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Effectiveness of Vertical Drains in Dissipating Excess Pore Pressures Induced by Cyclic Loads in Clays

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Abstract: The purpose of this paper is to investigate the effectiveness of Prefabricated Vertical Drains (PVDs) in dissipating the excess pore water pressures induced by cyclic loading in soft clays. Cyclic triaxial testing on soft clay samples with vertical drains has been carried out using a large scale cyclic triaxial apparatus designed and built at the University of Wollongong. The samples used were 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 of the field. Stress-controlled cycles were then applied to the soil samples with different loading frequencies. The excess pore water pressures were measured by several transducers located at different positions along the radius and height of the soil specimen. The results of the excess pore water pressures and settlements are presented. The advantages of soft subsoil stabilized with PVDs under high frequency cyclic loading conditions are investigated and discussed together with the results of a numerical analysis using PLAXIS finite element code.

1 INTRODUCTION

Rail track subgrade is very important for railway stability and therefore the behaviour of soft soil subgrade under cyclic loading is of paramount significance in railway engineering. Most of Australian rail tracks travel through coastal areas comprising of soft soils and highly compressible marine deposits. These soft soils deposits in the low lying marshy areas have very low bearing capacity and excessive settlement characteristics, affecting rail tracks infrastructure in a dramatic way.

Due to rapid urbanisation in the coastal areas, the use of the poorest of soft formations has become inevitable. Load cycles from moving trains rapidly generate high excess pore pressures. In the absence of good drainage conditions, cyclic pore pressure will dramatically reduce the effective load bearing capacity of the soft formation, leading to clay pumping, ballast fouling and excessive subsidence (Attya & Indraratna, 2006).

Prefabricated vertical drains (PVDs) with preloading is one of the popular methods to stabilise soft soil deposits prior to construction (Indraratna et al., 1994), inducing most of the ultimate settlement by promoting rapid radial consolidation (Richart, 1957). This results in a gain in the shear strength of the soft formation soil.

2 LABORATORY TESTING SETUP

2.1 Equipment

Large-scale testing is necessary in order to model the PVD improved soil in the laboratory. Therefore, large-scale cylindrical triaxial equipment shown in Fig. 1 was used. This equipment was designed and built at the University of Wollongong (Indraratna, 1996; Indraratna et al., 1998). It uses a dynamic actuator of hydraulic type to apply load cycles to the sample. The schematic diagram in Fig. 2 shows the main five components of the triaxial apparatus: 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 can handle specimens of 300 mm in diameter and 600 mm in height as shown in Fig. 3(a) and Fig. 3(b). In order to measure the excess pore pressure at various locations inside the soil sample, a modification was essential to the apparatus and was accomplished by fitting miniature type pore pressure transducers through the base of the triaxial cell to the specimen with providing the proper seal to fitting holes, as illustrated in Fig. 4.

2.2 Test Specimen

Soil samples were taken from North-eastern NSW. The samples were normally consolidated with Specific Gravity of 2.65, liquid limit \( w_L = 68\% \), plastic limit \( w_P = 30\% \), plasticity index \( I_p = 38\% \), compression index \( C_c = 0.86 \) and swelling index \( C_s = 0.16 \). Reconstituted clayey soil specimens were prepared from these samples and used in this test.

The sample preparation procedure is as follows (Attya & Indraratna, 2006):

1. The clay was wet-screened through a \# 40 sieve (0.425 mm opening size) to remove larger particles and any coarse organic materials.
2. The clay was then re-mixed with water using a rotary mechanical mixer to a water content approaching the liquid limit.
3. The rubber membrane was clamped to the base of the triaxial equipment, and a geosynthetic filter layer was placed at the bottom to prevent clogging of the drainage line.
4. 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^2.
5. During the placement of the clay, four pore pressure transducers were positioned at selected locations (Fig. 3).
6. A vertical band drain was inserted into the centre of the clay specimen. A geosynthetic filter was placed at the top of the sample, after inserting the PVD and prior to placing the top loading cap, in order to protect the top drainage holes from clogging.
2.3 Test Procedure

The sample was consolidated under anisotropic conditions of \( k_r = 0.6 \) in an attempt to appropriately simulate the field conditions. At the end of the consolidation stage, a cyclic loading was applied to the soil sample. The frequency of loading was chosen to be 5 Hz simulating the loading frequency commonly encountered in rail track environments in Australia, i.e. corresponding to train speeds of 80 to 100 km/h. The consolidation stress history and cyclic stress state are shown in Fig. 5. The tests were 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 \( q_{\text{cyclic}} \) to the effective initial overburden pressure \( \sigma'_{vo} \) (i.e. CSR = \( q_{\text{cyclic}} / \sigma'_{vo} \)). It should be noted here that this is the maximum cyclic stress ratio that clay can sustain in undrained conditions before reaching failure (Larew & Leonards, 1962; Sangrey et al., 1969).

