INFLUENCE OF SPECIMEN SHAPE AND TEST BOUNDARY CONDITIONS ON THE STRESS-STRAIN BEHAVIOUR OF SOIL

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ABSTRACT
A comparative study of the observed soil behaviour under triaxial compression and extension loading conditions is presented based on the data obtained from a series of strain controlled isotropically-consolidated undrained shear tests performed on normally consolidated Kaolin clay specimens having three shapes: Cube, Solid cylinder, and Hollow cylinder. The paper concentrates on the effect of specimen shape and boundary conditions on the interpreted mechanical response. Lubricated-end triaxial system with radial drainage is used to obtain the consolidation and undrained shear behaviour of soil using solid cylinder and cubical specimens. Cubical specimens have also been tested using flexible-boundary true-triaxial system that allows equal drainage all around the specimen. Hollow cylinder specimen is tested using a triaxial system with frictional ends. Despite using identical techniques for specimen preparation and similar consolidation history, the soil behaviour obtained from the four types of tests showed observable variations, demonstrating the importance of specimen shape and loading/boundary conditions.

RÉSUMÉ
Une étude comparative du comportement de sol observé sous la compression et extension triaxial conditions est présentée basé sur les données obtenues d'un feuilleton de tension a contrôlé isotropically consolidé undrained les tests de cisailles ont exécuté sur les spécimens normalement d'argile de Kaolin consolidés ayant trois formes: le Cube, le cylindre Solide, et le cylindre Creux. Le papier concentre sur l'effet d'en forme de spécimen et frontière conditionne sur la réponse mécanique interprétée. Lubrifié-termine le système triaxial avec le drainage radial est utilisé pour obtenir la consolidation et le undrained comportement de cisailles de sol utilisant le cylindre solide et les spécimens cubiques. Les spécimens cubiques ont été essayés utilisant aussi la flexible-frontière système vrai-triaxial qui permet le drainage égal tout autour le spécimen. Le spécimen creux de cylindre est essayé utilisant un système triaxial avec les fins de friction. Malgré l'utilisation techniques identiques pour la préparation de spécimen et l'histoire de consolidation similaire, le comportement de sol obtenu des quatre types de tests a montré des variations observables, démontrant l'importance d'en forme de spécimen et chargement/frontière conditionne.

1. INTRODUCTION

The mechanical behaviour of soil is complex and is often evaluated by obtaining the stress-strain behaviour and volumetric response using single element laboratory testing. Conventionally, these triaxial tests have been performed on solid cylindrical specimens with frictional end boundary conditions (Henkel 1959, Parry 1960). A significant development in the field of conventional triaxial testing was the use of lubricated ends (Rowe and Barden 1964) in order to improve the uniformity of deformation during shearing. However, testing a solid cylinder specimen can only be used to study the soil behaviour under axisymmetric stress conditions (axial compression and extension). Advances in testing methods have added the capability of studying generalized mechanical behaviour of soils in three dimensions using true-triaxial testing on cubical specimens (Ko and Scott 1967, Sture and Desai 1979) and combined axial-torsional testing on hollow cylinder specimens (Saada 1988). In these testing methods, specimens are assumed to respond as a single element for interpreting the stress-strain data from the measured load-displacement information and assumed specimen geometry. These testing methods use significantly different specimen shapes and end boundary conditions (rigid, flexible, lubricated, and frictional), which may have a significant influence on the interpreted shear stress-strain, strength, and volumetric response of soil (Jamiolkowski et al. 1985).

An experimental study on the effects of specimen shape and loading/boundary conditions on the mechanical behaviour of normally consolidated Kaolin clay during triaxial compression and extension is presented in this paper. In this study, lubricated end triaxial system with radial drainage is used to obtain the undrained shear behaviour of soil using solid cylinder and cubical specimens. Cubical specimens have also been tested using flexible boundary true-triaxial system that allows equal drainage all around the specimen (Prashant and Penumadu 2004). Hollow cylinder specimen is tested using a combined axial-torsional triaxial system with frictional ends. Despite using identical techniques for specimen preparation and similar consolidation stress state, the interpreted undrained shear behaviour of soil was significantly different for the four types of tests used in this study. The focus of current paper is to demonstrate the significance of specimen shape and loading/boundary conditions on the observed mechanical behaviour of soil.

