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Shear Testing Data of Soil: A function of Boundary Friction in Triaxial Setup

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Key words

Triaxial, lubricated, frictional, conventional, shear testing, clay

Abstract: For past several decades, triaxial testing has been a common practice across the world to obtain the shear strength parameters of soils. However, the boundary conditions provided to the soil specimen in a triaxial test could not have been still simulated with the boundary conditions of the soil at site. Many studies have been performed in this direction resulting in to the invention of lubricated end boundary system several years ago; which is found to be fairly similar to the site conditions. However, this system could not be further explored due to its complicated procedure and time consuming nature. Thus, no such system is commercially available and no significant research could have been performed to evaluate and quantify the benefits of lubricated end boundary system over the conventional or frictional boundary system considering all aspects of boundary and drainage conditions. In the current research, three different boundary conditions of triaxial testing have been chosen to perform the triaxial tests on clay specimens to obtain the best possible easy way of simulating the site boundary conditions of soil in the laboratory; and then that boundary system has been further evaluated for its appropriate drainage arrangements. This research reports that shear strength testing data of a given soil changes largely with the variation in friction at boundary conditions of soil specimen in triaxial setup.

Introduction

A significant amount of effort has been devoted in the last several decades to characterize the shear strength behavior of clays using conventional and advanced frictional end triaxial systems. The conventional or advanced frictional end boundary system used in most of the previous researches provide fixed-fixed end boundary conditions to the soil specimen during its shearing; however lubricated end boundary system provides free-free end boundary conditions to the soil specimen, which is the closest boundary conditions of soil at site. Thus conventional or frictional boundary system exhibit the non-uniformity of stress and deformation state along the height of a specimen during externally applied load/ deformation. The main source of this non-uniformity is the shear stress in the radial direction at the frictional ends, which can cause both the barreling effect and the concentration of dilation (volume expansion due to shear) in local zones, which in turn results in the possibility of premature development of failure state in conventional or advanced frictional end boundary systems. However, the use of lubricated end platens minimizes the friction at the specimen ends so that the specimen deforms uniformly over its full height and provides a marked increase in the uniformity of pore pressure distribution within the clay specimen. This motivated the author to investigate the effect of boundary conditions on triaxial testing data of soil by performing a series of triaxial tests on Kaolin clay under three different boundary conditions: i) conventional boundary, ii) advanced Frictional end boundary, and iii) lubricated end boundary. Then the best boundary system was evaluated for its different drainage conditions to achieve the complete pore pressure dissipation and its efficient functioning throughout the triaxial test, as external drainage system may influence the measurement of shear strength properties of soil especially under drained shearing conditions.

Previous Investigation

Frictional end boundary conditions could provide relatively good drainage conditions in drained testing with the use of porous stones at the frictional ends, but could lead to barreling effect and non-uniform deformation within the clay specimen. However, lubricated ends had smooth platens, which minimized the radial stress at the specimen's ends and reduced the problems regarding barreling effect and the concentration of dilation in local zones of the soil specimen (Rowe and Barden 1964, Barden and McDermott 1965, Sarsby et al. 1982). The available data using lubricated end triaxial system (Taylor et al. 1969, Sridharan et al. 1971, Kimura and Saitoh 1983) involved mostly undrained triaxial compression