Cyclic loading was applied for thousand cycles \( (N = 1000) \) simulating an approximate train passage time of about 3 minutes. The cyclic load was then removed 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 replicating the actual field conditions encountered by a PVD installed in deep soft clay deposit. The excess pore water pressures at the locations shown in Fig. 3 were recorded during the period of cyclic loading, and the resulting vertical deformations were also monitored.

3 TEST RESULTS

The results of the excess pore water pressure development for transducers T1 and T4 are shown in Fig. 6. 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 excess pore water pressure. Also, the plastic vertical deformations are plotted against the number of load cycles (Fig. 7).

In order to illustrate the beneficial effect of the PVDs, a comparison is made with some of the published data by Zhou & Gong (2001) on undrained cyclic loading of clay. The pore pressure ratio \( u' = \Delta u / \sigma'_{vo}, \Delta u, \) excess pore water pressure, \( \sigma'_{vo}, \) effective initial overburden pressure) is introduced for this purpose. The variation of \( u' \) versus the number of loading cycles is plotted in Fig. 8. Comparison between these two sets of data indicates that the use of PVDs effectively controls the rate of excess pore water pressure buildup during cyclic loading. As shown in Fig. 8, for a cyclic stress ratio of 0.6 with absence of PVD, the failure occurred quickly only after small number of cycles.

Upon removal of cyclic loading, the top drainage allowed the dissipation of the excess pore pressures that had developed and sustained during the loading cycles. The time-dependent excess pore water pressures for the 4 transducers are shown in Fig. 9. 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.
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 may significantly reduce 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 applied by the forthcoming trains.

Fig. 4 Fitting of the miniature pore pressure transducer through the base of the equipment.

Fig. 5 Stress history and cyclic stress state.

Fig. 6 Excess pore pressure development for T1 and T4.

Fig. 7 Plastic deformations versus number of load cycles.

Fig. 8 Cyclic excess pore pressures response of soft clay with and without PVD.

Fig. 9 Dissipation of excess pore water pressure after removal of cyclic loading.
To investigate the soil behavior improved by PVDs under rail tracks, a plane strain finite element analysis was conducted using the finite element code, PLAXIS V 8.3 (2006). Fig. 10 shows a typical cross-section of the formation beneath the rail track, where a stiff crust is underlain by soft formations. Triangular elements with 6 displacement nodes and 3 pore pressure nodes were considered. The Mohr-Coulomb (M-C) model was used for the stiff crust and ballast bed, whereas Soft Soil Model was used for the soft clay layer. A static load of 60kPa with an impact factor of 1.3 was applied to represent the dynamic forces. Table 1 summarizes the material properties used in the analysis.

Fig. 11 shows the excess pore pressures developed due to the train load. It shows that the applied load usually propagates within the first several meters (6-8m) of the formation, assuming sufficient ballast and subballast depths are provided. In this regard, relatively short PVDs without prolonged preloading may still be adequate in design. Based on equivalent plane strain analysis for multi-drain (Indraratna & Redana, 2000), Short PVDs (5-8m) with a spacing of 1.5 and 2m were simulated. Apart from accelerating excess pore pressure dissipation (Fig. 12), application of PVDs can curtail the lateral movement (Fig. 13), and most of the volumetric strains constitute the vertical strains.

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 pressure 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 significantly less when PVDs were present. 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 in detail 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. It was also shown that short prefabricated vertical drains (PVDs) may be used under rail tracks to dissipate cyclic excess pore pressure and to curtail lateral displacements to improve stability, if preloading is not used. However, where preloading can be applied, deeper soft formations can be stabilised using longer vertical drains, for more resilient soft soil foundations.

REFERENCES