2. EXPERIMENTAL METHODS USED TO STUDY THE SHEAR BEHAVIOUR OF SOILS

In this research, the undrained shear behaviour of Kaolin clay was studied using three types of single element testing methods: lubricated end triaxial tests, combined axial-torsional tests, and flexible boundary true triaxial tests. The stress states of a soil element using these testing methods are shown in Figure 1.

The lubricated end triaxial test is one of the simplest testing procedures used to study the shear behaviour of soils that provides a good control over the drainage conditions and relatively uniform deformation of the specimen during shearing. This test is performed using solid cylinder specimen. As shown in Figure 1a, the soil behaviour can only be studied under axisymmetric stress conditions i.e. triaxial compression and extension. The normal stresses in two principal directions (σ_r' and σ_θ') remain equal throughout the test.

Combined axial-torsional test on hollow cylinder specimen provides a significant advantage of studying the influence of principal stress rotation on the mechanical response of anisotropic soils. A drawback of this testing procedure is the use of frictional end boundary conditions, because of which the specimen experiences non-uniform deformations during shearing and requires certain assumptions in approximating the stress state from applied loading conditions and geometry of the specimen. Figure 1b shows the stress boundary conditions applied on a hollow cylinder specimen and the principal stresses acting on a corresponding soil element. By applying a rotational shear stress $\sigma_{\theta z}$ about the axis of the specimen, the principal stresses can be continuously rotated (change in β angle) between two extreme conditions corresponding to triaxial compression (β = 0º) and extension (β = 90º) cases. The normal stress on outer wall of the cylindrical specimen is usually the same as the normal stress on the inner wall, which is the case represented by the stress state of a soil element in Figure 1b. In such a case, the relative magnitudes of principal stresses can not be controlled independently and have a constant relationship with the inclination of principal stresses from the axis of specimen.

During true triaxial test on cubical specimen, the principal stresses are applied independently on the faces of the specimen as shown in Figure 1c. Therefore, this test method is used to study the influence of the relative magnitude of principal stresses without changing the orientation of principal stresses. However, this test can allow a jump rotation of the principal stresses by 90º as shown in Figure 1c. End boundary conditions are lubricated and can be rigid or flexible or a combination of both.

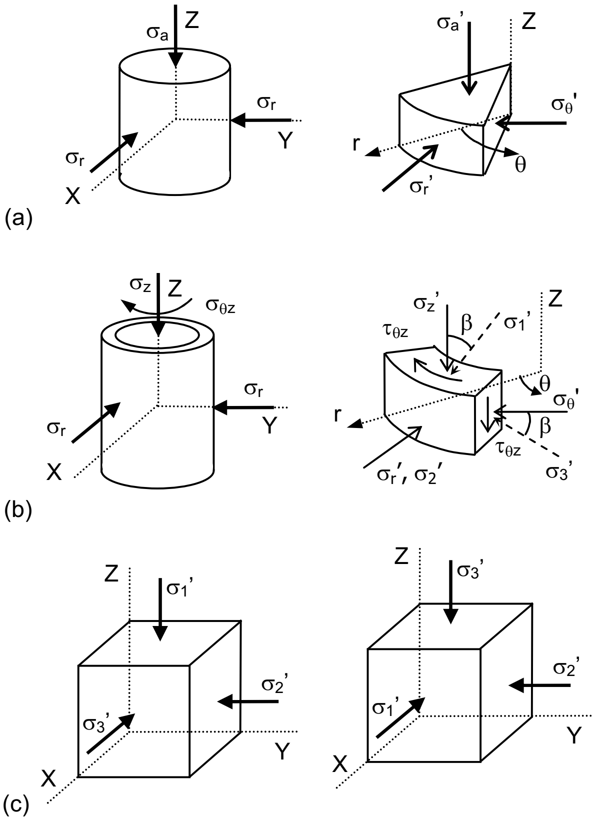

Figure 1. Stress States of soil elements in Three Testing Methods, (a) Lubricated End Triaxial Test on Solid Cylinder specimen, (b) Combined Axial-Torsional Test on Hollow Cylinder specimen, and (c) True Triaxial Test on cubical specimen.