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tests. Henkel (1956), Bjerrum et al. (1958), Simons (1960 a&b), and Ladanyi (1965) performed both drained and undrained triaxial compression tests on different clays using frictional ends, and reported that the angle of internal friction (ϕ') under drained conditions was slightly lower (about 1^0) than the ϕ' under undrained conditions for both normally consolidated (NC) and overconsolidated (OC) specimens. Similar studies were also performed by Crawford (1964), Mesri and Olson (1970), and Balasubramaniam and Chaudhry (1978), and they reported 2^0-3^0 lower ϕ' value for drained conditions in comparison to undrained using conventional boundary system. Germaine and Ladd (1988) and Mitachi et al. (1988) performed isotropically consolidated undrained triaxial compression (CIUC) and extension (CIUE) tests on NC and OC specimens of different clays using frictional ends and reported that the ϕ' value was 5^0-8^0 higher for extension shearing in comparison to compression. Vaid and Campanella (1974), and Nakase and Kamei (1986) performed similar series of tests but the specimens were consolidated anisotropically before shearing (CAUC and CAUE tests), and reported 13^0-16^0 higher ϕ' value for extension tests in comparison to compression using frictional end boundary system. The previous research works were performed on soils mostly using conventional or advanced frictional boundary systems and a few times using lubricated boundary system; but none of these researches could provide the complete experimental comparative analysis which could efficiently evaluate the effect of boundary conditions of triaxial setup on its shear testing data for a given soil.

Material Properties and Specimen Preparation

The present investigation was carried out on commercially available Kaolinite clay, obtained from English Indian Clays Ltd., Kerala, India. The Kaolin clay used in this research has a liquid limit of 65%; plastic limit of 30%; plasticity index of 35% and a specific gravity of 2.6. To obtain solid cylindrical specimens of clay, the powdered Kaolin clay was mixed with de-aired and de-ionized water with 162.5% water content (2.5 times of Liquid limit). Clay slurry was then consolidated under K_0 condition at 250 kPa vertical stress using slurry consolidation setup (Sachan and Penumadu 2007a). Solid cylindrical clay specimens of 102 mm diameter and 102 mm height were obtained after slurry consolidation.

Effect of Boundary Conditions on Triaxial Data

Three series of triaxial tests on Kaolin clay specimens were performed for three different boundary conditions to assess the effect of boundary friction on shear testing data: i) conventional boundary system (triaxial system used in practice), ii) advanced frictional end boundary system (automated triaxial system used for research), and iii) lubricated end boundary system (automated triaxial system with smooth end platens used for advanced research) as listed in Table 1. Conventional and Advanced Frictional End boundary systems are very common and generally provided by the manufacturing company of the triaxial equipment. Thus, these cases regarding preparation of end platens are not being discussed here. However, lubricated end boundary system is not possible to be obtained commercially as No company produce the triaxial with lubricated end boundary system. In the current research, lubricated end boundary system was designed and fabricated in the I.I.T. Kanpur laboratory considering all aspects of triaxial testing on clays including drained shearing.

Preparation of Lubricated End Boundary System

Two smooth and polished aluminum platens were fabricated to develop the lubricated end boundary system. Each platen had six radial drainage ports at its outer surface. Circular filter paper (Whatman 1) strips were used to cover all the radial drainage ports completely for achieving good drainage conditions. In order to prepare the lubricated end platens for testing the clay specimens, the end platens were cleaned thoroughly, a thin layer of high vacuum grease was spread uniformly over each platen, and a circular piece of latex membrane was then laid on to the grease and pressed in such a way as to minimize the amount of entrapped air. A circular piece of filter paper, with much larger diameter than the platen was placed on top of the latex membrane in a way that the filter paper completely covered the grooves on the sides of the platens for radial drainage ports. A picture of the modified triaxial cell with lubricated end boundary system is shown in Figure 1. It is important to note that the latex membrane placed on specimen was marked with dots in a grid pattern to perform strain localization study of Kaolin clay using DIA technique (Sachan and Penumadu 2007b).

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TABLE 1 Shear strength behavior of Kaolin clay specimens under different boundary conditions of triaxial testing

Triaxial test and its Boundary Conditions *(All the undrained triaxial compression tests were performed on normally consolidated clay specimens; c'=0)*	Confining stress (kPa)	Δu (kPa)	σ_d (kPa)	φ' (deg)
1. Conventional Boundary System *Porous stones were used at the specimen's ends.*	300	123.0	180.3	
	375	166.0	473.3	26.5
	450	227.0	569.3	
2. Advanced Frictional end Boundary system *Porous stones were used at the specimen's ends & computer controlled measurements of pore pressure at the end of specimen*	300	215.9	151.0	
	375	228.6	224.9	27.3
	450	302.5	260.0	
3. Lubricated end Boundary system *Smooth platens were used at the specimen's ends& computer controlled measurements of pore pressure at the end of specimen.*	300	214.1	179.7	
	375	271.6	217.7	31.5
	450	325.2	294.2	

