Variability in the soil properties of laboratory consolidated clay beds

Y. A. Kolekar and S. M. Dasaka*

Preparation of uniform and consistent clay beds is a prerequisite for understanding the behavior of clay to external loads under laboratory environment. Different methods, such as, self weight consolidation, dead weight consolidation, vacuum consolidation, seepage induced consolidation, etc. have been used previously by several researchers to prepare the clay beds. Clay deposits are formed by process of consolidation, and it is simulated in the present study to prepare reconstituted clay beds in the laboratory. Clay beds are prepared from slurry state by method of consolidation using lever arm based incremental loading technique. Two series of tests: A and B, with each series having seven tests, are performed to prepare consolidated clay beds, and these clay beds are subjected to consolidation pressure of 18 and 36 kPa, respectively. The coefficients of variation (COVs) of measured water content and shear strength of consolidated clay beds are observed well below the acceptable limits, thus indicating that the lever arm based loading technique is simpler and produces consistent and uniform clay beds.

Keywords: Marine clay, Consolidation, Lever arm loading, Water content, Shear strength, COV

Introduction

Marine clays are formed as a result of deposition of marine sediments from each tidal wave and undergo consolidation over a geological time scale. Marine clays found along the coastal regions are characterized by very high water content, very low strength, and high compressibility, which can endanger the structures constructed over it. These clays pose challenges to geotechnical engineers to improve their engineering properties. To understand the behavior and performance of clay to external loads, laboratory studies on clay plays a significant role and preparation of a consistent and repeatable clay beds is a prerequisite. It is also observed from the literature that method of sample preparation plays an important role and has far reaching effects on the behavior of clay.

Literature

There are broadly two categories of tests that have been in use to prepare clay beds of required consistency in the laboratory, namely, method of consolidation and method of compaction. Techniques such as seepage induced consolidation, suction induced seepage consolidation, self weight consolidation, and dead weight consolidation come under the first category (Imai, 1979; Been and Sills, 1981; Bo *et al.*, 1999; Blewett *et al.*, 2002; Robinson *et al.*, 2003; Ghosh and Yasuhara, 2004), and in this method the clay beds are prepared from slurry state to the required consistency.

In the method of compaction, compacted clay beds are prepared by tamping moist clay at desired water content. Malarvizhi and Ilamparuthi (2004), Ambily and Gandhi (2007), Ammar *et al.* (2009), Liu *et al.* (2009), Shivshankar *et al.* (2010), Deb *et al.* (2011), and El-Garhy *et al.* (2011) adopted the compaction method to prepare the clay beds for laboratory studies, but this technique does not assure the uniformity of compacted bed and complete saturation due to the presence of air voids. Moreover, clay deposits in nature are formed through the process of consolidation and not through compaction, which would eventually influence the performance of clay beds under external loads. Also, there is a marked difference in the performance and behavior of natural clay and the same clay when air dried (Pandian *et al.*, 1991).

Imai (1979) proposed a new method for consolidating soils by utilizing the seepage force resulting from the difference of water heads, however, this method has not been tested at higher stresses. Seepage induced consolidation technique was further modified by Sridharan and Prakash (1999) to produce small size specimens, over a very low effective stress range. Been and Sills (1981) conducted studies on self weight consolidation of clay for measuring

Department of Civil Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India

*Corresponding author, email dasaka@civil.iitb.ac.in

Received 24 July 2013; accepted 24 October 2013
DOI 10.1179/1939787913Y.0000000020

density profiles with specimens of height 1929–643 mm, but the above method may not be practical to produce clay beds consolidated to higher stresses. Bo *et al.* (1999) used the large consolidation cell to study the deformation behavior of high water content soils when subjected to external load. The above setup, though capable of preparing larger samples, has limitations such as intricate and sophisticated equipment and instrumentation.

