Small-strain stiffness of Auckland residual clay
Rigidité aux petites déformations de l'argile de décalcification d'Auckland

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ABSTRACT
This paper presents the laboratory test results on the complete stress-strain curve for specimens of Auckland residual clay for axial strains ranging from less than 0.001% up to 1.0% using very sensitive LVDTs attached directly to the specimen. Three LVDTs were positioned around the periphery of the specimen to measure axial strains over a gauge length of 100mm. The axial load applied to the specimen was measured with a load transducer inside the triaxial cell. Use of a 16 bit A/D converter ensured accurate measurements of axial strains (resolution better than 1 micron over a gauge length of 100 mm) and load readings (resolution of 0.4N). The problem associated with the rotation of the end cap in conventional testing was resolved by fixing the cap against rotation, thus ensuring the same axial compression across the specimen. Moreover, to ensure excellent specimen end preparation, a thin layer of plaster was applied and the trimming mould was used to ensure the ends were parallel whilst the plaster sets. Using these measures, we were able to get very good quality axial strain data from less than 0.001%. Moreover, we applied the hyperbolic curve to the relationship between deviator stress and axial strain in order to estimate the small-strain stiffness of the soil.

RÉSUMÉ
Ce papier présente les résultats d'essais de laboratoire portant sur les graphes contrainte-déformation d'échantillons d'argile de décalcification d'Auckland pour des niveaux de contraintes axiales allant de 0.001 % à 1.0 % en utilisant des LVDT a haute résolution. Trois LVDT ont été positionnes a la périphérie de l'échantillon pour mesurer les contraintes axiales pour une longueur de référence de 100 mm. Le chargement axial de l'échantillon a été mesure a l'aide d'un capteur d'effort a l'intérieur de la cellule triaxiale. L'utilisation d'un convertisseur analogique numérique 16 bit a garanti une précision en accord avec les mesures de contraintes axiales (résolution supérieure a 1 micron pour une longueur de référence de 100 mm) et la cellule de chargement (résolution de 0.4 N). Le premier problème de rotation de l'extrémité de l'échantillon a été résolu par le blocage de sa rotation, assurant ainsi une même compression pour tout l'échantillon. La seconde étape pour garantir une préparation excellente de l'échantillon a été de lui appliquer une fine couche de plâtre et d'utiliser un moule de détourage pour assurer le parallélisme des extrémités. Grace a ces mesures, nous avons pu obtenir des données de déformation axiales d'une qualité supérieure a 0.001%. De plus, nous avons appliqué la courbe hyperbolique a la relation entre la déviation de contraintes et la déformation axiale, nous avons ensuite pu calculer la rigidité aux petites déformations..

Keywords : small strain stiffness, LVDTs, undisturbed sample, residual clay

1 INTRODUCTION

It has long been established that the measurement of small strain stiffness in triaxial testing requires that sensitive instrumentation be attached directly to the soil specimen so that errors caused by bedding and other effects at the top and bottom platens are eliminated (Brown et al. 1980; Burland & Symes 1982; Costa Filho 1985; Cuccovillo & Coop 1997; and DaRe et al. 2001). The technique discussed in this paper was based on the work of DaRe et al (2001) and employed LVDTs (Schaevitz 025 MHR, 050 MHR, 100 MHR type) with a linear range of about ±0.64 to ±2.54 mm attached to the periphery of the specimen. In conjunction with a 16 bit A/D converter, these were found to be able to resolve displacements smaller than 1 micron, i.e. an axial strain of less than 0.001% over a 100 mm gauge length. The aim of the work was to develop a method for measuring the full stress-strain curve of undisturbed soil specimens, so that the relationship between the shear modulus and axial strain could be established. This paper considers two distinct aspects of this measurement: first, specimen set-up requirements; and second, processing of the data obtained so that the small strain soil properties can be determined.

