A Model for Vacuum-assisted Soft Soil Consolidation with PVDs

Un modèle pour la consolidation de sols souples sous vide avec des PVD

Rui Zhong, Buddhima Indraratna, Cholachat Rujikiatkamjorn, Mojtaba Kan
Centre for Geomechanics and Railway Engineering, Department of Civil, Mining and Environmental Engineering, University of Wollongong, Wollongong City, NSW 2522, Australia, indra@uow.edu.au

Philippe Vincent
Menard Oceania Pty Ltd, Australia

Greg Ryan
SoilWicks Australia

ABSTRACT: To maintain the ground stability and reduce the post-construction settlement, the soft deposits characterised by high water content, high compressibility and low permeability need to be treated by an appropriate ground improvement method prior to the construction of infrastructure. Application of PVD is a well-practiced ground improvement method for consolidating the soft clays. PVD can be used in conjunction with a fill surcharge, vacuum pressure or a combination of the two. An analytical unit cell model was proposed to capture the large strain geometry and the non-linear soil properties during the large settlement. This model showed an advantage over the traditional model in predicting the soft ground consolidation behaviour. In this paper, this model is used to analyse some case histories.

RÉSUMÉ : Pour maintenir la stabilité du sol et réduire l'implantation après la construction, les dépôts doux caractérisés par une teneur en eau élevée, une grande compressibilité et une faible perméabilité doivent être traités par une méthode appropriée d'amélioration du sol avant la construction de l'infrastructure. PVD est une méthode d'amélioration du sol bien pratiquée pour la consolidation des argiles molles. PVD peut être utilisé en conjonction avec une surtaxe de remplissage, la pression de vide ou une combinaison des deux. Un modèle de cellule unitaire analytique a été proposé pour capturer la grande géométrie de la déformation et les propriétés non linéaires du sol pendant la grande colonisation. Ce modèle a montré un avantage par rapport au modèle traditionnel dans la prédiction du comportement de consolidation du sol mou. Dans ce document, ce modèle est utilisé pour analyser certains cas.

KEYWORDS: PVD, vacuum preloading, unit cell model, large strain

1 INTRODUCTION

The rapid growth of the world's economy and population has resulted in an increased use of lands with highly compressible alluvial and marine deposits along many coastal areas. To mitigate the ground instability and reduce the long term deformation, the soft estuarine deposits require an appropriate ground improvement prior to the infrastructure construction. Many types of vertical drains, including the sand drains, stone columns, sand compaction piles and prefabricated vertical drains (PVDs), have been used to accelerate the dissipation of excess pore pressure under fill surcharge. Among these ground treatment facilitators, PVD is considered to be the most cost effective one. Combined with surcharge and vacuum preloading, PVDs can be used to stabilise the ground by increasing the shear strength and reducing the post-construction differential settlement (Bergado et al. 2002, Chai et al. 2010, Geng, etal. 2012, Mesri and Khan, 2012, Yan and Chu, 2005, Indraratna et al. 2005abc).

The principle of vacuum consolidation is shown in Fig. 1 (Indraratna et al. 2005c). There are a number of key factors such as smear effect, vacuum distribution, and time-dependent loading pattern which need to be included in the analytical model of PVD-stabilised soft ground (Hansbo 1997, Long et al. 2013, Walker et al. 2007, 2012, Rujikiatkamjorn et al. 2013). It is noted that the conventional models are mostly based on a constant coefficient of consolidation, which implies linear soil properties, Darcian flow, and small strain assumption. However, it may lose validity when a very large settlement occurs. Thereafter, an analytical model is proposed with capturing non-linear soil permeability and compressibility, non-Darcian flow properties, and large strain geometry. The model shows an advantage over the traditional model in predicting the soft ground consolidation behaviour. The incorporation of soil disturbance captures the disturbance on both permeability and compressibility due to mandrel driving, resulting in a better agreement with the field data, and showing the influences of soil structure characteristics on consolidation responses. The proposed model for large strain analysis is applied to the simulation of field cases.