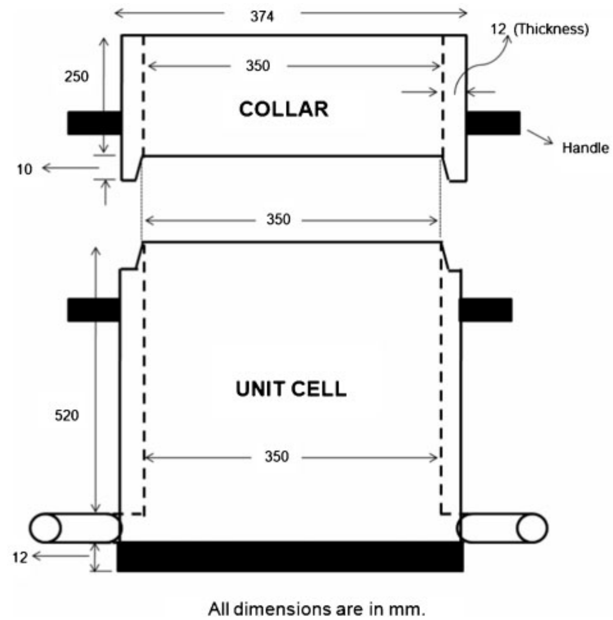
Blewett *et al.* (2002) have developed novel hydraulic consolidation cell with fully automated system to simplify the specimen preparation, but large specimen sizes were not studied. Robinson *et al.* (2003) applied suction at the base to induce seepage consolidation for studying the hydraulic fracture phenomenon, which occur as a result of the very high hydraulic head used in seepage consolidation, and the specimens obtained have an initial height of 260 mm. Ghosh and Yasuhara (2004) in their multi-purpose apparatus to study the characteristics of geosynthetic material prepared clay specimen by applying compressed air pressure. Clay specimen with an initial height of 300 mm, diameter of 150 mm, and maximum compressed air pressure of 400 kPa can be applied. The apparatus had limitations of automated complex setup. The above developed consolidation systems for laboratory consolidation of soft soils had the disadvantage of either high cost of equipment, sophisticated intricate elemental parts, or limited size of specimen.

Murugesan and Rajagopal (2007) have conducted studies using dead weight method of consolidation, similar to the one used in present study, for preparing the clay samples. Consolidation pressure of 10 kPa was applied on a tank of $1{\cdot}2 \times 1{\cdot}2$ m, which required a total dead weight of 14·40 kN. Dead weight method, though effective, has an inherent problem of applying a huge dead weight on the soil for consolidation.

It is clear from the literature that none of the above studies made any explicit effort to evaluate the variability in the soil properties of the consolidated clay bed, namely, variation of water content and shear strength, and assumed that the prepared clay beds were uniform throughout.

Hence the present study aims at in-depth understanding of the variation of water content and shear strength of a consolidated clay bed. In the present study, a gravity loading methodology using lever arm technique is adopted to produce large clay bed samples through consolidation, which eliminates the need of applying huge dead weights on the clay bed. The loading system used in the present study has the advantage of applying pressures in the range of 10–100 kPa on the clay bed, without much difficulty, and can accommodate specimen sizes as high as 1·0 m. The consolidated clay beds thus prepared are further used to understand the behavior of stone column reinforced clay bed.

The objective of the present study is to develop a simple and inexpensive consolidation setup to consolidate large clay beds in the laboratory and to ascertain the variability of soil properties of the consolidated clay bed, such as water content and shear strength, which can facilitate better control over laboratory studies.