We encountered several difficulties in achieving our aim. The difficulties revolved around the preparation and mounting of the specimen in the triaxial cell. Initially, it was found that the top loading cap needed to be restrained against rotation. Previous experience in testing residual soils from around Auckland had alerted us to the fact that the material is variable, even in a volume of soil as small as that of a 75 mm diameter and 150 mm high specimen. This means that an unrestrained loading cap may rotate at even very small axial strains, with the consequence that the LVDTs on one side of the specimen could indicate compressive axial strain whilst on the other side the strains are extensional. The first step in countering this problem was to restrain the top cap against rotation. A great improvement ensued but then it was noticed that the specimen trimming procedures were not achieving end faces that were flat and parallel. This was remedied by developing a special three-part trimming mould which resulted in much better end conditions. Finally, for specimens that were difficult to trim with smooth ends, a thin layer of plaster was used. These procedures are illustrated below and some of the results achieved to data are presented.

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-221

2 TEST PROGRAM

2.1 *Triaxial test set-up*

The sample used was an undisturbed residual cohesive soil from a site near Auckland, with typical properties shown in Table 1. The specimen size used was 75 mm in diameter and 150 mm high. The specimens were trimmed from samples which were obtained in the field by pushing 200 mm diameter by 200 mm high steel sampling tubes, fitted with a low angle cutting shoe, into the ground with a hydraulic jack. The tubes were then recovered by hand digging, the ends trimmed level and sealed with caps held in place with tie bolts, and with a thin rubber disk inserted between the soil and the cap. When required, these blocks were removed from the tubes using a laboratory hydraulic sample extruder. The block was cut down to approximately the size of the specimen using a bandsaw and then trimmed to the required diameter using a hand operated soil lathe.

Three LVDTs were attached on the periphery of the specimen, as shown in Figure 1. The LVDT blocks have an inner surface lined with emery paper and they are held against the rubber membrane using a rubber band. The top and bottom blocks are positioned using an alignment pin and the gauge length set to 100 mm. A mid-height pore pressure transducer was also installed through the rubber membrane and sealed with silicone sealant. This method of mounting the LVDTs seems simpler than the usual approach of having a pair of spring-loaded cradles attached to the specimen. It also has the advantage that specimens of different diameters can be accommodated easily. The LVDTs were immersed in silicon oil as cell fluid, rather than water. The instrumentation was logged using a 16 bit A/D converter. The triaxial cell had a 3 kN internal load cell installed.

The resolution of these two instruments over a period of approximately 5min is shown in Figure 2. Since a constant displacement rate of 0.1 mm/sec was used in the compression tests, an axial strain in the specimen of 30% can be achieved within this period of time. From the figures, it is apparent that the displacement transducers can resolve distances less than 1 micron (axial strain of 0.001% for a 100 mm gauge length), while the load cell can resolve forces of less than 0.4 N, i.e. an axial stress of <0.1 kPa on a specimen of 75 mm diameter.

Table 1. Index properties of the Auckland residual soil tested.

Specific gravity of soil particles	Liquid limit	Plastic limit	Natural water content	Unit weight of wet specimen
G_s	w_L	w_P	w_n	γ_t
-	%	%	%	kN/m^3
2.694	63.8	30.4	32.1	17.7

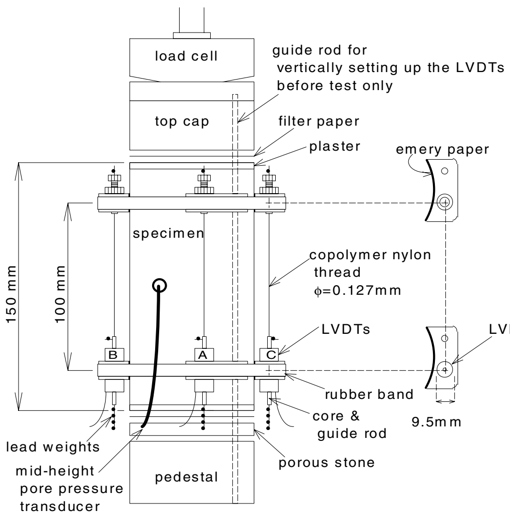
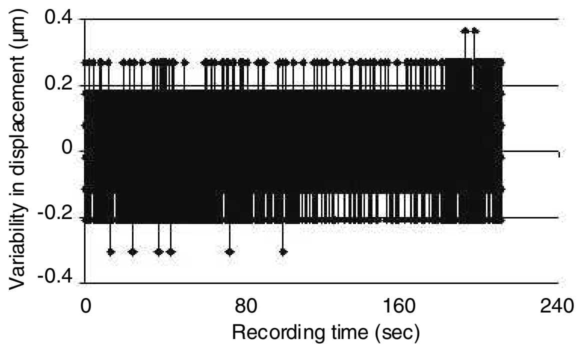


