness evaluation.

In the present study, the small strains behaviour of a compacted clayey soil is investigated. Quality triaxial tests were conducted in a hydraulic stress path controlled cell. For the accurate measurements of the small strains deformations, the cell was equiped with several local strains measurement devices. Initially identical isotropicaly compacted specimens of re-constitued clay were subjected to triaxial isotropic confinning pressure, the sample was then subjected to a variety of stress paths. For the interpretation of the results obtained use was made of the method of strains energy contours. For the compacted soil investigated, the strains measurements, the stress path dependency and the effect of the initial isotropic confining pressure are discussed.

MATERIALS AND METHODS

Stress path cell: The tests involved in this research were performed in an automated triaxial stress path cell for specimens of 100 mm diameter and 200 mm height. A comprehensive description of this cell and its past performance has been presented by Rouili (1992). Although there are differences of practical detail, the design of the cell is similar in principle to that of Bishop and Wesley (1975). This triaxial apparatus used in the present research is fully automated; it was equipped with a pressures control systems (for the monitoring of the lower chamber and the cell pressures) and computerized data logger for the control of the test and the monitoring of the results.

Local strains measurements: To account for the small strains behaviour of this soilseveral methods involving



Radial strains measurement

Axial strains measurement

Fig. 1: Arrangement of the local strain measurement devices

external and local strains measurement devices were used. For local axial strain measurement two methods were used: The first consist of mounting 2 pairs of submerssible transducers to measure the axial displacement corresponding to the vertical movement of targets mounted on special rings attached to the specimen. The second method consist of pair of transducers measuring the axial strain between the specimen end caps. For the purpose of comparing the results, an additional LVDT was mounted externally for the axial strain as deduced from the vertical displacement of the loading ram.

For radial strains measurement a pair of submersible transducer was used, mounted on fixed brackets to measure the lateral displacement of the sample by means of a collapsible targets fixed to the specimen. The local strains are computed as the average of the strains measured from the 2 sides of the specimen. The arrangement of the local strain measurement devices are presented in Fig. 1.

Soil and sample preparation: The material used in this investigation was a glacial till from a site near Cowden on the Holderness Coast (United Kingdom). It was sampled from depth varying between 3 and 7 m, where the soil profile consists mainly of fairly gravely clay of low to medium plasticity.

This soil is well graded and contains around 30% of clay-sized particles. In its natural state the soil has a moisture content around 14-5% and the liquid and plastic limits are 35 and 17%, respectively. The sample was prepared in a mould and compacted statically in nine layers, provided that the height to diameter ratio of the specimen is not greater than 1: 2, research has shown that static compaction gives the most uniform samples (Sivakumar, 1993).

Testing programme and procedure: The testing programme was conceived in relation to the constitutive relationships of the elastic model for anisotropic elasticity of natural clays proposed initaly by Graham and Houlsby (1983) and used by many researcher in modelling small strain behaviour (Puzrin and Burland, 1998; Ling *et al.*, 2000). In this model the behaviour is expressed by the relationships between shear stress and volumetric strain and between normal stress and shear strain, as presented in the following equations:

For total stress conditions:

$$\delta\varepsilon_s = \delta q/3G + \delta p/J_1 \tag{1}$$

$$\delta\varepsilon_v = \delta q/J_2 + \delta p/K \tag{2}$$

Where:
$\delta\varepsilon_s$, $\delta\varepsilon_v$ δp and δq are the increment of the shear strains, volumetric strain, deviator stress and the mean stress, respectively. G is the shear modulus and K is the bulk modulus. J_1 and J_2 are the moduli cross-coupling shearing and volumetric effects.

As shown in Fig. 2 some additional stress path orientations were utilised in the testing programme in order to study directly the effect of the stress path orientation on the behaviour of the soil and cross check the stiffness parameters.