1 Unit cell along with collar

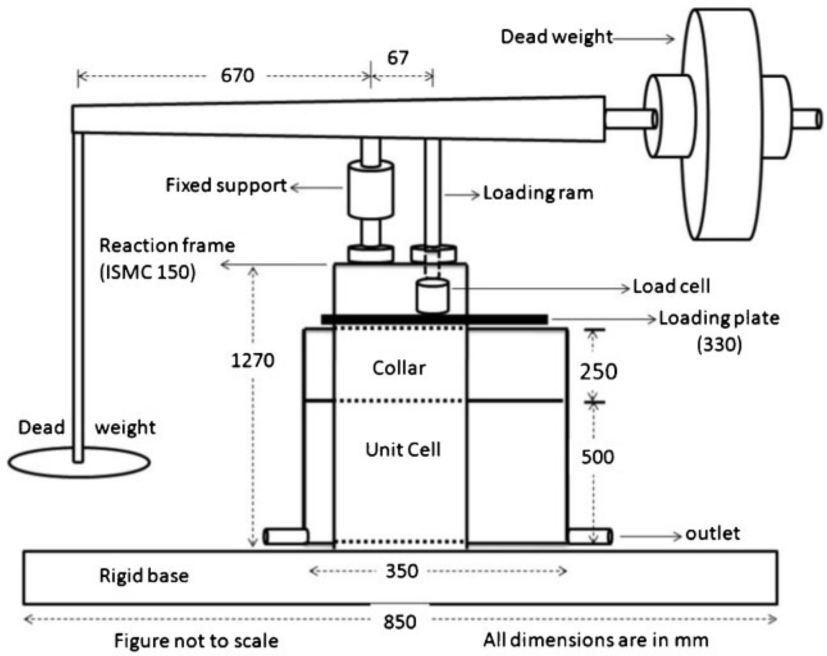
Test setup

The setup consists of unit cell and detachable collar of internal diameter 350 mm with the height of unit cell and collar being 520 and 250 mm, respectively. The setup has three outlets provided 120° apart at the base of the unit cell to dissipate the excess pore water pressure as shown in Fig. 1.

Detachable collar is subsequently removed once the consolidation process is complete. For applying the gravity loading by lever arm based technique, a special reaction frame was designed as shown in Fig. 2. The reaction frame uses counter balance mechanism and has a lever arm ratio of 1 : 10, which permits to apply 1/10th of the actual load to which the clay beds are required to be consolidated. Moreover, the reaction frame shown in Fig. 3 can accommodate four samples at a time, thereby consolidating four clay beds simultaneously, and facilitate consolidation of more samples in a limited time.

Clay bed

The marine clay used in the present study was obtained from Uran, near Navi Mumbai, India. The soil was collected from a depth of 2–3 m below ground level with a Poclain. However, undisturbed samples for laboratory testing were collected using a core-cutter. The particle size distribution of the marine clay is shown in Fig. 4, and some of the engineering properties of soil obtained from laboratory tests are shown in Table 1. While preparing clay beds, a layer of geotextile was placed over the aggregates at the bottom of the unit cell to act as a drainage layer and prevent clay particles from the slurry leaving the unit cell. On the inner surfaces of the unit cell and collar, a coat of grease was applied over which a thin plastic sheet was placed to reduce the side friction. Above this plastic sheet, a geotextile layer was placed, which

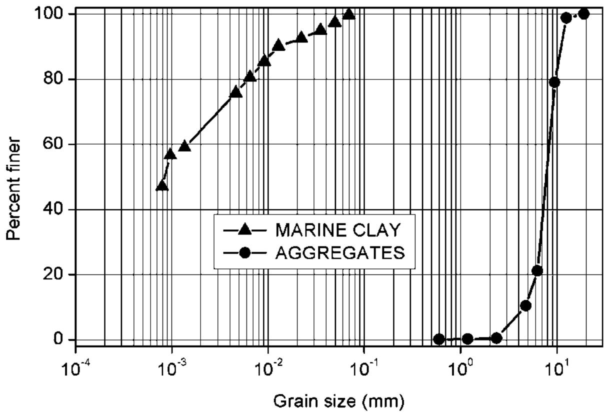


2 Schematic diagram of the reaction frame

provides radial drainage for the pore water that would be collected at the bottom of the cell, and removed through an outlet provided there. This radial drainage assists in expediting the rate of consolidation.

Clay collected from the site is soaked in water and then slurry is prepared using mechanical stirring for an hour to ensure homogeneous mixing. It is ensured that slurry has a water content of 1·5 times the liquid limit to produce a homogenous sedimentation of clay particles (Sridharan and Prakash, 2003; Murugesan and Rajagopal, 2007). The high water content in the slurry enhances workability and minimizes the possibility of presence of entrapped air. The slurry is then placed in the unit cell followed by light tamping all around the outer wall with the help of wooden mallet to remove entrapped air, if any, present in the slurry. A layer of geotextile is placed on the top of clay slurry followed by a layer of sand, sandwiched between the geotextile layer and the loading plate. A steel loading plate of 330 mm diameter and 12 mm thick with perforations is placed on the geotextile layer, as shown in Fig. 5, for