3. SPECIMEN PREPARATION

The Kaolin clay specimens of various shapes were reconstituted in the laboratory by means of slurry consolidation. Slurry was prepared with initial water content of 155% in de-aired and de-ionized water and then deposited through a funnel into a slurry consolidometer lined with Teflon. The cubical clay specimens were prepared in a slurry consolidometer with square cross-section (102x102 mm) as described by Penumadu et al. (1998). Solid cylinder and hollow cylinder specimens were prepared in similar consolidometers with circular cross-sections. The slurry was consolidated one-dimensionally by applying a vertical pressure of 207 kPa. After completion of primary consolidation, the specimen was extruded. The resulting cylindrical specimen dimensions were approximately 102 mm in diameter and 102 mm in height. Rowe and Barden (1964) showed that the lubricated end triaxial tests performed best for the cylindrical specimens with slender ness ratio (Height to diameter ratio, H/D) of 1. The H/D =1 provided appreciably stable geometry, which led to uniform distribution of stress and deformation throughout the test. The cubical specimens used in lubricated end triaxial system were prepared by trimming off the cylindrical specimens using a specimen-trimming device developed for this study. These cubical specimens had a square cross-sectional area (72 mm x 72 mm) with a diagonal dimension of 102 mm and height of 102 mm. The specimens were actually prismatic, but the diagonal dimension was chosen to match the diameter of a cylindrical specimen. The cubical specimens used in true-triaxial system were prepared using slurry consolidation and the resulting specimen had three equal sides of 102 mm. The typical height of the HC specimen was about 230 mm, outer diameter, 102 mm and inner diameter, 71.2 mm. These dimensions were used to minimize the effects of frictional specimen ends that are required in torsional-shear testing (Saada 1988).

4. TESTING EQUIPMENTS

4.1 Lubricated End Triaxial System

Lubricated end triaxial tests with radial drainage were performed on cylindrical and cubical specimens of Kaolin clay (Figure 2). In this system, the lubricated end caps have a diameter of 108 mm and allow the specimen to deform uniformly from top to bottom, resulting in negligible friction at end boundaries during the application of deviator stress. Drainage is provided through the use of holes which are drilled into the side of the end caps. A complete drainage path from the sample to the drainage lines was provided using filter paper strips. Lubrication is provided through the use of 0.6 mm thick latex membranes and a thin layer of vacuum grease.

4.2 True Triaxial System

True triaxial tests were performed using a device recently developed by Mandeville and Penumadu (2004) that applies three mutually perpendicular principal stresses on cubical soil specimens using flexible membrane boundaries. The details of this device are shown in Figure 3, in which a space frame holds a 102 mm cubical soil specimen. The six faces of this space frame are attached to six cylindrical pressure housings, which are separated from the faces of soil specimen using flexible membranes. Each pressure housing contains a linear variable displacement transducer (LVDT) for measuring the deformation at the centre of each face of the specimen. Electro-pneumatic transducers are connected to three axes of the frame, and apply individual principal stresses at the desired rate using closed-loop proportional, integral, and derivative (PID) control based on adjusting the output channel to match a target command in real time. Internal and external pore pressures are measured using absolute pressure transducers. All of the electronic transducers are connected to a computer for use in data acquisition and control. Custom software automates various phases of triaxial testing such as saturation, consolidation, and application of normal stresses for predetermined stress path or strain path.

4.3 Combined Axial-Torsional Test Setup

Triaxial tests on hollow cylinder specimens were performed using an MTS 858 loading equipment with a Series 359 Axial-Torsional Load Unit. The triaxial cell used for hollow cylinder testing is shown in Figure 4. Transducers for measuring and controlling axial load, torque, axial displacement, and rotation were interfaced with TEST STAR® electronic interface and TESTWARE-SX® software. To measure the cell and pore pressure, 2 external pressure transducers were used. The volumetric change is measured by monitoring the amount of water coming out of the specimen by using a differential pressure transducer and burette system. In addition, by using an electro-pneumatic transducer, automated control of cell pressure was achieved. Applied stresses and deformations were controlled through the computer using the PID feedback control algorithm, and any desired stress path with different rotation of principal stresses were achieved in a precise and completely automated manner. A detailed approach for interpreting the complete state of stress and strain during isotropic consolidation and the subsequent phase of applying shear stress during