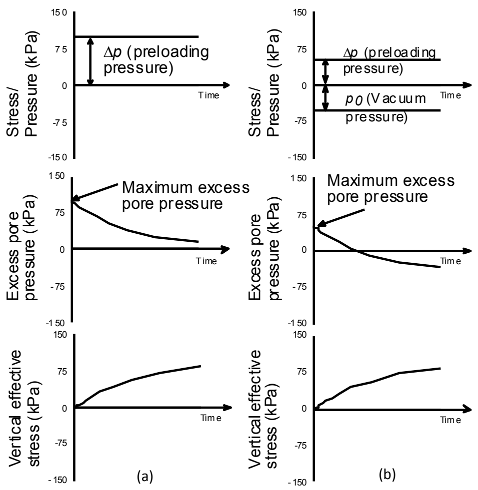

Figure 1. Principle of surcharge and vacuum preloadings (Indraratna et al. 2005c).

2 ANALYTICAL MODELLING

2.1 *Governing Equation*

A number of authors have contributed to the large strain analysis in vertical and radial consolidation (Gibson et al. 1967, 1981, Hu et al. 2014, Indraratna et al. 2016). Indraratna et al. (2016) proposed a unit-cell radial consolidation model that captured the nonlinear soil permeability and compressibility, non-Darcian flow, and large strain effect. The consolidation of a soil element via radial and vertical drainage paths is governed by

$$\frac{1}{1+e}\cdot\frac{\partial e}{\partial t}+v_r(r)\cdot\frac{2r}{r_e^2-r^2}=0 \tag{1}$$

where e is the void ratio, r is the radius and r_e is the radius of the influential area of the drain, and v_r is the flow velocity towards the drain.

Although Darcy's Law is considered valid for most cases, the non-Darcian flow may occur in cases of low-porosity soils or low hydraulic gradient (Kianfar et al., 2013). A practical method for considering the non-Darcian flow is to adopt an exponential relationship between the seepage velocity and the hydraulic gradient (Hansbo 1997),

$$v_r = ki^\beta = k\left(\frac{1}{\gamma_w}\cdot\frac{\partial u}{\partial r}\right)^\beta \tag{2}$$

where k is the initial coefficient of permeability ($k = k_s$ and k_h inside and outside smear zone, respectively), i is the hydraulic gradient in radial direction, β is the non-Darcian flow exponent, u is the excess pore pressure and γ_w is the unit weight of water.

The soil permeability decreases with the reduction of void ratio, which can be governed by:

$$e = e_0 + C_k \log\left(k/k_0\right) \tag{3}$$

where C_k is the permeability change index, e_0 is a reference void ratio and k_0 is the coefficient of permeability corresponding to e_0. When data for above equation is not available, an alternative is to adopt the Carman-Kozeny equation (Carman, 1956):

$$k = k_0\frac{e^3(1+e_0)}{e_0^3(1+e)} \tag{4}$$

By combining all equations above, the large-strain governing equation that captures the nonlinear soil properties and non-Darcian flow is derived as

$$\frac{1}{1+e_0}\cdot\frac{\partial e}{\partial t}+k_0(r)\exp\left[\frac{(e-e_0)\ln 10}{C_k}\right]\left[\frac{1}{\gamma_w}\cdot\frac{\partial u(r)}{\partial r}\right]^n\frac{2r}{r_e^2-r^2}=0 \tag{5}$$

2.2 *Soil structure characteristics*

For reconstituted soils, the change of void ratio has a logarithmic linear relationship with the change of effective stress, i.e.

$$e = e_0 - C_c\log\left(\frac{\sigma'_v}{\sigma'_{v0}}\right) \tag{6}$$

where σ'_v is the average effective stress within the influential area; C_c is the compression index, and σ'_{v0} is the effective stress corresponding to the reference void ratio e_0.

Although nonlinear relationship between σ'_{v0} and e given in Eq. (6) is more realistic than the linear relationship adopted in conventional models, it is only valid for reconstituted soils. The field behaviour of soft clays is different from laboratory test due to the soil structural characteristics. Rujikiatkamjorn and Indraratna (2014) developed a model for radial consolidation that considered the characteristics of soil structure. The conceptual model for soils disturbed by mandrel-driving (Rujikiatkamjorn et al. 2013) was for partially disturbed soil

when $\sigma'_v \geq \sigma'_{yiD}$

$$e = e_{ic} + \left(e_{iD} - e_{ic} + C_c\log\sigma'_{yiD}\right)\left(\frac{\sigma'_{yiD}}{\sigma'_v}\right)^b - C_c\log\sigma'_v \tag{7}$$

when $\sigma'_v < \sigma'_{yiD}$

$$e = e_{iD} - C_r\log\left(\frac{\sigma'_y}{\sigma'_{yiD}}\right) \tag{8}$$

where e_{ic} is the void ratio of reconstituted soil under a vertical effective stress of 1 kPa, C_s is the swelling index, σ'_{yiD} is the initial yield stress of the soil, and e_{iD} is the corresponding void ratio.