3 Reaction frame along with unit cell and collar



4 Particle size distribution for marine clay

applying incremental gravity loading. The perforations in the steel loading plate permit excess pore water pressure to dissipate from the top, thereby providing drainage boundary at the top as well, thus simulating a double drainage condition apart from radial drainage. The diameter of loading plate is 20 mm less than the internal diameter of the unit cell and collar, to prevent friction generated at the boundary during the incremental loading application. Load is applied on the clay bed through a loading ram, as shown in Fig. 2. The applied load consists of dead weights, weight of hook, loading arm, and loading ram. After 25–30 days when settlements are less than 1 mm day^{-1} the collar is removed and any excess clay projecting above the unit cell is trimmed.

Viscometer

The clay in bulk quantity was obtained from the site, and stored in a $5\times3\times6$ m covered storage bin in the laboratory premises for long-time usage. Each time the clay was taken out from the bin in the required quantity, and used for the present study and other research activities. This clay stored in the storage bin exhibited wide variations in the water contents, which varies throughout the depth and width of the bin and seasons too. For preparing slurry, the clay was soaked in water for a month's time, which results in evaporation losses. These variations in water content made it difficult to determine the quantity of water required for preparing slurry with a water content equal to 1·5 times the liquid limit (w_L). To overcome this difficulty, it was decided to measure the viscosity of the slurry and determine the time required for 500 ml of slurry at 1·5 times w_L to flow through the viscometer.

For this purpose a slurry meter was devised in the present study. The time required for 500 ml of slurry to flow through the viscometer, with a water content of 1·5 times w_L is 58 s, as shown in Fig. 6. Viscometer assists in maintaining a better control over the quantity of water to be added to clay to achieve water content of 1·5 times w_L. This is necessary as higher water content in slurry result in the segregation of soil particles and lower water content would prevent the homogeneous sedimentation of the slurry (Bo *et al.*, 1999; Sridharan and Prakash, 2003; Ghosh and Yasuhara, 2004).

Table 1 Properties of marine clay

Properties	Values
Natural moisture content/%	84
In situ bulk density/kN m^{-3}	14·96
In situ vane shear strength/kPa	8–9
Specific gravity of soil solids/G_s	2·74
Liquid limit, w_L (natural)	101
Liquid limit, w_L (oven dried)	51
Plastic limit, w_P	40
Plasticity index	61
Unified soil classification	OH
Preconsolidation pressure, p_c/kPa	18
Free swell index/%	31