Δu =Excess pore pressure at failure; σ_d =Deviator stress at failure; ϕ'=Effective friction angle; c'=Cohesion

TABLE 2 Shear strength parameters of Kaolin clay under Lubricated boundary conditions for Case I, II & III drainage conditions

Drainage Condition of the lubricated end triaxial testing setup		t_{100} (min)	Drained test (shear data at failure)				Undrained test (shear data at failure)		
			φ' (deg)	q (Kpa)	ε_v (%)	ε_a (%)	φ' (deg)	q (Kpa)	ε_a (%)
Case I	Poor Drainage	404	18.3	253	4.1	14.4	29.9	154.3	11.9
Case II	Intermediate Drainage	210	21.5	321	6.2	20.6	30.0	154.0	11.5
Case III	Good Drainage	60	26.8	448	8.3	26.0	30.0	160.0	14.0
Case III (repeat)	Good Drainage	60	27.0	445	8.5	26.3	29.9	162.3	13.6

ε_v =Volumetric strain; ε_a =Axial strain; t_{100} = Consolidation time

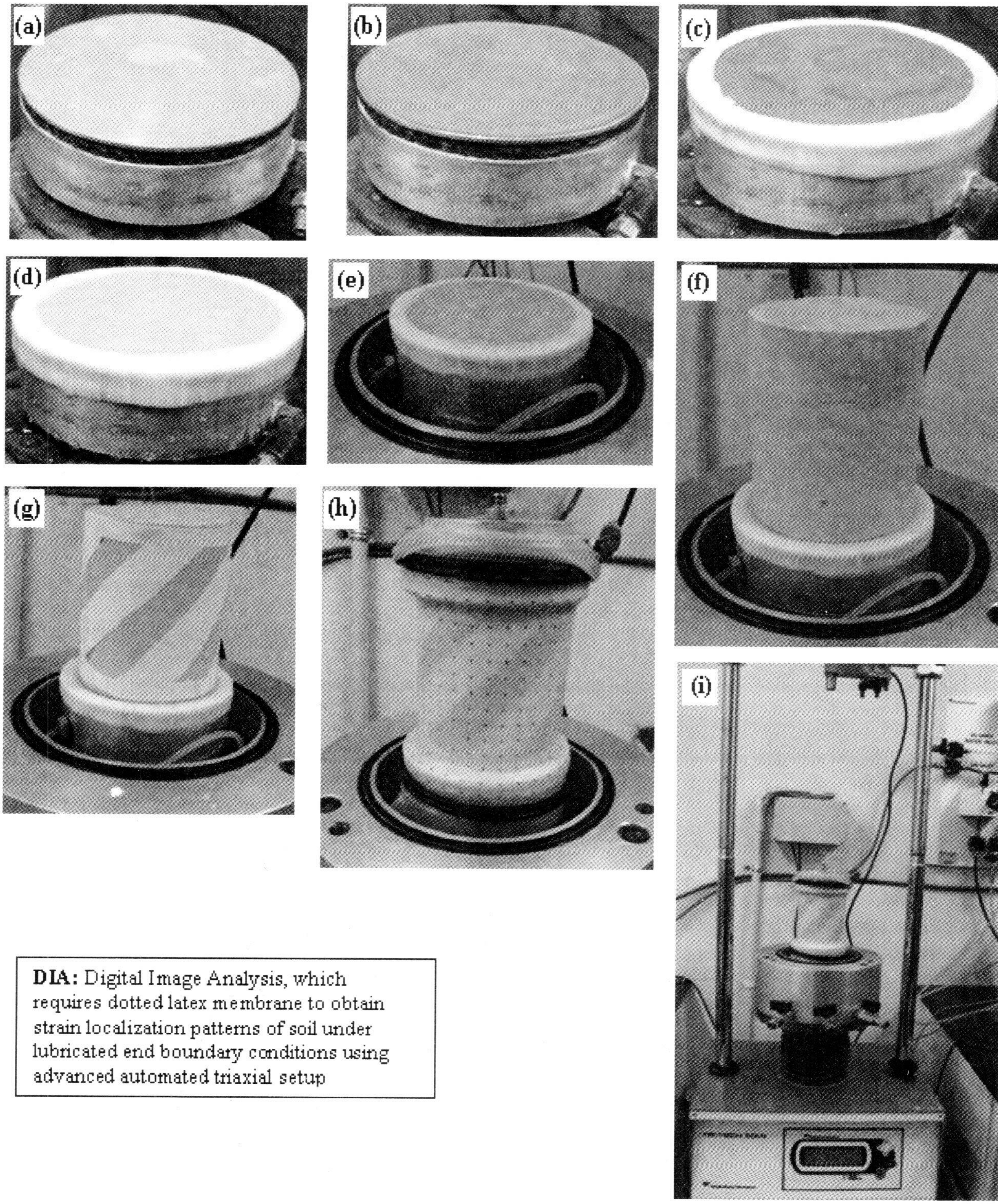

FIG. 1 Lubricated end boundary system for Advanced Automated Triaxial setup. (a) Smooth metal platen, (b) Platen with vacuum grease and latex membrane, (c) Platen with side filter paper strips, (d) Completed Lubricated end platen, (e) Bottom platen, (f) Specimen with lubricated end platens, (g) Specimen with radial drainage strips required for lubricated ends, (h) Specimen with dotted latex membrane for DIA, (i) Complete setup of Lubricated end boundary triaxial system

Experimental Program

First series of tests were performed on conventional triaxial setup, a manual triaxial system which is used for regular soil testing in practice. Second series of tests were performed on advanced automated triaxial setup with frictional end boundary system, which had the porous stones (frictional ends) at both the ends of specimen. This advanced microprocessor controlled triaxial system was also equipped with three Pressure transducers, Volume change measurement device, Cell volume control device, and LVDT (Linear Variable Displacement Transducer) for displacement measurement. Third series of tests were performed on the above advanced automated triaxial test with lubricated end platens at ends of the specimen. All 3 sets of tests were performed for 3 effective confining stresses 300 kPa, 375 kPa and 450 kPa at strain rate of 0.05% per min to observe the variation in shear strength parameters (c', ϕ') of Kaolin clay due to the change in boundary conditions of triaxial setup. Stress-strain and pore pressure response of soil were also analyzed for these three boundary conditions keeping other testing conditions constant and the results are presented in Figure 2.

