LARGE-SCALE CYCLIC TRIAXIAL TESTING OF SOFT CLAY

Anass Attya[1] and Buddhima Indraratna[2]
[1]PhD Candidate, [2]Professor of Civil Engineering
School of Civil, Mining and Environmental Engineering, University of Wollongong

ABSTRACT

The behaviour of saturated soft clays subjected to cyclic loading is of considerable importance in railway engineering. The use of prefabricated vertical drains (PVDs) with surcharge preloading is one of the popular methods of soft ground improvement as they accelerate the consolidation by shortening the drainage path. In this paper, the behaviour of a soft clay from North-eastern NSW subjected to cyclic loads is investigated using large-scale triaxial testing. Cyclic triaxial tests on remoulded soft clay samples with vertical drains were carried out using a large scale triaxial apparatus designed and built at the University of Wollongong, using samples of 300 mm in diameter and 600 mm in height. The samples were anisotropically consolidated under k_o condition to simulate the *in situ* stress history. Stress-controlled cycles were then applied to the soil samples. The results of the excess pore water pressure and settlement of the soft clay are presented. The advantages of soft subsoil stabilization with PVDs under cyclic loading conditions are discussed.

1 INTRODUCTION

A problem of considerable importance in geotechnical engineering is that of the prediction of the behaviour of soils under cyclic loading. The behaviour of soft clays subjected to cyclic loading is of paramount significance in both railways and roadway design. Due to the rapid increase in population and associated urbanisation, most new construction activities have to utilise the poorest of soft soils. Soft clays that exist in the coastal regions of Australia usually have low bearing capacity and high compressibility properties, affecting the performance of major transportation infrastructure. It is well known that failure in soft clays under cyclic loads occurs at strengths well below the undrained shear strength obtained from the standard static tests (Larew and Leonards, 1962; Sangrey *et al*., 1969). The rapidly generated excess pore water pressures due to cyclic loads play a key role in causing failure of the clay subgrade as it dramatically decreases effective stress under undrained cyclic loading.

Vertical drains with preloading have been widely utilised to stabilise soft soil deposits prior to construction (Indraratna *et al*., 1994), inducing most of the expected ultimate settlement under the given loading by promoting rapid radial consolidation (Richart, 1957). This results in a gain in the shear strength of the soft formation soil.

Although the theoretical and practical aspects of static preloading with prefabricated vertical drains (PVDs) has been well established (Barron, 1948; Hansbo, 1979; Hansbo, 1981) followed by even more rigorous analytical and numerical models together with experimental verifications and/or field case studies (Hird *et al*., 1992; Indraratna *et al*., 2005), the application of cyclic loading on soft clays with PVDs has not been investigated in the past, except some preliminary work reported by Indraratna *et al*. (2006). The purpose of the current study is to investigate the effect of cyclic load application to soft clay improved by PVD, and to discuss the potential advantages of PVDs under cyclic loading situations such as in railway environments.

2 LABORATORY INVESTIGATIONS

2.1 TESTING APPARATUS

A large-scale cylindrical triaxial equipment shown in Figure 1(a) was used (Indraratna, 1996; Indraratna *et al*., 1998). The apparatus utilises a hydraulic type dynamic actuator to apply the cyclic load. As shown in the schematic illustration of Figure 2(a), this apparatus consists of five main parts: the triaxial chamber, the axial loading unit, the air pressure and the water control unit, the pore pressure measurement system and the volumetric change measurement device. It has the capability of accommodating specimens of 300 mm in diameter and 600 mm in height as shown in Figures 1(b) and 2(a). The apparatus has been modified to measure the excess pore pressure at different locations inside the specimen by fitting miniature type pore pressure transducers through the base of the triaxial cell, as illustrated in Figure 1(c).

(a) (b) (c)

Figure 1: (a) Large-scale triaxial apparatus, (b) Soil specimen and (c) Miniature pore pressure transducers.