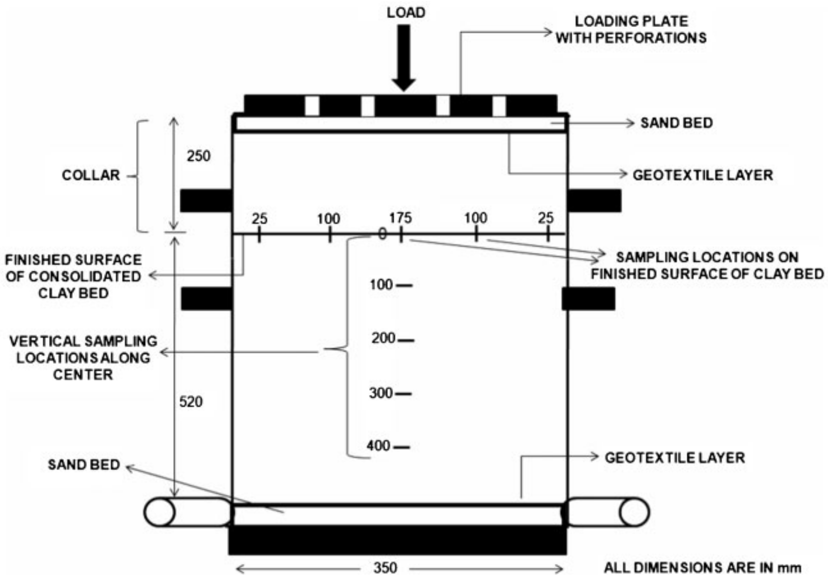
Testing methodology

In the present study, two series of tests were carried out with seven tests in each series. In the first series 'A', tests 1–7 were conducted by subjecting the clay slurry to a consolidation pressure of 18 kPa, and in the second series 'B', tests 8–14 were subjected to a consolidation pressure of 36 kPa, as reported in Table 2. The preconsolidation pressure of clay specimen collected *in situ* was obtained as 18 kPa. To simulate the field conditions, clay slurry was subjected to a consolidation pressure of 18 kPa, which yielded lab vane a shear strength of 8–9 kPa. However, it was noted that the stone columns perform better if the undrained shear strength of unreinforced clay bed was in the range of 15–50 kPa (Barksdale and Bachus, 1983). Accordingly, the consolidation pressure for second series 'B' tests was therefore doubled to 36 kPa, which yielded a lab vane shear strength of 18–20 kPa. Initially, a lower consolidation pressure of 1–2 kPa was applied for 3 days to prevent the squeezing out of marine clay slurry from the gap between loading plate and collar under sudden loading. Thereafter, the entire consolidation pressure was applied for the 'A' and 'B' series respectively till the rate of settlement was less than 1 mm day^{-1}, in accordance with the recommendations of Murugesan and Rajagopal (2007). It requires approximately 25–30 days to satisfy the above requirement.

The water content and vane shear strength for these clay bed specimens were recorded on the surface at a distance of 25, 100, 175, 250, and 325 mm from the edge of the unit cell. Water content of the clay beds were also recorded along the core made at the center of clay bed with the help of auger at depths 0, 100, 200, 300, and 400 mm from the top, as shown in Fig. 5.

Results and discussion

According to Phoon and Kulhawy (1999) the inherent soil variability is modeled as a random field and can be best explained with coefficient of variation (COV), which is defined as the ratio of standard deviation and mean. It is recommended that if the COV of any geotechnical parameter obtained from the laboratory testing lies below 10%, the sample preparation and testing can be considered acceptable, in view of the large uncertainties involved



5 Loading arrangement and locations of sample collection

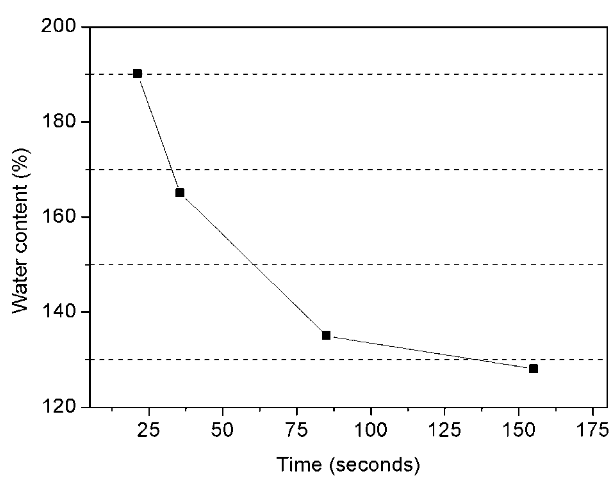
in the associated processes. In the present study, the variation of water content, shear strength, and settlement are presented in terms of COV.

Water content: horizontal profile

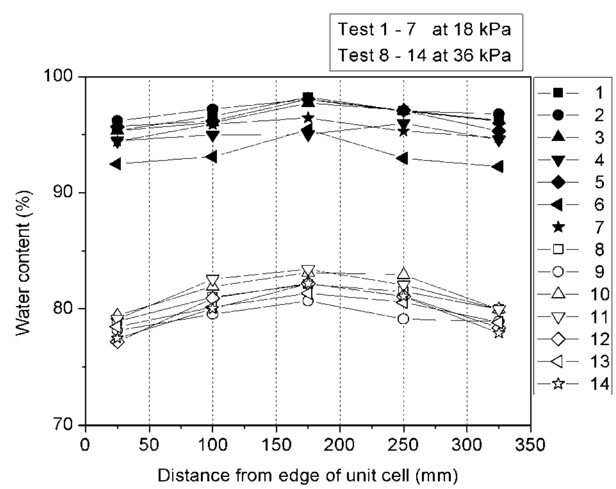
The variation of water content along top surface of clay bed is shown in Fig. 7. For clay beds consolidated to 18 and 36 kPa pressures, the water content is higher in the central part of clay bed and reduces laterally toward the boundaries. This is due to the presence of drainage boundary at the periphery. The COVs of water content in the horizontal direction for clay beds consolidated to 18 and 36 kPa consolidation pressures are 0·96 and 1·95%, respectively. The average water content at the surface of the consolidated clay bed is in the range 93–97%, and 78–83%, for consolidation pressures of 18 and 36 kPa, respectively. However the variation in water content at any location, for the seven tests of 18 and 36 kPa is not more than 3–4%.