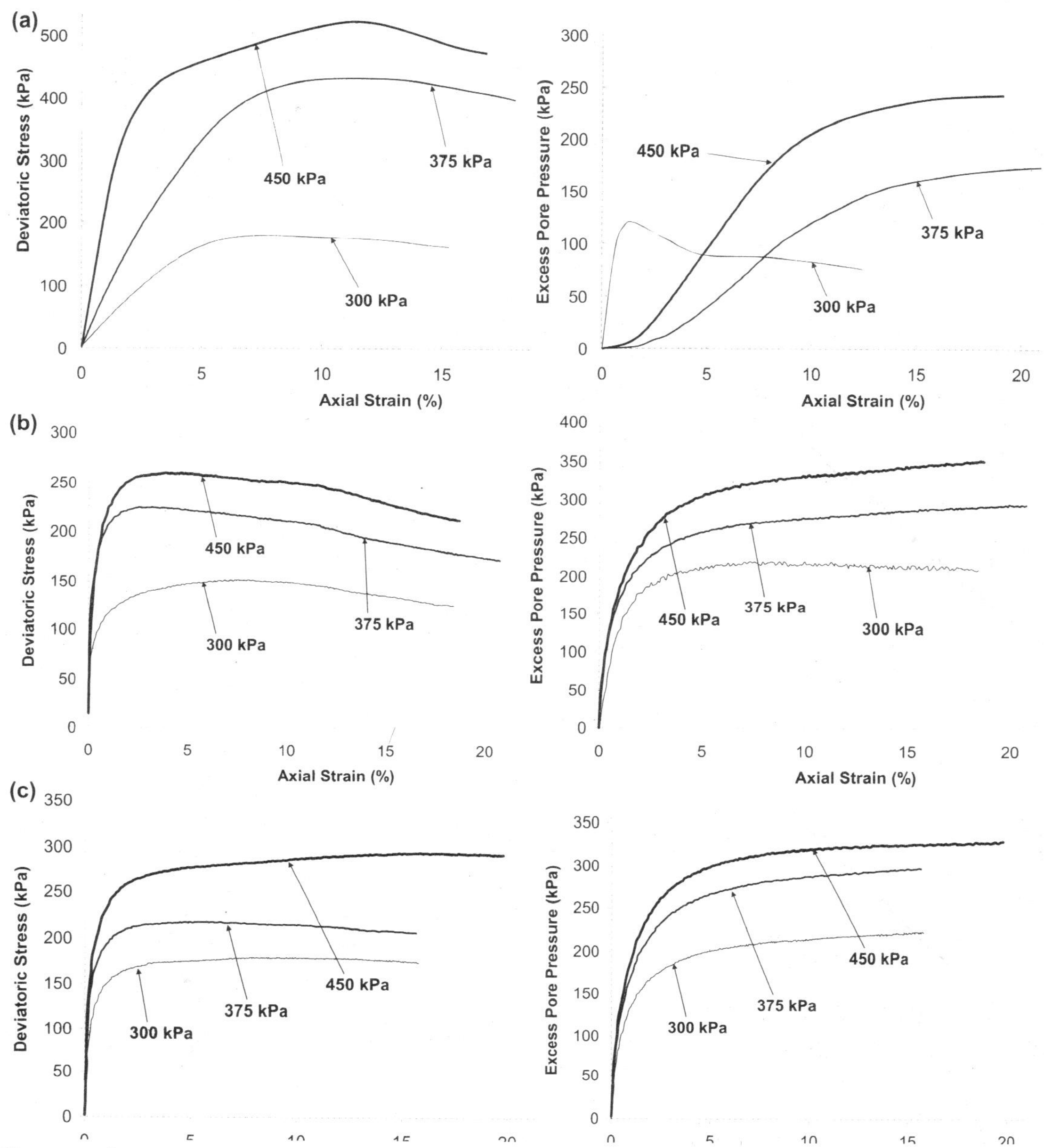

Fig. 2 Stress-strain and pore pressure response of Kaolin clay under different boundary conditions of triaxial setup. (a) Conventional boundary system, (b) Advanced Frictional end boundary system, (c) Lubricated end boundary system

Results and Discussion

Pore Pressure Evolution

Figure 2 presents the relationship of excess pore pressure and axial strain at three boundary conditions during undrained triaxial compression testing: i) Conventional boundary system, ii) Advanced Frictional end boundary system, and iii) Lubricated end boundary system. Excess pore pressure at failure showed a marked increase with the reduction in friction at the boundaries; from conventional to lubricated end boundary system. The reason could be attributed that the radial stress at the ends were almost zero in Lubricated end boundary system providing the specimen free-free boundary conditions; however, other two cases had moderate to large radial stresses at the ends of specimen leading to partially or completely fixed-fixed boundary conditions in other two cases.

