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A partially drained model for soft soils under cyclic loading considering cyclic parameter degradation

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Abstract

Cyclic loading induced foundation instabilities including loss of bearing capacity and excessive plastic deformation of the subgrade are among the major concerns for the design and construction of transport infrastructure. There were limited studies on the modelling of cyclic loading of soft soils due to its complexities compared to static loading. In this study, a model for soft clays under partially drained condition subject to cyclic triaxial loading has been developed based on the Modified Cam-clay theory. The yield surface contraction for elastic unloading was governed by two additional cyclic degradation parameters to the modified Cam-clay model. This model was validated using the results of a series of undrained and partially drained cyclic triaxial loading tests on kaolin. A good agreement between the numerical prediction and the measured excess pore pressures was obtained. Furthermore, the factors which influence the cyclic performance of soft soils, e.g. the cyclic stress ratios, the anisotropic consolidation stress and the coefficient of consolidation were investigated. This model was then applied to the consolidation of soft soils under cyclic loading, which represents the application of partially penetrated vertical drains for road and rail infrastructure, at the soft soil sites for a rail project in Sandgate, NSW. The objective of the partially penetrated drains within this deep estuarine soil layer was to consolidate the shallow soft clays and stabilise the new built tracks.

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A partially drained model for soft soils under cyclic loading considering cyclic parameter degradation

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ABSTRACT

Cyclic loading induced foundation instabilities including loss of bearing capacity and excessive plastic deformation of the subgrade are among the major concerns for the design and construction of transport infrastructure. There were limited studies on the modelling of cyclic loading of soft soils due to its complexities compared to static loading. In this study, a model for soft clays under partially drained condition subject to cyclic triaxial loading has been developed based on the Modified Cam-clay theory. The yield surface contraction for elastic unloading was governed by two additional cyclic degradation parameters to the modified Cam-clay model. This model was validated using the results of a series of undrained and partially drained cyclic triaxial loading tests on kaolin. A good agreement between the numerical prediction and the measured excess pore pressures was obtained. Furthermore, the factors which influence the cyclic performance of soft soils, e.g. the cyclic stress ratios, the anisotropic consolidation stress, and coefficient of consolidation were investigated. This model was then applied to the consolidation of soft soils under cyclic loading, which represents the application of partially penetrated vertical drains for road and rail infrastructure, at the soft soil sites for a rail project in Sandgate, NSW. The objective of the partially penetrated drains within this deep estuarine soil layer was to consolidate the shallow soft clays and stabilise the new built tracks.

Keywords: cyclic loading, soft clays, cyclic degradation, cyclic stress ratio, consolidation, vertical drains

1 INTRODUCTION

Under cyclic loading, the excess pore pressures and shear strains of soft soils may keep increasing as the number of cycles increases. The instability of the soft ground caused by loss of effective stress and excessive lateral deformation is one of the major concerns for transport infrastructure, including railway tracks, under significant cyclic loadings. Experimental studies in the past few decades have investigated the factors which influence the cyclic performance of soft soils, such as the cyclic stress intensity, load frequency, consolidation pressure, and partially drainage (Larew and Leonards 1962; Takahashi et al. 1980; Sangrey et al. 1969; Seed and Chan 1966; Hyodo, et al. 1992; and Sakai, et al. 2003). A number of cyclic models have been developed based on laboratory test data (e.g. Procter and Khaffaf 1984; Ansal and Erken 1989; Hyodo, et al. 1992; and Sakai, et al.), but those test oriented model were mostly based on empirical assumptions and adopted empirical parameters. Carter et al. (1980, 1982)'s model, based on the Modified Cam-clay theory (Roscoe and Burland 1968), interpreted the excess pore pressure generation as a consequence of yield surface contraction, which was described by only one additional cyclic parameter, that could be readily determined by cyclic triaxial loading tests. Ni et al. (2014) extended this parameter from a constant into a variable decreasing with the number of cycles. According to this modified model, the generation rate of excess pore pressure gradually goes down as the number of cycles increases, which is consistent to some of the previously reported tests (Takahashi et al. 1980; Miller et al. 2000; Zhou and Gong 2001; and Sakai et al. 2003).