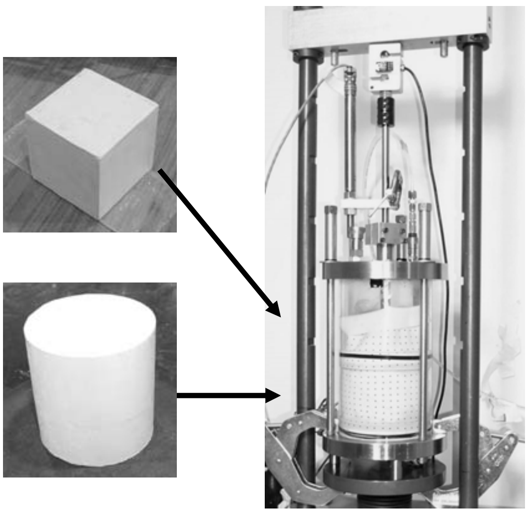

Figure 2. Lubricated end Triaxial System

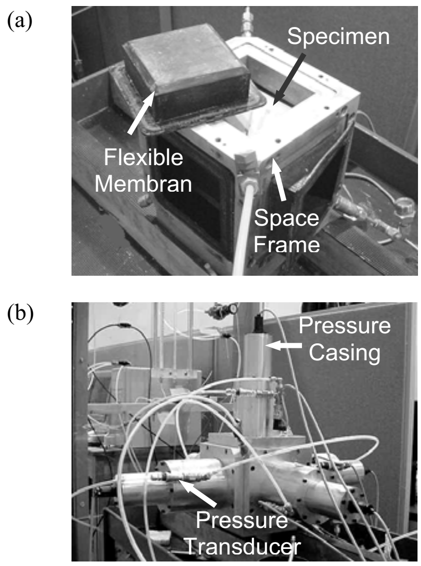

Figure 3. True Triaxial System (a) Before Assembly, and (b) Assembled

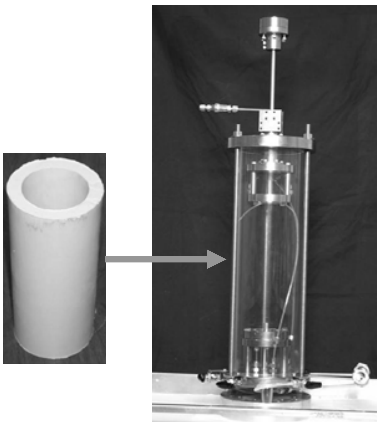

Figure 4. Triaxial Cell for Hollow Cylinder Specimen

a combined axial-torsional test, ncluding the correction for specimen geometry and correction for the forces taken by the membrane, was given by Lin and Penumadu (2002).

5. EXPERIMENTAL PROGRAM

The assembly of the solid cylinder and hollow cylinder specimens in their respective apparatus follows the general procedures in ASTM Standard D4767-95 for consolidated undrained triaxial compression test for cohesive soils. In order to reduce the necessary time for consolidation and pore pressure equalization, filter paper strips (Berre 1982) were used around the outer surface of the specimen to provide radial drainage. A similar procedure was used to assemble the cubical specimens in lubricated end triaxial system and true triaxial apparatus. The cubical specimen in lubricated end triaxial system was placed such that the σ_1-axis at the end of slurry consolidation was coinciding with the axial direction of loading fame. During true triaxial test, three axes were identified on the space frame, x, y and z. The specimens were placed on the space frame such that the σ_1-axis at the end of slurry consolidation coincides with z-axis. Considering the use of all around flexible boundary conditions during true triaxial test, the filter paper applied to the cubical specimen was not cut into strips.

Table 1. List of the tests performed in this study.