Stress-Strain Relationships

The stress-strain relationships for these three boundary systems are shown in Figure 2.. Figure 2 exhibited that deviatoric stress at 300 kPa effective confining stress was observed to be much smaller than 375 kPa and 450 kPa in conventional triaxial boundary system. However, other two boundary systems showed a uniform change in deviatoric stress with respect to the confining stress variation. The similar response was observed in several repeat tests. Effective friction angle showed a marked change with respect to the variation in boundary conditions in triaxial testing. Lubricated end boundary system showed 31.5° which was 4° higher than the Frictional end boundary system and 5° from conventional boundary system. It exhibited the importance of simulating the boundary conditions of soil at site while performing triaxial testing in the laboratory. The boundary conditions of soil at site are similar to the soil specimen in the free-free end conditions like in lubricated end boundary system. However, boundary conditions are fixed-fixed in frictional or conventional boundary system. Thus, Lubricated end boundary system for triaxial testing was observed to be the best boundary system which efficiently simulated the boundary conditions of soil at site and also provided the maximum value of effective friction angle for a given soil as compared to the conventional and advanced frictional end boundary systems.

Effect of Drainage Conditions on Triaxial Test Data using Lubricated End Boundary System

Most of the drained triaxial tests reported in the past literature were performed using frictional end boundary conditions, which can provide relatively good drainage conditions with the use of porous stones at the frictional ends, but can lead to barreling effect and non-uniform deformation within the clay specimen. However, the lubricated ends have smooth platens, which minimize the barreling effect and the concentration of dilation in local zones (Bishop and Henkel 1962, Rowe and Barden 1964, Barden and McDermott 1965, Sarsby et al. 1982, Berre 1982, Leroueil et al. 1988). Smooth platens require special arrangement for good drainage conditions in the triaxial system, which can be acquired by having few drain holes on the side of platens and connecting them to the specimen drainage using filter paper strips. However, with such an arrangement, the connectivity of complete drainage system could become a critical issue during the phase of triaxial testing with drained boundary conditions. Most of the previous investigations using lubricated ends were performed using undrained triaxial compression testing, which had the drainage valves open only during the consolidation phase of testing. During a drained triaxial test, the external drainage conditions might influence both consolidation and shearing stages of testing with a significant impact on the interpreted soil properties. Thus, it is required to investigate the influence of external drainage system on the measured soil properties and modify the lubricated end boundary triaxial testing setup to achieve good drainage conditions.

The three drainage conditions in triaxial drained test using lubricated end boundary system were created to evaluate the importance of appropriate drainage conditions in triaxial testing. Figure 3 shows the variation in filter paper arrangement in three different drainage conditions: Poor, Intermediate, and Good drainage conditions corresponding to Case I, Case II, and Case III respectively. The consolidation under isotropic pressure of 276 kPa showed that the time of 100% consolidation for Case I (t_{100} = 404 min) was much higher than that for Case III (t_{100} = 60 min). In Case I, only 20% surface area of the porous-plastic strip was covered with the circular filter paper; whereas, 60% and 100% of the surface area was covered in Case II and Case III respectively. Therefore, the consolidation time (t_{100}) was decreased from Case I to Case III, as listed in Table 2. Therefore, the limiting factor for the rate of pore-pressure dissipation during consolidation process was not the permeability of clay; rather, it was the external specimen drainage system. A series of compression tests were performed on normally consolidated Kaolin clay specimens sheared under drained and undrained conditions for Case I, Case II, and Case III to study the issues regarding drainage conditions in lubricated end triaxial setup.