Use of prefabricated vertical drains in soft ground can effectively dissipate the excess pore pressure, thus consolidate the soft soils (e.g. Indraratna, et al, 2011, 2012; and Rujikiatkamjorn and Indraratna, 2007). If the ballast layer on top of the soft soil layer cannot provide sufficient drainage to dissipate the excessive excess pore pressure developed by cyclic loading, vertical drains can also be installed into the soft soils to accelerate the consolidation and control the lateral strain. The unit-cell model of vertical drains is here combined with the cyclic model of Ni et al. (2014) for soft soils. Finally, this model was applied to the consolidation of soft soils under cyclic loading at a railway site in Sandgate, NSW, Australia.

2 MODEL FOR CYCLIC BEHAVIOUR OF SOFT SOILS

2.1 Development of excess pore pressure by cyclic loading

Under repeated unloading-reloading process, the excess pore pressures and shear strains of saturated soft clays often keep increasing as the number of cyclic increases. This phenomenon cannot be explained by the Modified Cam-clay model, but could be interpreted as the change of the yield surface by unloading process. Assuming that the shape of the yield surface does not change, a cyclic parameter θ was introduced to describe the contraction of the yield surface when the soil is elastically unloaded (Carter et al. 1980, 1982):

$$\frac{\mathrm{d}p_\mathrm{c}^{'}}{p_\mathrm{c}^{'}} = \theta \frac{\mathrm{d}p_\mathrm{y}^{'}}{p_\mathrm{y}^{'}} \tag{1}$$

where, the hardening parameter $p_\mathrm{c}^{'}$ is the value of p' at the intersection between the initial yield surface and the p' axis, while $p_\mathrm{y}^{'}$ is a variable defined as (Roscoe and Burland 1968):

$$p_\mathrm{y}^{'} = p^{'} + \left(\frac{q}{M}\right)^2 \frac{1}{p^{'}} \tag{2}$$

In the above, M is the slope of the critical state line in $p' - q$ space, where p' and q are the effective mean stress and deviator stress.

Ni et al. (2014) extended the constant parameter θ into a parameter θ^* that degrades with the increasing number of cycles, N, i.e.

$$\theta^* = \frac{1}{\xi_1 N + \xi_2} \tag{3}$$

where, ξ_1 and ξ_2 are constants which can be determined experimentally.

2.2 Dissipation of excess pore pressure via vertical drains

With application of partially penetrated vertical drains, the dissipation of excess pore pressure via radial drainages are given as,

$$c_h \left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} \right) = \frac{\partial \left(u + u_p \right)}{\partial t} \tag{4}$$

where c_h is the coefficient of consolidation, u_p is the excess pore pressure induced by cyclic loading, r and t are the radius and consolidation time respectively.

The stress path for normally consolidated soils under cyclic loading with drainage is shown in Fig. 1 (after Ni et al. 2013). In the first loading period, when the stress path moves from point A' to point A, the excess pore pressure increases while the effective mean stress decreases. During the unloading period, the stress path travels from point A to A^*, and the effective mean stress remains constant. In the first stage of the second cycle, the stress path travels from point A^* to point B' and the soil behaves elastically. Afterwards, in the second stage, the stress path moves from point B' to B, and the effective mean stress decreases, while the soil behaves plastically.

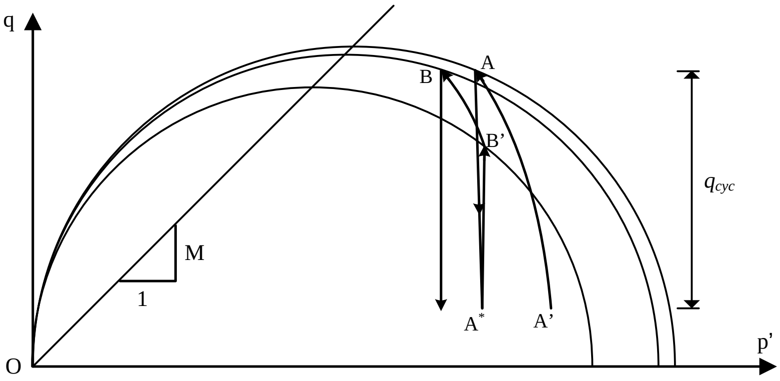

Figure 1. The stress path of soft soil under cyclic loading (after Ni, et al., 2013)