Rujikiatkamjorn et al. (2014) validated and compared this model with a previous solution that did not consider the disturbance of the soil structure, using the field data from the Ballina bypass project. The measured settlement is given in Fig. 2 and compared with the analytical solutions of Walker and Indraratna (2007) and Rujikiatkamjorn and Indraratna (2014). Walker and Indraratna (2007) captured the variation of permeability in the smear zone, while Rujikiatkamjorn and Indraratna (2014) considered the effects of soil disturbance on both permeability and compressibility in the smear zone. Their results indicated that the method capturing the effect of soil disturbance on compressibility can provide a better agreement with the field data, which shows the importance of in-situ soil structure characteristics.

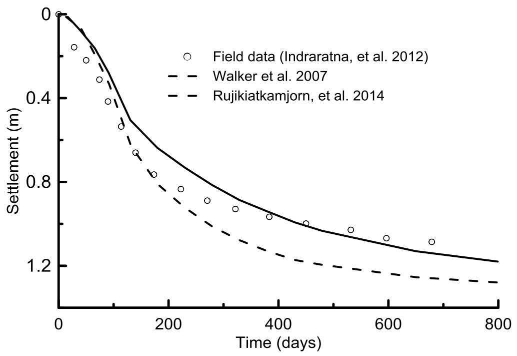

Figure 2. Predicted and measured settlement at SP1 of Ballia bypass (after Rujikiatkamjorn, et al. 2014).

3 CASE HISTORIES

3.1 *Tianjin Port*

To facilitate the expansion of Tianjin Port in Tianjin, China, a new pier was constructed on a reclaimed land for construction of a storage facility. The reclaimed soil layer has a thickness of about 5 m, below which are a 5 m-thick soft soil layer of muddy clays and a 6 m-thick soft silty clay layer, and a stiff silty clay layer. Vacuum preloading was applied to accelerate the consolidation with PVDs and surcharge loading. The load history, the settlement and excess pore pressure are plotted in Figure 3, which compares the results of the prediction against the field data published by Rujikiatkamjorn et al. (2008). A good agreement between the prediction and measurement is observed for both the settlement and excess pore pressure. The prediction indicates a significant rebounding of excess pore pressure at around 70 days and 130 days when the fill surcharge increases, but the field measurement does not show such behaviour. The comparison also shows that the results of large-strain and small-strain methods look very similar, indicating that the strain occurred in this case was not very large and the traditional small-strain based methods were good enough to predict this case.

Table 1: Basic soil properties at Tianjin Port

Depth (m)	C_c	C_r	γ (kN/m^3)	e_0	k_{h0} (10^{-10} m/s)
0.0-3.5	0.276	0.069	18.3	1.1	20
3.5-8.5	0.322	0.069	18.8	1.0	40
8.5-16.0	0.461	0.092	17.5	1.35	20
16.0-20.0	0.230	0.046	18.5	0.9	5

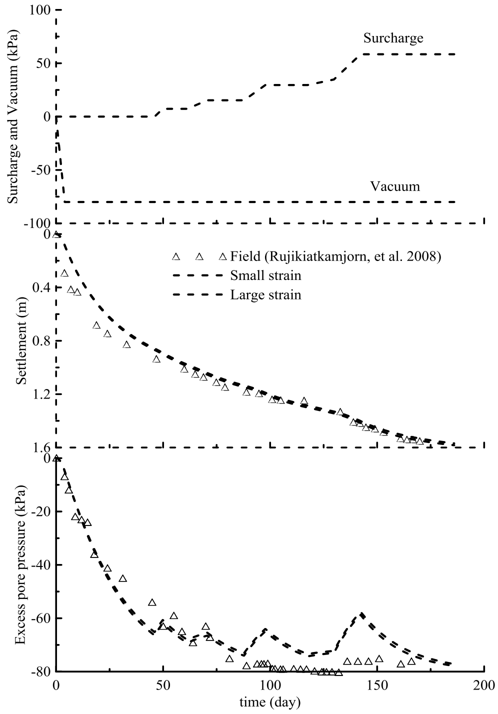

Figure 3. Load history, settlement and excess pore pressure at the project at Tianjin Port

3 .2 *Second Bangkok International Airport*

The Second Bangkok International Airport (SBIA) is about 30 km to the east of Bangkok, Thailand. The soft soil layer is covered by a relatively uniform and weathered crust with an average thickness of 1.5 m. Beneath the soft soil layer, a stiff clay layer situates within the depth of about 20-24 m. The soil generally has very high water content due to frequent flooding during the wet seasons. The basic properties of the soft clays are given in Fig. 4.