Water content: vertical profile

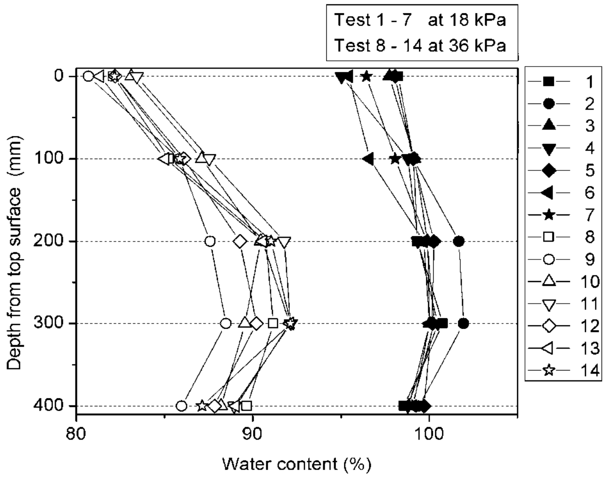
The water content variation in the vertical direction is also analyzed along the central core of clay bed, as shown in Fig. 8. For test series 'A', the water contents are nearly uniform over the depth and for test series 'B' it shows a slight variation in the profile. The water content at the top surface is the least, increases downward, and then decreases at the base. This is due to the proximity of drainage boundary at the base and top of the soil specimen. It is observed that the variation in the water content is quite minimal, indicating that repeatable and uniform clay beds can be obtained with the present setup. The COVs of water content in the vertical direction for clay beds consolidated to 18 and 36 kPa are 1·46 and 4·07%, respectively.



6 Viscosity of slurry



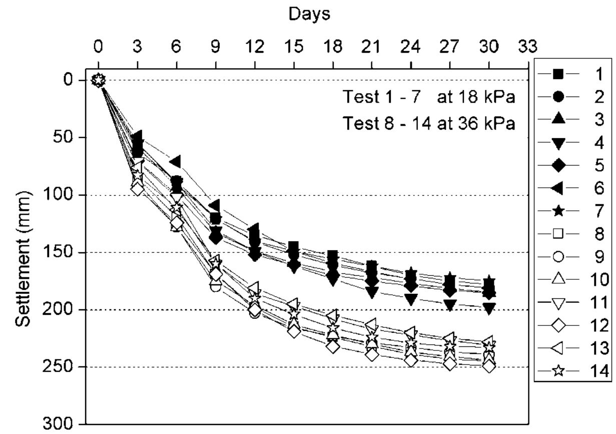
7 Horizontal water content profile at top surface for 'A' and 'B' series



8 **Vertical water content profile along the center of clay bed for 'A' and 'B' series**

Shear strength

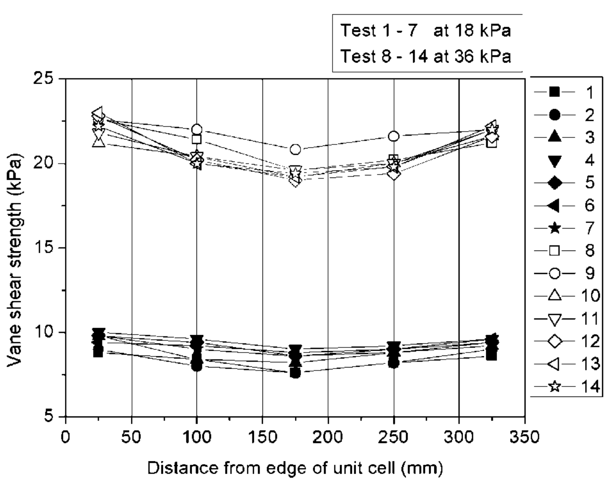
Lab vane shear apparatus is used to measure the undrained shear strength of the consolidated clay bed. Figure 9 shows the variation of shear strength with the horizontal distance along the top surface of clay bed. For test series 'A', the shear strength varies in the range 8–9·5 kPa and for test series 'B', it varies in the range 18–22 kPa. The variation of shear strength is in tandem with the measured water content of the consolidated bed. The COVs of shear strength for 18 and 36 kPa consolidation pressures are 5·42 and 5·77%, respectively. As shown in Fig. 8, the water content is higher at the center than at edges, hence, higher values of shear strength are recorded at the edges than that at the center. It is observed that COVs of measured shear strength is well below 10%, thus indicating uniform clay samples obtained in the present study. The average vane shear strength at the surface of the clay bed is obtained as 8–9 kPa and 20–22 kPa, for series 'A' and 'B', respectively.