3 COMPARISON WITH TEST RESULTS

Undrained and partially drained cyclic triaxial tests were carried out on the specimens of reconstituted and saturated kaolin-water mixtures with cyclic triaxial facilities. The undrained tests were conducted on specimens with the dimension of 38 mm in diameter and 76 mm in height. The partially drained tests were carried out with large-scale triaxial facility at University of Wollongong, with a height of 600 mm and diameter of 300 mm for specimens. A PVD with cross section of 22mm ×4 mm was installed at the centre of the specimen. The excess pore pressure was measured at the radius of 130 mm. The cyclic stress ratio was defined as the ratio of cyclic stress to the maximum static deviator stress at failure ($\mathrm{CSR} = q_{\mathrm{cyc}} / s_{\mathrm{u0}}$). The latter was obtained through the conventional monotonic triaxial tests. Table 1 provides the parameters of soils properties and initial states. The cyclic loading parameters are: ξ_1 = 2.8, 2.7, 2.7, and 2.8 and ξ_2 = 50, 280, 400, and 550, for frequency *f* = 0.1Hz, 1Hz, 2Hz and 5Hz, respectively, which indicates that ξ_2 increases with an increasing loading frequency.

Table 1: Parameters for soil properties and initial states (Ni et al., 2014, with permission from ASCE)

Soil properties			Initial states		
λ	κ	M	p_0' (kPa)	q_0 (kPa)	e_0
0.18	0.03	1.68	30	16	1.32

The variation of normalized excess pore water pressure, for both undrained and partially drained tests, is given in Fig. 2. A good agreement can be observed between the predicted results and the experimental data. Under partially drained condition, the excess pore pressure was effectively reduced compared to the undrained condition. When $\mathrm{CSR}=0.8$, the failure of specimen is observed at *N* ≈ 1800 for undrained condition, and at *N* ≈ 3000 for partially drained condition. This indicates that the drainages provided by the prefabricated vertical drains can effectively reduce the risk of soft soil instability subject to cyclic loading.

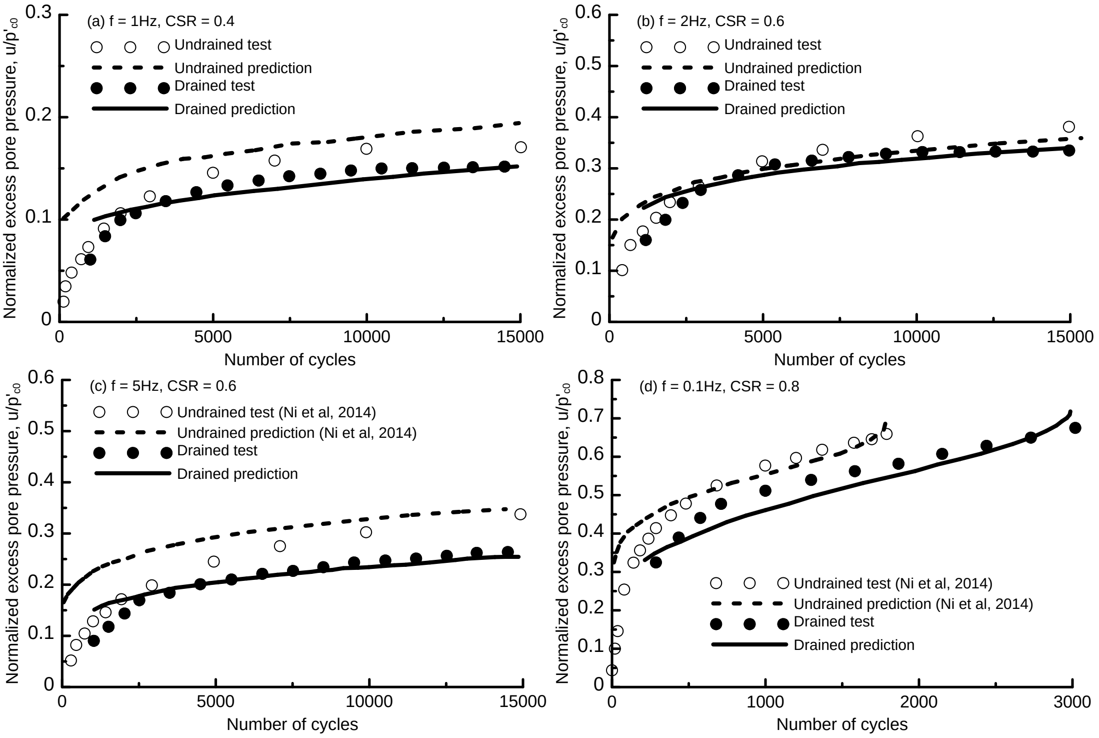

Figure 2. Predictions of excess pore pressures under undrained and partially drained conditions: (a) f=1Hz, CSR=0.4 *(b)* f=2Hz, CSR =0.6 *(c)* f=5Hz, CSR =0.6 *(d)* f=0.1Hz, CSR =0.8