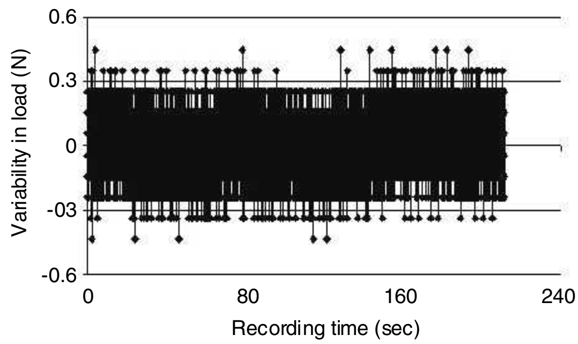
Figure 1. Mounting of LVDTs on the specimen

2.2 *End cap restraint*

Earlier tests on Auckland residual clay showed that it was quite variable even within the size of the specimens tested. When testing with conventional unrestrained top caps, this variability within the specimen was manifested by the rotation of the top of the specimen even at very small axial strains. The immediate consequence was that the deformation of the specimen was no longer uniform and any accurate measurement of small strain stiffness was not possible. This problem was solved by restricting the end cap rotation by having the flat end of the internal load cell bear directly on the top of the loading platen, as shown in Figure 1.



(a) LVDT



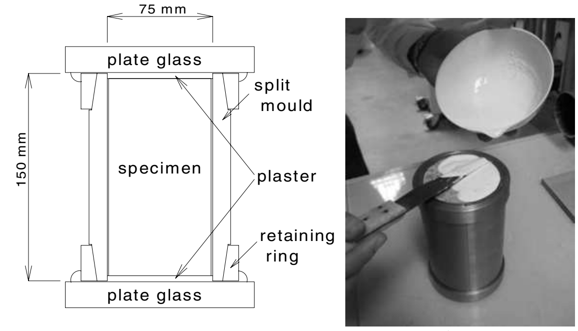
(b) Load cell

Figure 2. LVDT and load cell stability for approximately 4 minutes of recording time.

2.3 *Specimen end preparation*

The use of the restrained end-cap did improve the results but it was still apparent that further improvement was necessary if we were to achieve accurate stress-strain curve data. Eventually, it was realised that the ends of the specimens were not sufficiently flat and parallel. To improve specimen-end preparation, a special three-part split mould was developed as shown in Figure 3(a). In cases where the material in the specimen does not trim to a flat surface with a knife and straight edge, the specimen was trimmed slightly at the ends and a thin layer of quick-setting plaster was used to form flat and parallel ends, as shown in Figure 3(b). This specimen preparation technique was found to give satisfactory test results.

The specimens were saturated with the application of 700 kPa back pressure, and then consolidated to an effective pressure of 65 kPa. During consolidation, a small axial load was maintained on the specimen to ensure that no rotation of the top cap occurred at the top of the specimen. Undrained shearing was done at a constant displacement rate of 0.1 mm/sec and the data logging system took 150 sets of readings every second.



(a) (b)

Figure 3. Three - way split mould used for final trimming of specimen ends: (a) mould details; and (b) application of thin plaster layer prior to smoothing with the plate glass platen.

3 TEST RESULTS AND DISCUSSION

3.1 *Shear stress – axial strain relations*

The main part of the data processing was directed towards developing the secant shear modulus - axial strain relationship. The test results on Auckland residual soil are shown in Figure 4. Figure 4(a) shows the shear stress plotted against the axial strain for strains up to 2.0% obtained from the three LVDTs and the external transducer. The three LVDTs showed similar values; however, the displacements recorded by the external transducer are much larger than those obtained by the on-specimen transducers, resulting in the shear stress – axial strain curve plotting below those from the three LVDTs, as shown in this figure. This is because external transducer measures displacements which incorporate bedding effects. Thus, transducers attached directly to the specimen are necessary to obtain accurate measurements of soil stiffness at small strains.