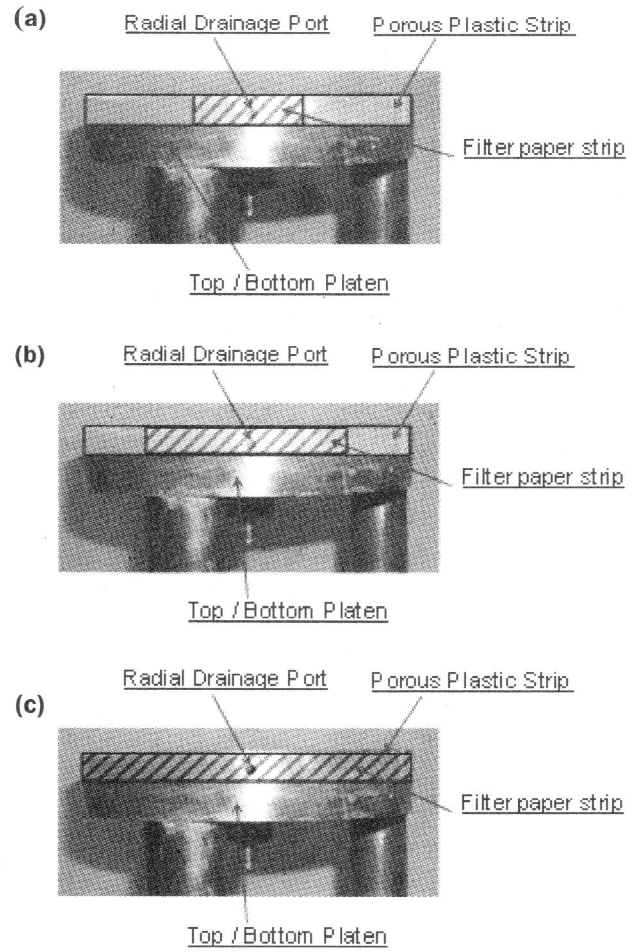

Fig. 3 Drainage conditions of triaxial setup with Lubricated end boundary system. (a) Case I: Poor drainage condition, (b) Case II: Intermediate drainage condition, (c) Case III: Good drainage condition

Prior to carrying out laboratory triaxial drained tests on cohesive soils, a suitable rate of loading must be estimated so as to ensure that the effect of the remaining pore-water pressure within the deforming clay specimen was very small. Appropriate strain rate was calculated by using the equations suggested by Bishop and Henkel (1962), and Germaine and Ladd (1988). Strain rates for Case I, II, and III were calculated under drained and undrained shearing conditions using the isotropic consolidation data obtained for solid cylindrical specimens of Kaolin clay. Time to failure (t_f) for drained and undrained testing was approximately estimated as suggested by Germaine and Ladd (1988). The slowest strain rate (0.005% per min) was chosen for all triaxial drained tests. The time required for 100% consolidation (t_{100}) was obtained by using the relationship between volume change and log(t) during isotropic consolidation, as suggested by Bishop and Henkel (1962).

Volumetric Response

Figure 4a presents the relationship of volumetric strain and axial strain for three drainage conditions (Case I, II, and III) during drained triaxial compression testing. Volumetric strain at failure showed a marked increase with the improvement of drainage conditions between specimen surface and end platens with radial drainage ports. Case I (poor drainage condition) exhibited 4.1% of volumetric strain at failure, whereas Case II and Case III showed 6.2% and 8.3% respectively. Although the drainage was allowed during shearing in Case I, a significant amount of pore water was not able to drain out from the specimen, which caused excess pore water pressure generation within the specimen. However, Case III provided the complete removal of pore water from the clay specimen resulting in no excess pore water pressure evolution under the good drainage conditions and higher value of volumetric strain at failure of the specimen. If there was a reliable way of measuring pore pressure inside clay pore-space during shear, this hypothesis could have been confirmed.