4 PARAMETRIC STUDY

The key parameters on the development of excess pore pressure were investigated with a parametric study by Ni et al. (2014). The coefficient of consolidation is studied to investigate its effect on the excess pore pressure dissipation under partially drained condition. The basic soil properties are given in Table 2.

Table 2: Parameters for parametric analysis (Ni et al., 2014, with permission from ASCE)

λ	κ	M	$p_0^{'}$ (kPa)	q_0 (kPa)	e_0	G
0.25	0.05	1.2	30	0	0.6	$200s_{u0}$

Note: $s_{u0} = p_{c0}^{'}\left(M/4\right)\left(2p_0^{'}/p_{c0}^{'}\right)^{\kappa/\lambda}$

4.1 Effect of CSR

The normalised excess pore pressures at various CSRs are given in Fig. 3. The results indicate that a critical state exists in an intermediate value of cyclic stress ratio (around 0.5 for this case). For a larger CSR, the excess pore pressure increases so fast and the stress state of the soft soils quickly reach the critical state line after the first few cycles. When CSR is smaller than the critical cyclic stress ratio, the rates of excess pore pressure generation gradually decrease and the specimens can reach a stable state with no significant increase of excess pore pressure afterwards. This analysis revealed that the CSR plays an dominant role which determine the failure condition of the soft soils under cyclic loading.

4.2 Effect of Anisotropic Consolidation Stress Ratio

The results under various initial anisotropic consolidation stress ratios ($k_0 = \sigma_{3c}^{\prime} / \sigma_{1c}^{\prime}$) are given in Fig. 4. The soft soil behaves stably under cyclic loading at relatively large values of k_0 (0.8, 0.9, and 1.0). When k_0 drops to 0.7, a significant increase of excess pore pressure can be observed, and the critical state is reached at around 400 cycles. With a smaller anisotropic consolidation stress ratio (k_0=0.6), the soil quickly goes to failure at around 100 cycles, because of the rapid build-up of excess pore pressure. This analysis indicated that the lateral confining pressure, which is determined by multiplying the vertical effective stress and the anisotropic consolidation stress ratio, is also a key factor that governs the failure of the soft soil under cyclic loading. Quick failure may be caused under even low cyclic loading if the field condition gives a small anisotropic consolidation stress ratio.

4.3 Effect of Coefficient of Consolidation

The results under partially drained condition are calculated with coefficient of consolidation c_h = 50 m^2/yr, and 100 m^2/yr, respectively. The equivalent radii of vertical drain and the undisturbed zone are r_w = 0.01 m and r_e = 0.15 m, respectively. The cyclic frequency is 0.1 Hz. The results are compared with the undrained results, as shown in Fig. 5. It is observed that the effect of radial drainage in dissipating the excess pore pressure is significant at the critical cyclic stress ratio (i.e. CSR = 0.5 for this case). When c_h = 50 m^2/yr, the increasing ratio of the excess pore pressure is much reduced after 200 cycles, although it continues build up slightly afterwards. When c_h = 100 m^2/yr, a more significant reduction of excess pore pressure is observed, and the excess pore pressure turns to drop down after 400 cycles. When CSR is smaller than the critical cyclic stress ratio (i.e. CSR = 0.3), the difference between undrained and partially drained results is very small, because the excess pore pressure generated by cyclic loading is insignificant thus no much dissipation is obtained. When CSR is larger (CSR = 0.7), the curves with undrained and partially conditions almost overlap, because the excess pore pressure sharply increases and causes soil failure, hence the dissipation does not have enough time to take place.