2.2 TESTING PROCEDURE

2.2.1 Sample Preparation

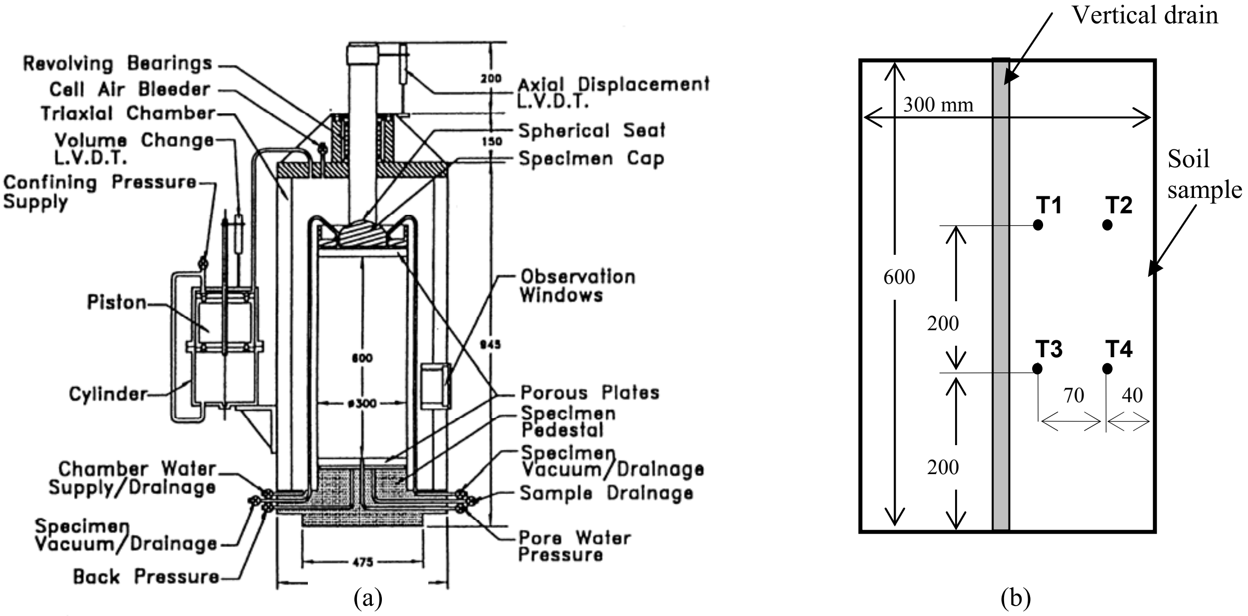
Reconstituted clay from North-eastern NSW was used in this test. The properties of this reconstituted clay obtained from standard consolidation testing and standard Atterberg limits test are summarised in Table 1.

Table 1: Soil properties of the reconstituted clay.

Specific Gravity, G_s	2.65
Liquid Limit, w_L (%)	66
Plastic Limit, w_P (%)	28
Compression Index , C_c	0.84
Swelling Index, C_s	0.14

The procedure for preparing the reconstituted sample was as follows:

- The clay was wet-screened through a # 40 sieve (0.425 mm opening size) to remove larger particles and any coarse organic materials.
- The rubber membrane was clamped into the base of the triaxial equipment and a geosynthetic filter layer was placed at the bottom to prevent clogging of the drainage line.
- Subsequently, the clay slurry was placed and lightly compacted in four layers (150 mm each) inside the membrane to a unit weight of about 15.5 kN/m^3.
- During the placement of the clay in the membrane, four pore pressure transducers were positioned at selected locations (Figure 2b).
- A vertical band drain was inserted into the clay specimen. A geosynthetic layer was placed at the top of the sample also, after inserting the PVD and prior to placing the top loading cap, in order to protect the top drainage holes from clogging.



(a) (b)

Figure 2: (a) schematic diagram of the large-scale triaxial cell, (b) location of pore pressure transducers inside the soil specimen.

2.2.2 Sample consolidation

The sample was anisotropically consolidated (k_o=0.6) to simulate the appropriate field conditions. The sample was then subjected to a vertical overburden pressure of 35 kPa and a horizontal pressure of 21 kPa. The consolidation process was carried out in 3 incremental stages to avoid shear failure. With the PVD, the consolidation process took about 8 weeks with both the top and the bottom drainage valves open.