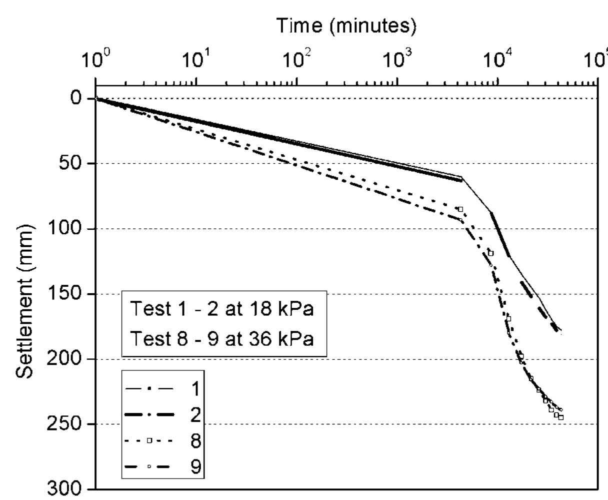
10 **Settlement of clay bed for 'A' and 'B' series**

Settlement

Figure 10 shows the settlements that occurred due to the consolidation of clay beds. After 6 days of consolidation pressure application, nearly 40–45% of the total settlements have already occurred, indicating gradual accumulation of shear strength of soil. It is obvious to note that as a result of greater applied pressure in series 'B', the soil shows higher settlements as compared to that of series 'A'. From the curves for the series 'A' and 'B', it can be observed that both series follow a similar trend, indicating that repeatable and consistent clay beds can be obtained with this setup. The COVs of settlement at 30 days, for clay beds consolidated to 18 and 36 kPa consolidation pressures are 4·04 and 3·33%, respectively. Figure 11 shows the settlement *versus* log(time) variation, throughout the consolidation process. It is observed that after 4320 min (3 days), the self weight consolidation is almost complete, hence the first increment of loading of 1–2 kPa is applied and at 8800 min (~6 days) the second bend in curve is evident resulting from the application of the entire consolidation pressure.



9 **Vane shear strength at top surface for 'A' and 'B' series**



11 **Variation of settlement-time during the consolidation process**

Benefits of the test setup

The setup devised in the present study has certain benefits over the setups previously used by various researchers (Imai, 1979; Blewett *et al.*, 2002; Robinson *et al.*, 2003). The previously developed setups would incur heavy initial cost along with specialized manpower to operate it. They have many controlling parts that necessitated meticulously following the procedure of sample preparation. The setup used in the present study for preparing large consolidated clay beds is very simple, versatile, easy to work with, and economical. It has the flexibility of preparing clay bed specimens of any diameter up to 1·0 m and any height up to 1·0 m. Moreover, the setup used in the study can prepare four specimens simultaneously, and is applicable to a wide range of pressure application of 10–100 kPa. The COVs of geotechnical parameters considered in the present study lie well below 10%. Thereby it is evident that the clay beds consolidated by lever arm based gravity loading are uniform and consistent. Also, the repeatability of soils samples is established with good accuracy.

Conclusion

A simplified and economical load testing setup is designed in the present study for preparing large uniform clay beds. The study in this paper is conducted on reconstituted marine clay specimens consolidated at two different preconsolidation pressures, and the following are important conclusions drawn from the study.