Test Method	Specimen	Loading	Designation
Lubricated end triaxial test	Solid Cylinder	Compression	LS-C
		Extension	LS-E
Lubricated end triaxial test	Cubical	Compression	LC-C
		Extension	LC-E
Frictional end triaxial test	Hollow Cylinder	Compression	TH-C
		Extension	TH-E
True triaxial test	Cubical	Compression	TT-C
		Extension	TT-E

After assembly, the specimens were saturated using backpressure. Skempton's (1954) parameter B was calculated from the pore pressure measurements during a small increment (35 kPa) of isotropic loading under undrained conditions. A minimum B-value of 0.98 was used as the criteria for ensuring full saturation. The Kaolin clay specimens were then hydrostatically (isotropically) consolidated to 275 kPa resulting in normally consolidated clay specimens. At this stage, the specimen was subjected to triaxial compression and extension stress paths under undrained conditions. An axial strain rate of 0.05%/min was found suitable for present clay to ensure pore pressure equilibrium under undrained condition. A list of the tests performed in this study is given in Table 1.

6. OBSERVATIONS FROM DIFFERENT LABORATORY SHEAR TESTING METHODS

Figure 5 shows the observed shear stress-strain (q-ε_q) relationship and excess pore pressure evolution (Δu) during triaxial compression tests on cubical, hollow cylinder, and solid cylinder specimens. A similar plot of the triaxial extension test data is shown in Figure 6. The deviatoric stress q and shear strain ε_q are defined as

$$q = (\sigma_1' - \sigma_3') \quad [1]$$

$$\varepsilon_q = 2\,(\varepsilon_1' - \varepsilon_3')\,/\,3 \quad [2]$$

Here, σ_1' and σ_3' are the normal effective stresses in major and minor principal directions respectively, and ε_1' and ε_3' are the corresponding normal strains. The failure point is defined as the point of peak deviatoric stress. In Figure 5 and 6, the location of failure is marked with big dots, and the curves are identified using the corresponding test designations listed in Table 1. The LS and LC tests had the same boundary conditions (rigid and lubricated ends) but different specimen shapes; whereas, the LC and TT tests had similar specimen shapes but different boundary conditions (one with rigid ends and the other with all around flexible boundaries). The specimens used in the LS and TH tests were axisymmetric but the shapes were different. For LS and TH tests, the axial boundaries were rigid in both the cases but the ends were frictional in one case and lubricated in the other.

Despite the same loading history in the four compression tests, the stress-strain relationship and the strength behaviour were significantly different. The cubical specimens, especially the TT-C test using all around flexible boundaries, showed relatively softer pre-failure response than the other axisymmetric specimens. The extension tests showed relatively less difference in stress-strain behaviour except for a small increase in the observed shear stiffness at small strains for lubricated end triaxial tests, LS-E and LC-E. The stress-strain relationship observed from TH tests on hollow cylinder specimen showed an upper bound in compression and lower bound in extension case, and the opposite bounds were approximately represented by the response of cubical specimens in LC tests.

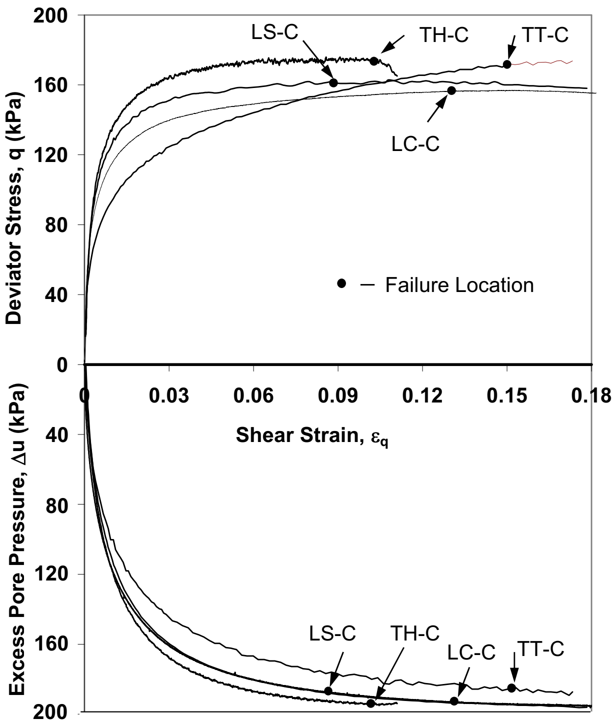

Figure 5. Stress-Strain Relationship and Pore Pressure Response from Triaxial Compression tests