The testing programme consisted mainly of 2 series of tests. In each series the sample was sheared starting from an isotropic stress state corresponding to values of 100 and 300 kPa, respectively. The axial stress and corresponding radial stress increments were applied, following the desired stress path (Fig. 3). The test was stopped automatically when the axial strain (measured from the external LVDT) reaches about 10%, supposed to overlap the small strains behaviour.

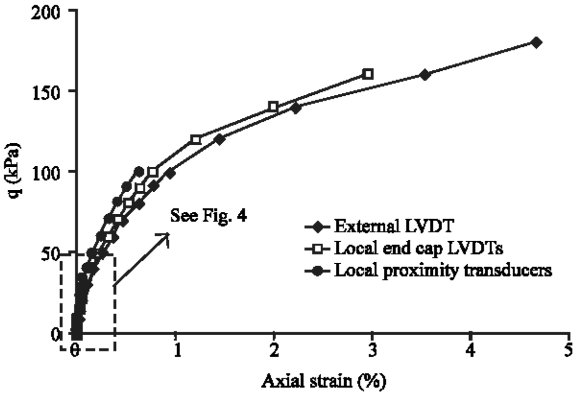


Fig. 2: Behaviour of the soil at small-intermediate strains level (0-5%)

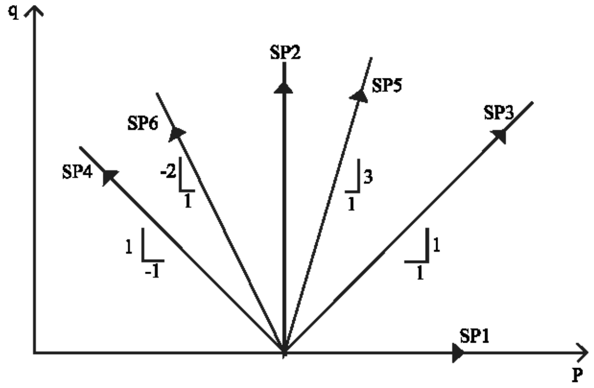


Fig. 3: Stress path orientations investigated

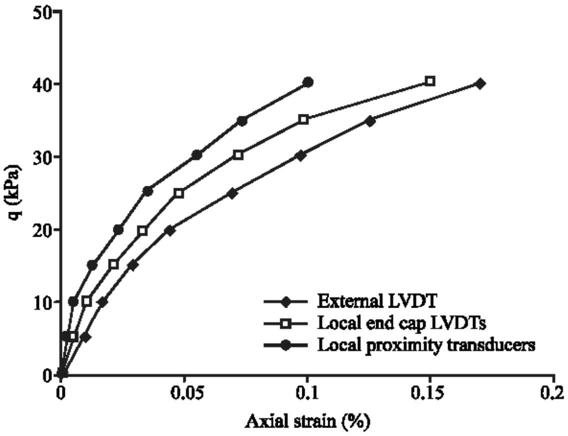


Fig. 4: Behaviour of the soil at small strains level (0-0.2%)

RESULTS

Differences in strain measurements: In Fig. 2 the deviator stress is plotted against the axial strains measured locally on the sample, between the end caps and externally. Typical discrepancy between the axial strains measured locally and externally is apparent. This figure is representative of the general trends observed in all the tests. The proximity transducers measured the axial strain at small and intermediate levels (up to 1%), at the same level of stress, the strains measured locally by the proximity transducers were generally less than the strains measured externally. This is a clear indication of the error that could be induced (about 20-30 % for the same stress level) by conventional triaxial apparatus where strains are measured externally.

As far the small strains behaviour of the soil is concerned, it is clear from the Fig. 2 that the soil stiffness is clearly non-linear, even at very small strain level. It is also shown in the inlarged diagram of Fig. 4 (Corresponding to strains ranging from 0-0.2%) that the non-linearity is predominent from an early stage of loading. These observations are in close agreement with the results obtained by Messerklinger (2006) where other methods of local strains measurement are used.

Strains energy contours: For the interpretation of the results obtained use was made of the method of strains energy contours. By computing the strain energy associated with the stress state change (Eq. 1 and 2), contours of strain energy are plotted in the in the q:p planes for each series of tests. The shape and the spacing of the contours of strain energy are important indicators of the generalised stiffness change and anisotropy of the soil.