1. The lever arm based gravity loading is simpler, economical, and produces large, uniform, and consistent clay beds.
2. With the use of a viscometer better control over the amount of water to be added to clay for slurry preparation can be maintained.
3. The COVs of water content, shear strength, and settlement are well below 10%, and hence, the sample preparation method described in this paper can be considered acceptable to produce large, uniform, and consistent clay beds.

References

Ambily, A. P. and Gandhi, S. R. 2007. Behaviour of stone columns based on experimental and FEM analysis, *J. Geotech. Geoenviron. Eng.*, **133**, (4), 405–415.

Ammar, A., Liu, X., Lin, H. and Ren, J. 2009. Enlarged base stone columns to improve soft clay soil. Proceedings of the International Conference on Transportation Engineering, ASCE, 4240–4246.

Barksdale, R. D. and Bachus, R. C. 1983. Design and construction of stone columns, Report No. FHWA/RD-83/026, Office of Engineering and Highway Operations Research and Development, Federal Highway Administration, Washington, DC, USA.

Been, K. and Sills, G. C. 1981. Self weight consolidation of soft soils: an experimental and theoretical study, *Geotechnique*, **31**, (4), 519–535.

Blewett, J., McCarter, W. J., Chrisp, T. M. and Starrs, G. 2002. An automated and improved laboratory consolidation system, *Can. Geotech. J.*, **39**, (6), 738–743.

Bo, M. W., Arulrajah, A., Choa, V. and Na, Y. M. 1999. One dimensional compression of slurry with radial drainage, *Soils Found.*, **39**, (4), 9–17.

Deb, K., Samadhiya, N. and Jagtap, N. B. 2011. Laboratory model studies on unreinforced and geogrid reinforced sand bed over stone column improved soft clay, *Geotext. Geomembr.*, **24**, (6), 190–196.

El-Garhy, B., Maraie, M. and Youssef, A. 2011. Behaviour of model footings resting on soft clay reinforced by floating granular piles: experimental study, *Int. J. Geotech. Eng.*, **5**, (4), 415–424.

Ghosh, C. and Yasuhara, K. 2004. Clogging and flow characteristics of a geosynthetic drain confined in soils undergoing consolidation, *Geosynth. Int.*, **11**, (1), 19–34.

Imai, G. 1979. Development of a new consolidation test procedure using seepage force, *Soils Found.*, **19**, (3), 45–60.

Liu, X., Ammar, A., Lin, H. and Ren, J. 2009. The stress concentration ratio of stone columns under confined condition, Proceedings of the International Conference on Transportation Engineering, *ASCE*, 4247–4255.

Malarvizhi, S. N. and Ilamparuthi, K. 2004. Load versus settlement of clay bed stabilised with stone and reinforced stone columns, Proc. GeoAsia-2004, Korean Geosynthetic Society, Seoul, Korea, 322–329.

Murugesan, S. and Rajagopal, K. 2007. Model tests on geosynthetic encased stone columns, *Geosynth. Int*, **14**, (6), 346–354.

Pandian, N. S., Nagraj, T. S. and Babu, G. L. S. 1991. Effects of drying on the engineering behaviour of Cochin marine clays, *Geotechnique*, **41**, (1), 143–147.

Phoon, K. K. and Kulhawy, F. H. 1999. Characterization of geotechnical variability. *Can. Geotech. J.*, **36**, (4), 612–624.

Robinson, R. G., Tan, T. S. and Lee, F. H. 2003. A comparative study of suction-induced seepage consolidation versus centrifuge consolidation, *Geotech. Test. J.*, **26**, (1), 1–10.

Shivshankar, R., Babu, M. R., Nayak, S. and Manjunath, R. 2010. Stone columns with vertical circumferential nails: laboratory model study, *Geotech. Geol. Eng.*, **28**, (5), 695–706.

Sridharan, A. and Prakash, K. 1999. Simplified seepage consolidation test for soft sediments, *Geotech. Test. J.*, **22**, (3), 235–244.

Sridharan, A. and Prakash, K. 2003. Self weight consolidation: compressibility behavior of segregated and homogeneous fine grained sediments, *Mar. Georesour. Geotechnol.*, **21**, 73–80.