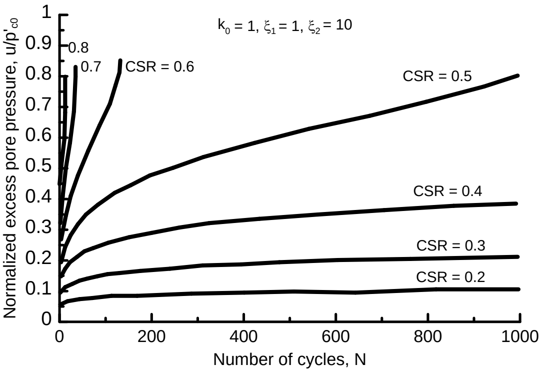

Figure 3. Excess pore pressure with different CSRs ($k_0 = 1,\ \xi_1 = 1,\ \xi_2 = 10$ *) (Ni et al., 2014, with permission from ASCE)*

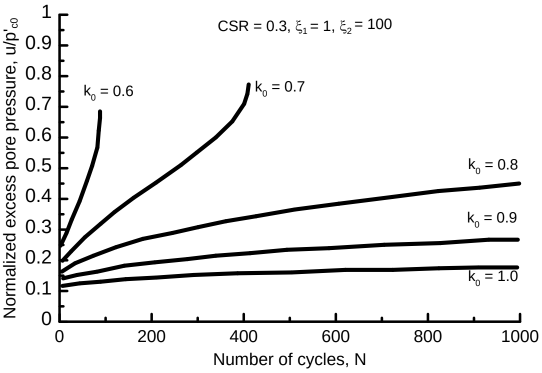

Figure 4. Excess pore pressure with different anisotropic consolidation stress ratios (CSR=0.3, ξ_1=1, ξ_2=100*) (Ni et al., 2014, with permission from ASCE)*

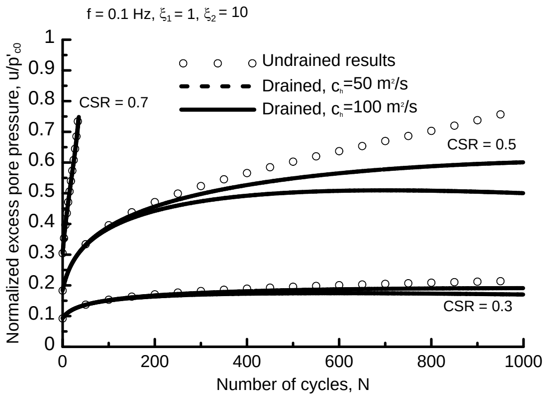

Figure 5. Excess pore pressure with different coefficient of consolidation.

5 APPLICATION TO A CASE STUDY

5.1 Sandgate Rail Grade Separation Project

As the Kooragang Island became a major export terminal and a large number of coal trains have to cross the main lines at Sandgate to enter Kooragang Island, two new lines were demanded to be built near the existing track in the lower Hunter Valley of New South Wales, Australia. Because of the stringent time, only the initial train load was considered as the external surcharge to consolidate the subgrade after the construction of the tracks. The Australian standard gauge was adopted with longitudinal distance between adjacent wheels 2.02 m and the width between the rails 2.55 m. The frequency of 5 Hz can typically simulate the frequency of cyclic load in the subgrade at a train speed of less than 40 km/h. The maximum intensity of the cyclic load conforms to axle load of 25 tonne.

The application of short PVDs was chosen to enhance the dissipation of excess pore pressure, as well as to control the excessive lateral displacement, in order to ensure the stability of the newly constructed rail track. The typical PVD with cross section of 100 mm × 4 mm was utilized. The length of the PVDs was determined to be only 8 m because it is deemed that the dynamic stress was generally restricted within a shallow depth in subgrade. The spacing of PVD was chosen as 2 m in a square pattern. This model is utilized to predict the settlement and compare with the observed field data of this project.

5.2 Soil parameters

The soil profile comprises layers of ballasts, fill materials, and soft subgrades. Each layer can be divided into several sub-layers with smaller thickness. The properties of the soft soils were determined by oedometer tests, field vane shear tests, and CPTU tests, and the results are shown in Figure 6.