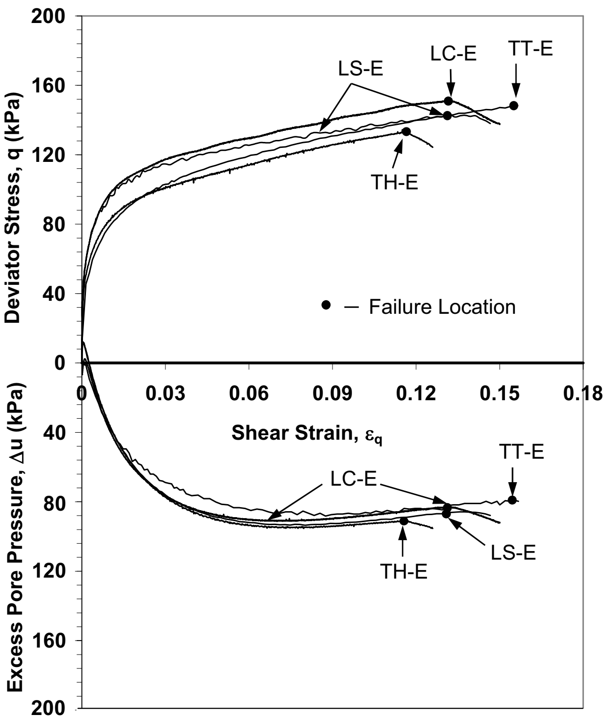

Figure 6. Stress-Strain Relationship and Pore Pressure Response from Triaxial Extension tests

As shown in Figure 5 and 6, the pore pressure response was identical for two lubricated end triaxial tests (solid cylinder and cubical specimens) and even for the frictional end triaxial test (hollow cylinder) it was not significantly different. However, the use of flexible boundaries in true triaxial tests, TT-C and TT-E, resulted in slightly lower pore pressure evolution during shearing.

The strain values at failure were relatively higher for cubical specimens (TT and LC tests). Compared to the other testing methods, the TH tests on hollow cylinder specimens showed highest shear strength in compression and lowest in Extension. Table 2 provides the strength parameters of soil, commonly used in practice, calculated using the data obtained from the four testing methods and Equations 3-7.

Table 2. Summary of the observed strength behaviour

Test	ε_q	S_u/σ_c'	ϕ'	M	A_f
LS-C	0.088	0.30	29.9º	1.20	1.16
LC-C	0.132	0.29	29.6º	1.18	1.23
TH-C	0.104	0.32	33.1º	1.34	1.12
TT-C	0.150	0.31	28.8º	1.14	1.08
LS-E	0.132	0.26	39.5º	1.05	1.60
LC-E	0.131	0.29	41.1º	1.08	1.55
TH-E	0.117	0.24	34.2º	0.95	1.68
TT-E	0.156	0.27	36.4º	0.99	1.54

$$S_u = q_f / 2 = (\sigma_1' - \sigma_3')_f / 2 \quad [3]$$

$$\Delta u_f = (\Delta\sigma_3) + A_f (\Delta\sigma_1 - \Delta\sigma_3)_f \quad [4]$$

$$\phi' = (\sigma_1' - \sigma_3')_f / (\sigma_1' + \sigma_3')_f \quad [5]$$

$$M = (q / p')_f \quad [6]$$

$$p' = (\sigma_1' + \sigma_2' + \sigma_3') / 3 \quad [7]$$

Here, σ_2' is the intermediate principal stress, p' is the mean effective stress, and subscript " $_f$" represents that the values correspond to failure location. All of the strength parameters were observed to be varying with the testing method, and the tests on hollow cylinder specimens showed the upper limit in compression and lower limit in extension for the strength behaviour. In true triaxial test the principal stresses were directly obtained from the pressure applied onto the flexible boundaries, whereas, in the other test methods, the stress tensor was obtained by dividing the external loading (axial or torsional) by an average cross-sectional area of the specimen assuming a uniform radial deformation from top to bottom. Varying method of obtaining the stress information might be one reason behind the observed difference in the stress-strain behaviour; however, this should not produce such a big difference. The other possible factor might be the variation in specimen shape and boundary/loading conditions, which may influence the observed stress-strain and strength behaviour significantly. At present, it is difficult to say which test is more representative of the true behaviour of soil. However, these tests may be used individually to study the soil behaviour in relative terms but not in absolute terms. For example, the strength parameters (see Table 2) were significantly different for compression and extension tests in comparison to the variation observed for different test methods.