2.2.3 Application of cyclic load

At the end of the consolidation stage, a cyclic load having a frequency of 5 Hz was applied to the soil sample. This specific frequency was chosen to simulate the loading frequency common on rail track environments in Australia, i.e. corresponding to train speeds of 80 to 100 km/h. The test was conducted at a cyclic stress ratio (CSR) of 0.6, where the cyclic stress ratio is defined by the ratio between the cyclic deviator stress q_{cyclic} to the effective initial overburden pressure σ_{vo}' (i.e. CSR= $q_{cyclic} / \sigma_{vo}'$). The corresponding loading pattern is shown in Figure 3.

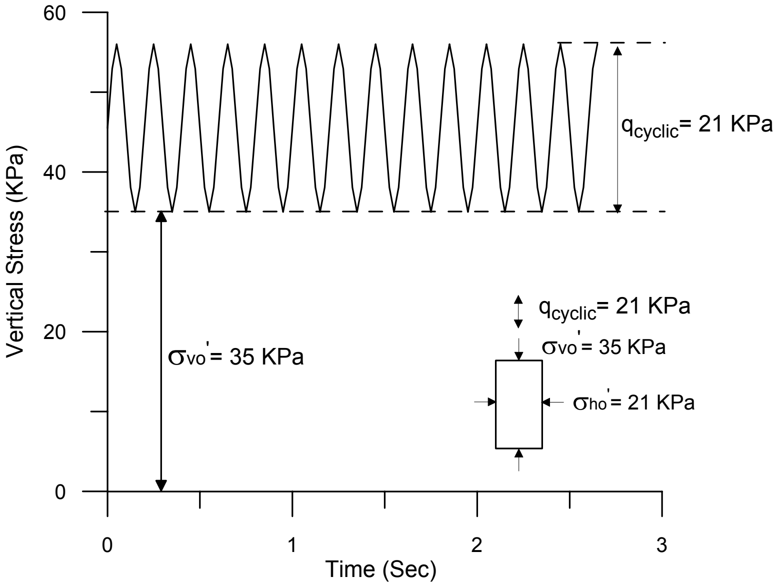


Figure 3: The pattern of cyclic loading.

A thousand cycles (N = 1000) was applied to the specimen to simulate a train passage time of about 3 minutes; the cyclic load was then terminated and followed by a drainage period to allow the dissipation of the excess pore water pressures thus developed. In this stage, the only drainage permitted was through the top of the sample, thereby simulating the actual field conditions encountered by a PVD installed in soft clay. The excess pore water pressures at the locations shown in Figure 2(b) were recorded during the period of cyclic loading and, also, the vertical deformations and the volume change were concurrently measured using linear variable differential transformers (LVDT).

2.3 TEST RESULTS

2.3.1 Pore pressure generation

The excess pore water pressure ratio u^* ($u^* = \Delta u / \sigma_{vo}'$, Δu, excess pore water pressure, σ_{vo}', effective initial overburden pressure) is defined for the purpose of analysis. The variation of u^* versus the number of loading cycles is plotted in Figure 4. The transducers T1 and T4 were chosen to show the effect of the drainage path length on the development of the cyclic pore pressures. T1 has the shortest drainage path as it is the closest to the central drain and the top drainage surface, whereas T4 has the longest drainage path. The results indicate that at the same number of cycles, T1 experienced a smaller excess pore pressure ratio than T4. At the end of the cyclic load application (N=1000 cycles), the excess pore pressure ratio at T4 is about 4 times greater than that of T1.

The residual vertical strains are plotted against the number of load cycles (Figure 5), which indicate that these strains are predominantly plastic. The results show that at the end of the cyclic load, the maximum plastic vertical strain was about 5.2%.