The change in strain was defined in terms of volumetric and shear strains. Therefore, the strain energy, defined as the work done per unit volume (δU) by the stress change (Δp, Δq) due to the increment ($\delta\varepsilon_v$, $\delta\varepsilon_s$), is given by the following equation:

$$\delta U = \Delta p\ \delta\varepsilon_v + \Delta q\ \delta\varepsilon_s \qquad (7)$$

Where Δ denotes the difference between the current and the initial state. the strain energy may be summed as follows:

$$U = \sum_{0}^{\varepsilon_V} \Delta p \delta\varepsilon_V \sum_{0}^{\varepsilon_S} \Delta p \delta\varepsilon_S \qquad (8)$$

The volumetric and shear strain were computed using the following equations:

$$\varepsilon_v = \varepsilon_a + 2\varepsilon_r \qquad (9)$$

$$\varepsilon_s = 2/3 * (\varepsilon_a - 2\varepsilon_r) \qquad (10)$$

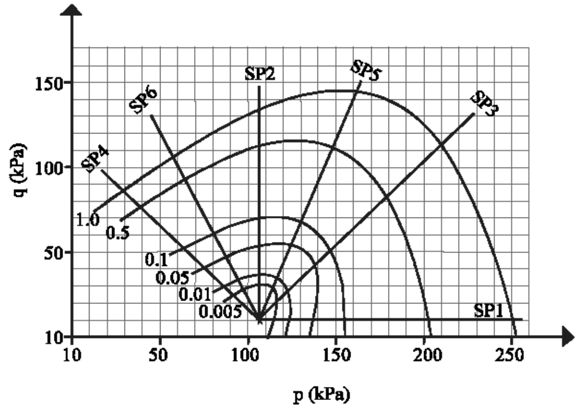


Fig. 5: Strain energy contours (Series 1)

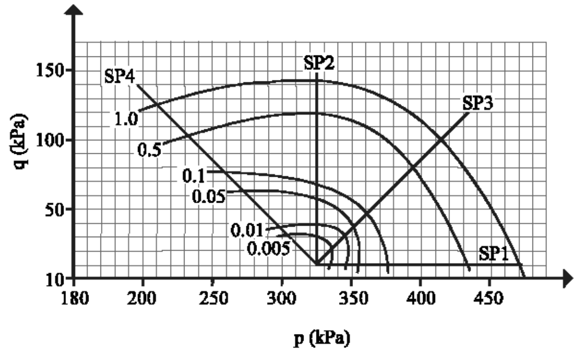


Fig. 6: Strain energy contours (Series 2)

Where ε_a and ε_r are the average local axial and radial strains, respectively, as recorded by the local proximity transducers. By convention, the compressive strains were taken positive.

In Fig. 5 the strains energy contours, associated with the six stress paths of the first series, are shown in the q:p plane. In the presentation of these contours, 6 strains energy levels are considered, ranging from a level of 0.005 to 1 kJ m^{-3}. In terms of local axial strains, the contours cover a range between 0.0025% and about 1%. The same applies for the contours associated with the stress paths of the second test series, presented in Fig. 6.

Referring to Fig. 5 and 6 it can be seen that in most case the contours of strain energy are approximately elliptical with the orientation of the major axis varying from one plot to another. The contours are incomplete since only compression tests were carried out in the present investigation. The contours undergo shape alteration as the strain energy level increases, as might be expected according to the work of (Burland and Georgiannou, 1991).

DISCUSSION

Effect of the initial stress state: The sample of the first and second test series were prepared in the same manner, but at the beginning of triaxial loading they were subjected to different initial isotropic states of stress. This difference in stress history would be expected to generate specimens with different overconsolidation ratio. A singular triaxial test was carried out to assess this difference in stress history. In this test, the sample was loaded following the stress path SP1, starting from a value of mean total stress of 50 kPa. The final value was about 600 kPa. This test has revealed the presence of a yield point at a mean stress of about 120 kPa, which constitutes a boundary between overconsolidation and normally consolidated states. Since the isotropic stress imposed on the sample of the first series was only 100 kPa, the sample can be regarded as very lightly overconsolidated. However for the second test series the samples were normally consolidated.