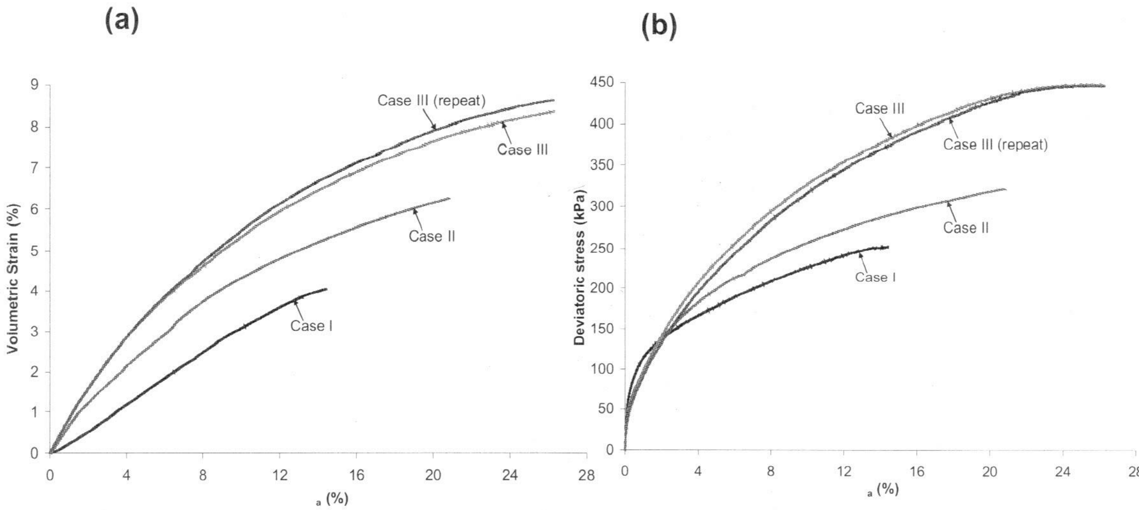

Fig. 4 Drained triaxial compression tests under lubricated end boundary conditions for drainage Cases I, II, & III. (a) Volumetric response, (b) Stress-strain curve

Stress-Strain Relationship

The stress-strain relationships for Case I, II, and III of drained triaxial compression tests are presented in Fig 4b. Deviatoric stress corresponding to good drainage conditions was found to be significantly larger than that for the other two drainage conditions throughout the shearing. The failure of Kaolin clay specimen was observed at 14% of axial strain for poor drainage conditions, whereas specimens sheared with intermediate and good external drainage conditions showed failure at the axial strain of 21% and 26% respectively. These experimental observations indicate that the drainage conditions of triaxial system with lubricated ends can significantly influence the shear deformation behavior of clay specimens and it is important to evaluate the suitability of drainage system being used for a given soil type and pore size distribution.

Shear Strength Properties

The shear strength of Kaolin clay was observed to be strongly dependent on drainage conditions during drained triaxial testing with lubricated end platens. The values of effective friction angle (ϕ') and deviatoric stress (q) at failure for Case I, II, and III are listed in Table 2. A difference of 8° in ϕ' values were observed for poor and good drainage conditions. The measured value of peak shear stress increased almost twice from Case I to Case III indicating the importance of good drainage conditions in lubricated end boundary system for drained triaxial testing. The reliability of the results for good drainage conditions was ensured by repeating many drained triaxial tests.

Conclusions

This research is focused on the effect of boundary conditions of triaxial testing and its associated drainage conditions on the obtained shear testing data for a given soil. Three series of triaxial undrained compression tests were performed on Kaolin clay specimens for three different boundary systems: i) Conventional boundary, ii) Advanced Frictional end boundary, and iii) Lubricated end boundary. The obtained experimental results for various boundary conditions reported that the Lubricated end boundary system had potential to simulate with the boundary conditions of soil at site, which possessed almost no friction at specimen's ends in the soil site. Therefore, Lubricated end boundary system was chosen for further evaluation to assess the proper drainage arrangement in the system in order to acquire the complete pore pressure dissipation throughout the triaxial test. Three different drainage conditions in Lubricated end boundary triaxial system were prepared based on its filter paper arrangements on radial drainage strip of each platen, which were further examined by performing a series of drained triaxial compression tests on Kaolin clay specimens. Key observations from this study are summarized as follows:

- A marked increase in excess pore pressure evolution was observed as the friction at the boundary got reduced due to almost no friction at the specimen's ends in lubricated end boundary system.
- The effective friction angle was observed to be 4-5 deg higher for lubricated end boundary as compared to the other two boundary systems indicating the strong impact of specimen's boundary conditions on its shear strength response.

- The shear strength of soil was found to be twice for Good drainage conditions as compared to the Poor drainage conditions.
- A difference of 8° in ϕ' values of soil was observed for poor and good drainage conditions exhibiting the importance of appropriate drainage conditions in a triaxial equipment facilitated with lubricated end boundary system.

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