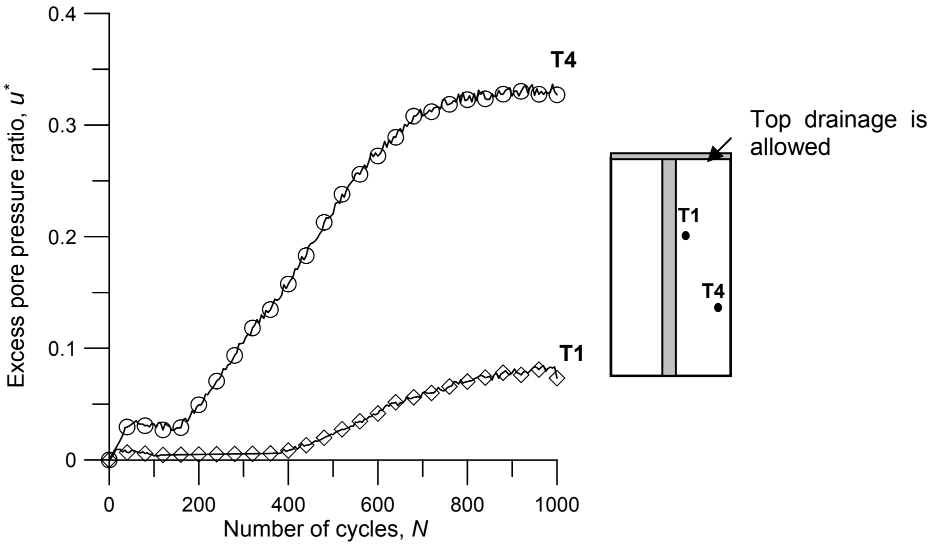


Figure 4: Pore pressure generation curves for transducers 1 and 4.

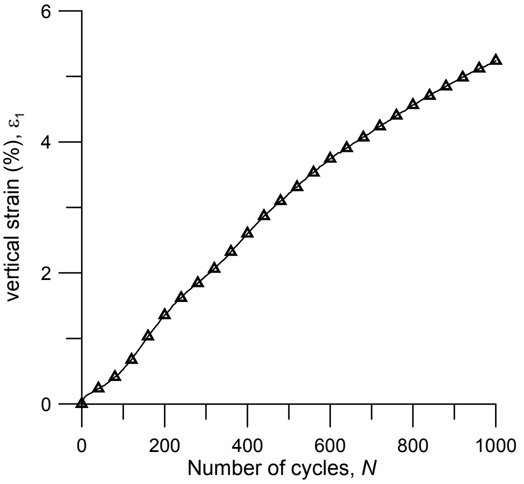


Figure 5: Vertical strains during cyclic load applications.

2.3.2 Comparison with undrained cyclic loading

Zhou and Gong (2001) carried out a series of undrained stress-controlled triaxial tests on Hangzhou normally consolidated clay under different cyclic stress ratios. Although no PVDs were used here, these tests provide a good idea about the expected behaviour of soft clays under cyclic loading conditions. In order to show how effective the PVDs are in dissipating the cyclic-generated excess pore water pressures, the results of T1 and T4 are plotted together with the results obtained by Zhou and Gong (2001) for stress ratios of 0.6, 0.5 and 0.35 in Figure 6. Comparison between these two sets of data indicates that the use of PVDs significantly controls the rate of excess pore water pressure buildup during cyclic loading. As shown in Figure 6, for a cyclic stress ratio of 0.6 with absence of PVD, the failure occurred quickly only after a small number of cycles. There is no doubt that a smaller cyclic stress ratio causes less pore pressure buildup.