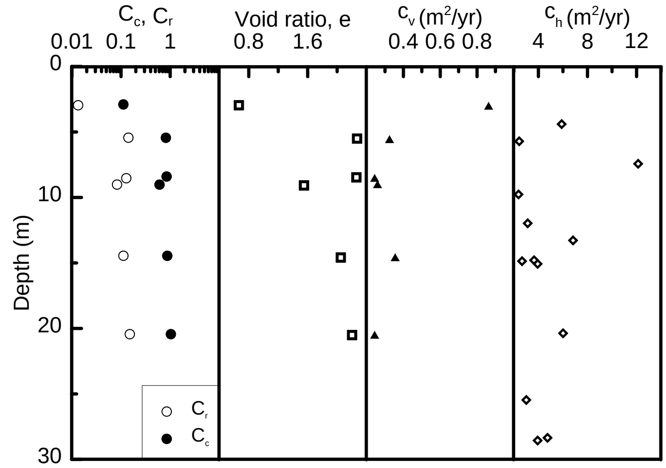

Figure 6. Properties of subgrade at Sandgate Rail Grade Separation (Indraratna et al., 2010, with permission from ASCE)

5.3 Comparison of observed and predicted settlement and lateral displacement

The predicted settlement at the centre line of the rail tracks is compared with the field data, as shown in Fig. 7. A good agreement can be observed between the prediction and the measured data. The increasing rate of the settlement gradually drops down, and a large part of settlement was achieved within the first half year. The lateral displacement at 180 days at the toe of the rail embankment is given in Fig. 8. As expected, the lateral displacement decreases significantly as the depth increases, and the major part of lateral deformation was restricted to the shallow depth. The prediction of lateral displacement is found to agree also well with the field data.

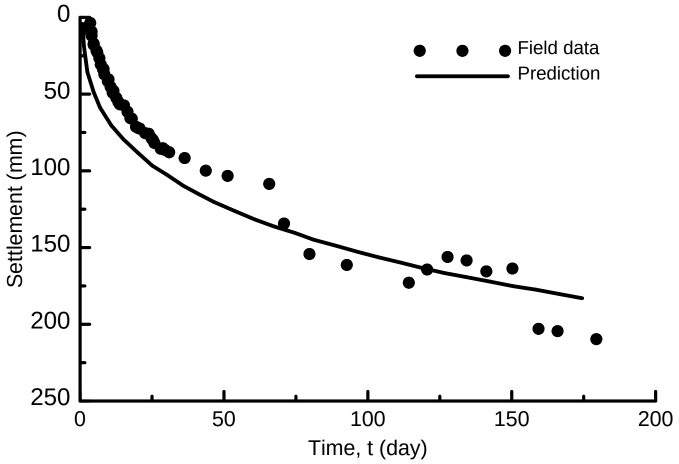

Figure 7. Predicted settlement at the centre line of rail tracks between and field data

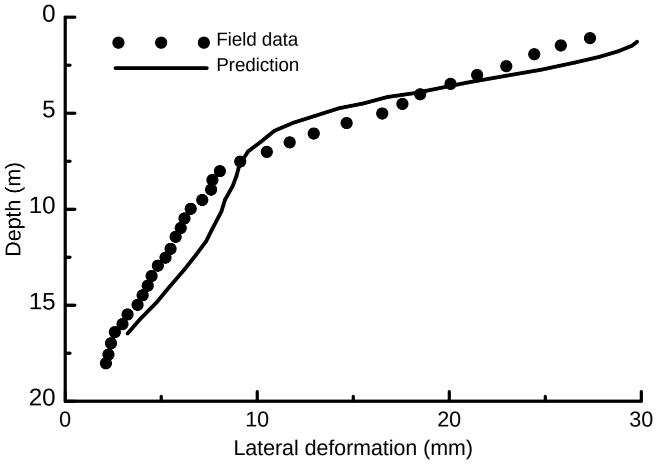

Figure 8. Predicted lateral displacement near the rail embankment toe at 180 days and field data

6 CONCLUSIONS

A cyclic model to simulate the behaviour of soft soils under repeated loading was proposed incorporating radial drainage facilitated by PVDs. The model of yield surface contraction, with two additional cyclic degradation parameters (ξ_1 and ξ_2) added to the modified Cam-clay model, was adopted to realise the development of excess pore pressure under cyclic loading. The comparison between undrained results and the results with partially drained condition indicated that the drainage can reduce the risk of instability due to excessive excess pore pressure. The parametric study showed that both CSR and anisotropic consolidation stress ratio have strong impacts on the development of excess pore pressures. A stable state may be reached with relatively small value of CSR and large value of the anisotropic consolidation stress ratio. The radial drainages can effectively control the development of excess pore pressure. The application of this theory to the consolidation of soft soils under cyclic loading at a rail project in Sandgate, NSW, Australia indicated that the predictions of the proposed model agreed well with the field data.

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