Figure 4(b) plots the shear stress – axial strain relation within a limited range of strains (i.e. up to 0.02%). The graph seems to show an initial linear portion for strains up to about 0.002%. Beyond this initial linear portion, there is a continuous decrease in stiffness as the strain level increases. Also shown in the figure is the least-square hyperbola fitted through the data points. Note that a hyperbolic model is frequently used to idealise the nonlinear stress-strain behaviour of soil (e.g., Tatsuoka, 1987; Ishihara, 1995). It is clear from these plots that the hyperbolic curve represents the trend in the data very well, with the initial slope of the hyperbola equal to the small-strain shear modulus of the soil. The plot in Figure 4(c) shows that the shear moduli from the test results and those estimated using the hyperbolic curve splice very well over the strain range of 0.004% to 0.1%. The small-strain shear modulus, G_0, shown in Figure 4(b) was obtained from the slope of the initial part of the hyperbolic curve. The shape of the curve depicted in Figure 4(c) conforms to the well-known relationship between shear modulus and strain.

From other measurements in the Auckland residual soils, it is known that the shear wave velocity is in the range 150 to 200 m/sec. The small strain shear modulus value of 50 MPa shown in Figure 4(b) corresponds to a shear wave velocity of 166 m/sec. One might express surprise that tests on sampled soil would give small strain stiffnesses in line with the in situ shear wave velocity. Part of the explanation must lie in the fact that the Auckland residual soils are not sensitive. However, a bigger part of the explanation is that once the errors inherent in "routine" triaxial testing are eliminated, the stiffness values obtained are true parameters for the material. Burland (1989) has made similar observations about small strain stiffness measurement.

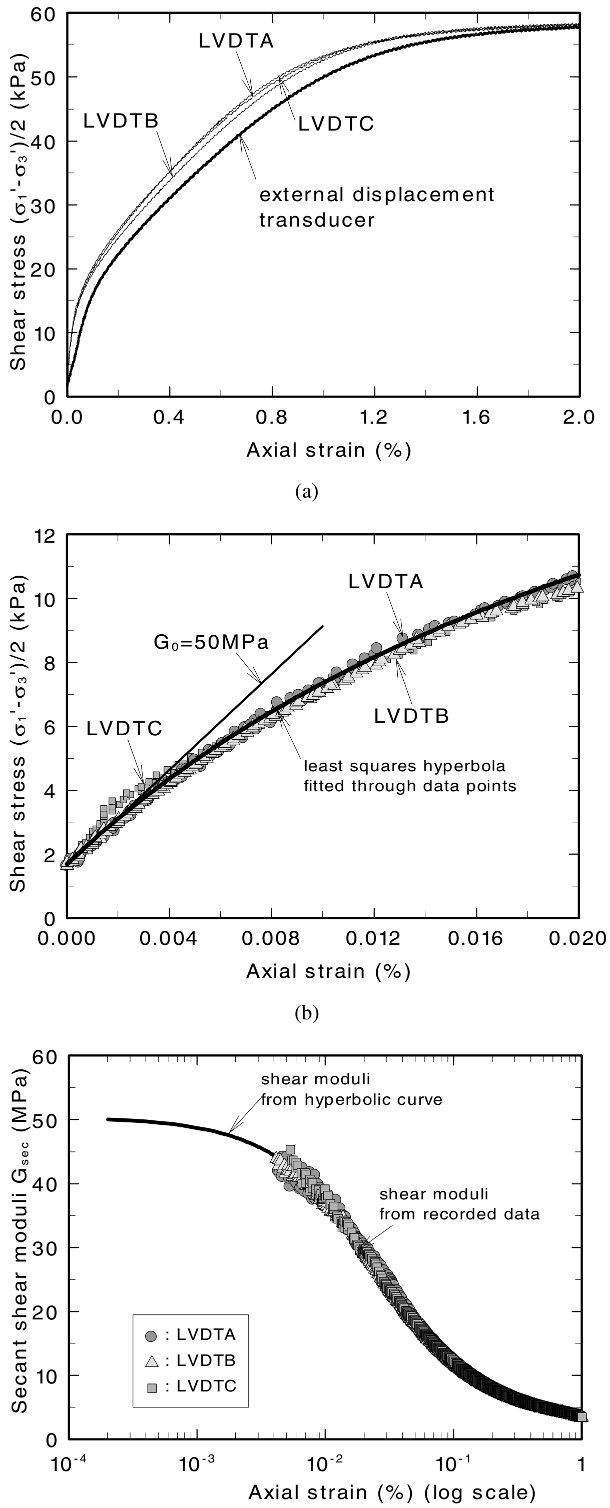
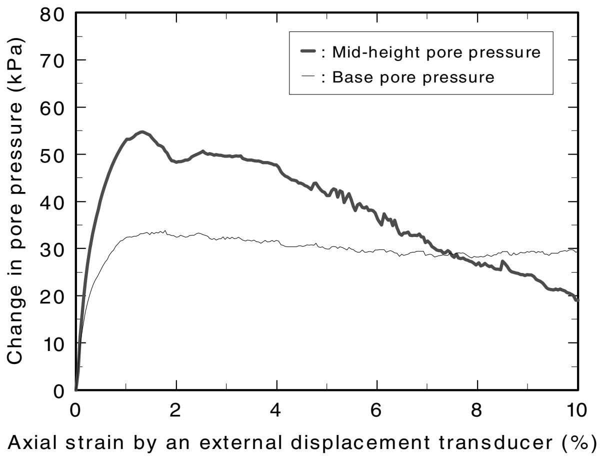