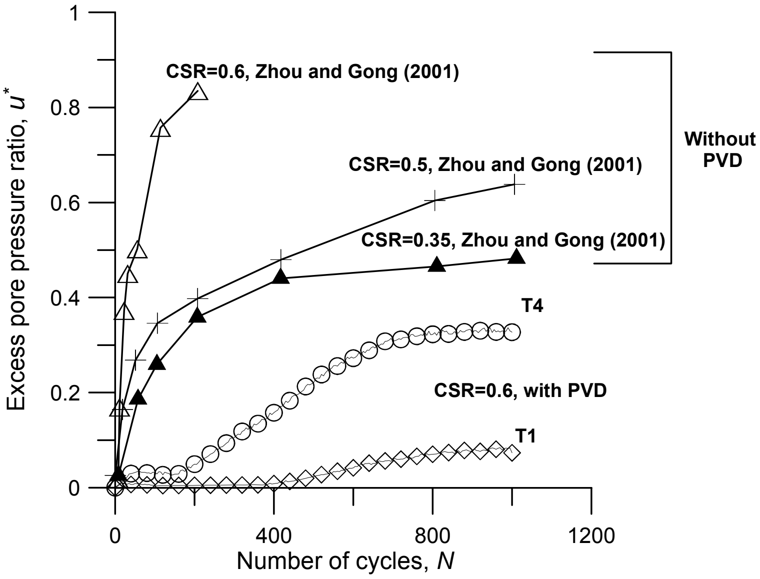


Figure 6: Cyclic excess pore pressures response of soft clay with and without PVD.

2.3.3 Post-cyclic loading dissipation

After termination of cyclic loading, the top drainage allowed the dissipation of the excess pore pressures developed and sustained during the loading cycles. The time-dependent excess pore water pressures for the 4 transducers are shown in Figure 7. The length of the drainage path plays a very important role and, as expected, the fastest dissipation rate was for T1 having the shortest drainage path length while the slowest rate was for T4. The responses of the other 2 sensors were observed to be between T1 and T4, with less pore pressure buildup indicated by T3 compared to T2 as the former was placed closer to the drain.

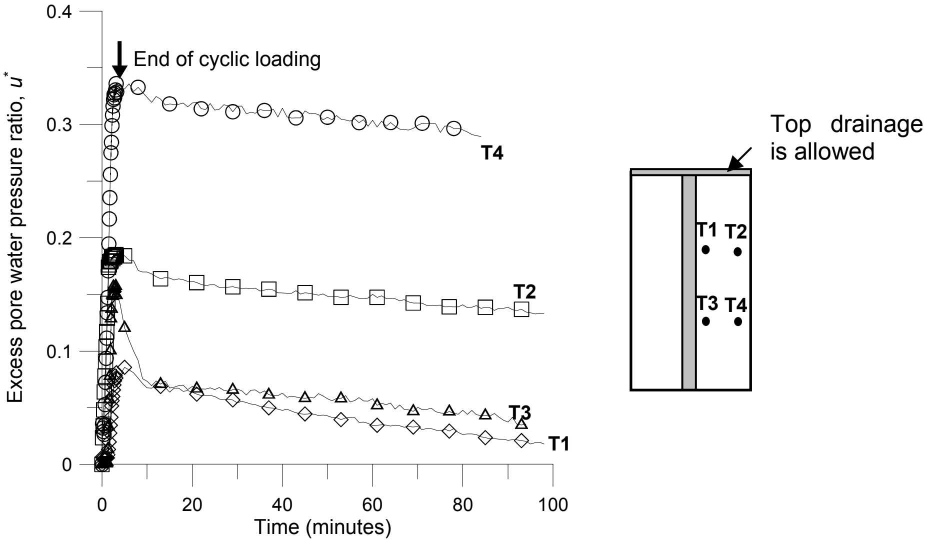


Figure 7: Dissipation behaviour after termination of cyclic loading.

The results clearly confirmed the expectation that the PVD assisted in the dissipation of the cyclically generated pore water pressures. This implies that having PVDs beneath rail tracks can lead to increased stability of the soft foundation and significantly reduces the risk of any potential shear failure. Especially during wet weather, having in-situ vertical drains will maintain continuing dissipation of excess pore pressure even after the passage of trains thereby making the track stable for the next loading stage by the forthcoming trains.

3 CONCLUSIONS

An experimental study was conducted to investigate the influence of prefabricated vertical drains (PVDs) on the cyclic behaviour of soft clay conducted using a large-scale triaxial equipment simulating typical cyclic loads encountered in railway environments. The excess pore water pressures ratio and the post-cyclic loading dissipation rate were considered in the assessment of the performance of PVDs.