7. CONCLUSIONS

The mechanical behaviour of soil is largely influenced by the stress path it is subjected to. To study the complex behaviour of soil in generalized stress space, numerous single element testing methods have been developed in past several decades, which involve various specimen shapes and loading/boundary conditions. Three of the testing methods were discussed in this paper describing their need in investigating the generalized behaviour of soil and the stress states possible on the soil elements. These testing methods were lubricated end triaxial test on solid cylinder, frictional end triaxial test on hollow cylinder, and flexible boundary true triaxial test on cubical specimens. Using these testing methods, the soil specimens were subjected to identical stress paths (undrained triaxial compression and extension tests) and the results were presented in this paper. Lubricated end triaxial tests were also performed using cubical specimen in order to isolate the influence specimen shape and boundary condition on interpreted soil behaviour. Despite identical stress path and consolidation history, four testing methods show significant variation in the observed stress-strain relationships, pore pressure evolution, and the calculated strength parameters. Therefore, it is necessary to carefully consider the influence of specimen shape and loading/boundary conditions while analyzing the experimental data to use in structural design.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

Berre, T. 1982. Triaxial Testing at the Norwegian Geotechnical Institute, Geotechnical Testing Journal, ASTM, GTJODJ, Vol. 5(½), 3-17.

Henkel, D.J. 1959. The relationship between the strength, pore-water pressure, and volume-change characteristics of saturated clay. Geotechnique, Vol. 9, pp. 119-135.

Jamiolkowski, M., Ladd, C.C., Germaine, J.T., and Lancellotta, R. 1985. New developments in field and laboratory testing of soils. Proceedings of the 11th International Conference on Soil Mechanics and Foundation Engineering, Vol. 1, pp. 57-153

Ko, H.Y., and Scott, R.F. 1967. A new soil testing apparatus. Geotechnique, Vol. 17, No. 1, pp. 40-57.

Lin, H. and Penumadu, D. 2002. Interpretation of combined axial-torsional test for 3-D constitutive behaviour of geo-materials. Proceedings of the 15th ASCE Engineering Mechanics Conference, 2002, Columbia University, NY.

Mandeville, D., and Penumadu, D. 2004. True triaxial testing system for clay with Proportional-Integral-Differential control. ASTM Geotechnical Testing Journal, Vol. 27, No. 2, GTJ11756: 1-12.

Parry, R.H.G. 1960. Triaxial compression and extension tests on remoulded saturated clay. Geotechnique, Vol. 10, pp. 166-180.

Penumadu, D., Skandarajah, A., and Chameau, J.-L. 1998. "Strain-rate effects in pressuremeter testing using a cuboidal shear device: experiments and modeling. Canadian Geotechnical Journal, Vol. 35, pp. 27-42.

Prashant A. and Penumadu D., 2004. Effect of intermediate principal stress on overconsolidated Kaolin clay. In Print, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 130, No. 3, pp. 284-292..

Rowe, P.W., and Barden, L. 1964. Importance of free ends in triaxial testing. *Journal of Soil Mechanics and Foundation Division*, Vol. 90, No. SM1, pp. 1-27.

Saada, A.S. 1988. Hollow cylinder torsional devices: their advantages and limitations. Advanced Triaxial Testing of Soil and Rock, ASTM STP 977, pp. 766-795.

Skempton, A.W. 1954. The pore pressure coefficients A and B. Geotechnique, Vol. 4, pp. 143-147.

Sture, S., and Desai, C.S. 1979. Fluid cushion truly triaxial or multiaxial testing device. Geotechnical Testing Journal, Vol. 2, No. 1, pp. 20-33.