By comparing tests of the same paths, but from different series (S1T1 and S1T2) it was found that the soil does exhibit a higher stiffness in the second series. If reference is made to the strain energy contours of the Fig. 5 and 6, it can be observed that a difference in behaviour is apparent in the two series, this relates to both the shape and the spacing of the contours, which is an evident indication of the effect of the initial isotropic stress state on the variation in stiffness. This apparent difference in behaviour can be attributed to the effect of the stress history. For example, the distance between the initial stress state and any given strain energy contour on SP4 is greater in the second series, indicating a higher stiffness. This can perhaps be explained by the fact that on unloading a normally consolidated sample (second series) is stiffer in a volumetric sense than lightly overconsolidated sample (first series) at a comparable void ratio.

Effect of the stress path orientation: If samples having the same stress history but tested following different stress paths are compared, it was found that they show entirely different strain behaviour. By reference to strain energy contours of the Fig. 5, corresponding to the first series, it was found that two distinct behavioural trends were observed, one below a strain energy level of 0.1 kJ m^{-3} (applying for the inner contours) and the other above this level (applying for the outer contours). The distance between the initial stress and the inner contours (stiffness) increases as the stress path direction is rotated anti-clockwise, indicating a softening response of the soil.

However, for the same rotation of the stress path, the distance to the outer contours decreases, indicating a softening of the soil.

As in the first series, in Fig. 6, the distance between the inner contours and the initial stress state increases as the stress is rotated anti-clockwise. However, for the outer contours the distance first decreases (from SP1 to SP2) but then increases again (from SP2 to SP4). This could be explained by the fact that a normally consolidated sample as in the second series would be in a volumetric sense stiffer when subjected to an unloading of mean normal stress (SP4) rather than an increase (SP1 and SP3).

The comments presented above suggest that in both test series the stress path direction affected the behaviour of the sample at both small and intermediate levels of strains (characterised in the interpretation by the inner and outer strain energy contours) but not in the same way. The difference can b attributed to the effect of the initial stress state discussed previously.

CONCLUSION

The combination of observational validation and numerical modelling has led to significant recent advances in our understanding of the small strains behaviour of soils. In the present study, an insight into the small strains behaviour of compacted clayey soil is given. The results presented could be relevant for futur validation of related constitutive models and eventual development of numerical models.

Initial stress state: Since all samples were prepared in the same manner at the same initial moisture content, any difference between the results from two series of tests of the same stress path was attributable to the confining stress. In general the stiffness of the sample was found to be greater in the second series. The changes in the stiffness of the sample with stress orientation were somewhat different in the 2 test series.

Stress path orientation: For strain energy levels below 0.1 kJ m^{-3} which correspond to local axial strain ranging from 0.07-0.6%, it was found that the stiffness of the soil tends to increase as the stress path was rotated anti-clockwise. This was valid in both series of tests. For strain energy levels above to 0.1 KJ m^{-3} it was found for the first tests series that the stiffness tends to decrease as the stress path was rotated anticlockwise. This was valid also for the second test series but only for the stress path with $\Delta p > = 0$, since with further rotation of the stress path stiffness tends to increase.

Small strains behaviour of the soil: The results related to the strains measurement indicates clearly the discrepancy between the strain measured locally on the sample and externally. This means that conventional triaxial apparatus where the axial strain measurement is based on the vertical displacement of the loading ram, leads to an over-estimation of the strength parameters, particularly when small strain level is concerned. The stress-strain curves observed in both series of tests indicate non-linearity from an early stage of loading. This non-linearity implies that if comparisons are to be made between laboratory and field data, corresponding strains (or stresses) levels have to be considered.

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