During the application of cyclic loading, the PVDs reduced the rate of generation of excess pore water pressure, when compared to the case without PVD. Under the same cyclic stress ratio, the magnitude of the excess pore pressure generated was also significantly less. The paper also showed evidence that the buildup of excess pore pressure (both the rate and the magnitude) would increase if the cyclic stress ratio were to increase. As expected, irrespective of the magnitude of the cyclic stress ratio and the number of cycles, the development of excess pore pressure was the least for the part of the soil specimen nearest to the central PVD, as indicated by the transducer located closest to the PVD.

While further testing is still ongoing to study the cyclic behaviour of soft clay stabilised by PVD, the findings reported here clearly suggest that railway tracks will benefit considerably by having PVDs installed in the soft subgrade, by reducing the risk of undrained failure and soil slurrying under high excess pore pressures.

4 AKNOWLEDGEMENTS

The first author is grateful for the financial support from the Australian Commonwealth Government (IPRS) and the University of Wollongong (UPA). The assistance of Dr Cholachat Rujikiatkamjorn is appreciated. The support of the laboratory technical staff at University of Wollongong is acknowledged.

5 REFERENCES

Barron, R.A. (1948) Consolidation of fine-grained soils by drain wells, *Transactions of the American Society of Civil Engineers, ASCE,* 113**,** 718-742.

Hansbo, S. (1979) Consolidation of clay by band-shaped prefabricated drains, *Ground Engineering***,** 16-25.

Hansbo, S. (1981) Consolidation of fine-grained soils by prefabricated drains, Proceedings of the 10th International Conference on Soil Mechanics, Stockholm, Sweden, 677-679.

Hird, C.C., Pyrah, I.C. and Russell, D. (1992) Finite element modelling of vertical drains beneath embankments on soft ground, *Geotechnique,* 42 (3)**,** 499-511.

Indraratna, B. (1996) Large-scale triaxial facility for testing non-homogeneous materials including rockfill and railway ballast, *Australian Geomechanics,* 30**,** 125-126.

Indraratna, B., Balasubramaniam, A.S. and Ratnayake, P. (1994) Performance of embankment stabilized with vertical drains on soft clay, *Journal of Geotechnical Engineering, ASCE,* 120 (2)**,** 257-273.

Indraratna, B., Ionescu, I. and Christie, H.D. (1998) Shear behaviour of railway ballast based on large-scale triaxial tests, *Journal of Geotechnical and Geoenvironmental Engineering, ASCE,* 124 (5)**,** 439-449.

Indraratna, B., Rujikiatkamjorn, C., Sathananthan, I., Shahin, M. and Khabbaz, H. (2005) Analytical and numerical solutions for soft clay consolidation using geosynthetic vertical drains with special reference to embankments, Proceedings of the Fifth International Geotechnical Engineering Conference, Cairo University, Egypt.

Indraratna, B., Rujikiatkamjorn, C., Wijeyakulasuriya, V., Shahin, M. and Christie, D. (2006) Soft soil stabilisation with special reference to road and railway embankments, Fourth International Conference on Soft Soil Engineering (4th ICSSE), Vancouver, British Columbia, Canada, October 4 - 6, 2006 (accepted July 2006).

Larew, H.G. and Leonards, G.A. (1962) A strength criterion for repeated loads, Proceedings of the Highway Research Board, No. 41, 529-556.

Richart, F.E. (1957) A review of the theories for sand drains, *Journal of the Soil Mechanics and Foundations Division, ASCE,* 83 (SM 3)**,** 1-38.

Sangrey, D.A., Henkel, D.J. and Esrig, M.I. (1969) The effective stress response of a saturated clay soil to repeated loading, *Canadian Geotechnical Journal,* 6 (3)**,** 241-252.

Zhou, J. and Gong, X. (2001) Strain degradation of saturated clay under cyclic loading, *Canadian Geotechnical Journal,* 38**,** 208-212.