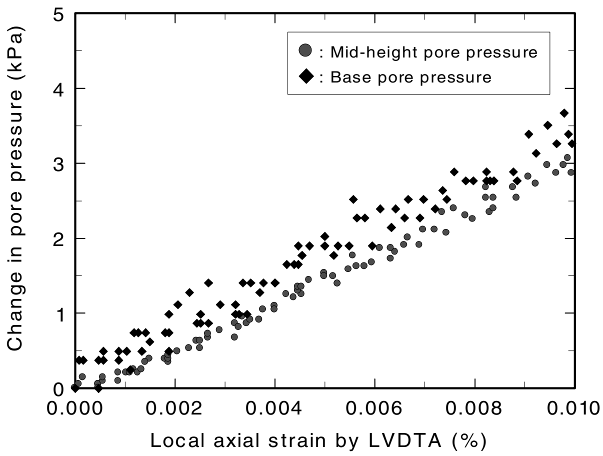
Figure 4. (a) Initial part of stress - strain curves with the small-strain shear modulus indicated; (b) small-strain behaviour with a least square hyperbola fitted through the data points; and (c) secant shear moduli - axial strain relationship.

3.2 *Development of excess pore water pressure*

The build-up of pore water pressure within the specimen during the shearing stage was monitored at the base and at the mid-height of the specimen (see Figure 1). The mid-pore water pressure transducer was inserted at the middle of specimen through the rubber membrane and sealed with silicone sealant in order to investigate the distribution of pore pressure within the specimen. Figures 5(a) and (b) show the relationship between the excess pore water pressure and axial strain up to a level of 10% and 0.01%, respectively. Both mid-height and base pore water pressures show positive response with straining; however, the mid-height pore pressure showed higher values (see Figure 5a), possibly because of the non-uniform shear strains within the sample and the high shearing rate of 0.1 mm/sec. Looking at the detailed response during the early stage of shearing (see Figure 5b), it is apparent that at small levels of axial strain, the generation of excess pore water pressure at the base and at the mid-height of the specimen has very similar trend. Therefore, in determining the small strain stiffness until the axial strain of 0.01%, the effect of non-uniformity of pore water pressure inside the specimen could be neglected.



(a) until 10% strain



(b) until 0.01 % strain

Figure 5. Build-up of pore pressure during shearing stage.

4 CONCLUSIONS

To measure the small-strain stiffness of Auckland residual soils the following steps, in addition to using very sensitive on-specimen displacement transducers and a sensitive internal load cell, were found to be necessary:

- the top loading cap must be restrained against rotation during the testing;
- the specimen ends need to be smooth and parallel. To achieve this, a special trimming mould, allowing the placement of a thin layer of plaster if necessary, was developed;

The stress-strain data gathered from the tests were of good quality. Nevertheless, special processing was performed to extract the shear modulus of the soil at small strains by using least squares fitting of a hyperbolic relationship through the stress-strain data points from which the moduli were calculated. Finally, the small strain shear modulus so determined corresponded to the shear wave velocities expected in the field.

ACKNOWLEDGEMENT

The authors are grateful to the New Zealand Earthquake Commission for supporting Dr Kikkawa. Valuable assistance was provided by the Northern Gateway Alliance in obtaining soil samples.

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