Several trial embankments have been constructed at this site to investigate the effectiveness of the PVD-assisted consolidation, including TV1 and TV2, where the vacuum was applied together with the surcharge preloading. The drains were installed at a spacing of 1 m in a triangular pattern. PVDs with 15 m length were installed with a hypernet drainage system in the TV1 area. PVDs with 12 m length were wrapped together with perforated and corrugated pipes in non-woven geotextile and installed in the TV2 area. Drainage blankets with a thickness of 0.3 m and 0.8 m (working platform) were built with sands for the TV1 and TV2 areas, respectively. A membrane system (Linear Low Density Polyethylene) has been used to maintain the airtight and watertight requirements. The membrane was sealed by a perimeter trench filled with bentonite at the edges.

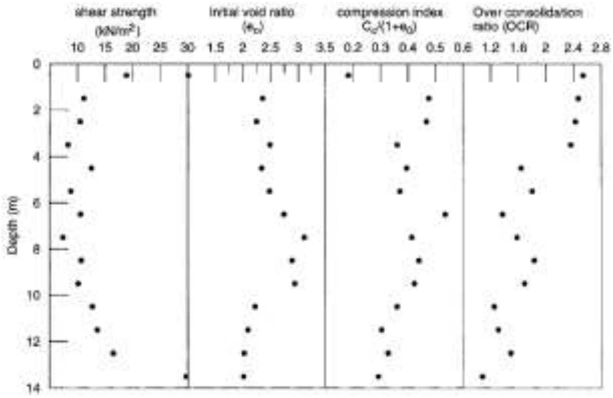

Figure 4. Basic properties of soft clayey deposits at SBIA (Indraratna et al. 2005c).

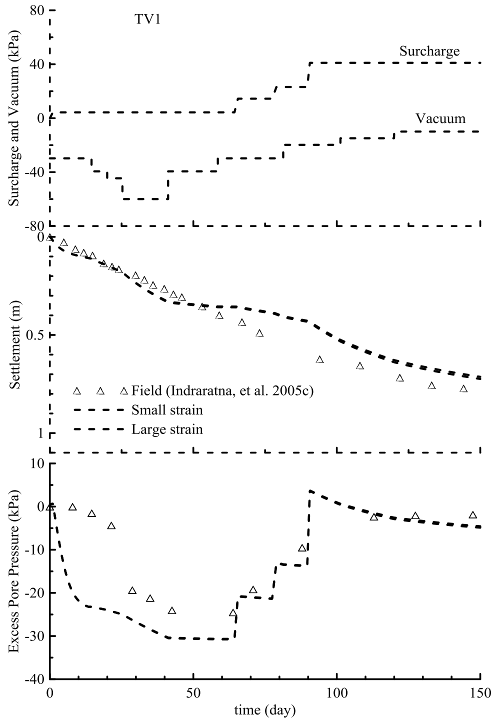

Figure 5. Prediction and field measurement of settlement and excess pore pressure (3 m depth) at TV1 of SBIA.

Indraratna et al. (2004, 2005b, 2005c) carried out plain strain numerical simulations to predict the settlement and excess pore pressure at TV1 and TV2. Here, the unit cell approach given in Eq. (5) is used to calculate the settlement and excess pore pressure with large strain and small strain geometries. The results from the field measurements and unit cell prediction are compared in Figs. 5 and 6 for TV1 and TV2, respectively. A good agreement between the prediction and field measurements are observed. The large strain simulation appears to be close to the small strain results for TV1, indicating that a small strain assumption is acceptable for this case. This might be because the total vertical strain is not substantial so the influence of the large-strain characteristic is relatively minor. However, the difference between large strain and small strain results for TV2 (Fig. 6) is more significant than that of TV1, because the settlement of TV2 was much larger. The excess pore pressures at both locations were negative for a long period of time due to the vacuum pressure application. The agreement between the prediction and the measurement were acceptable.

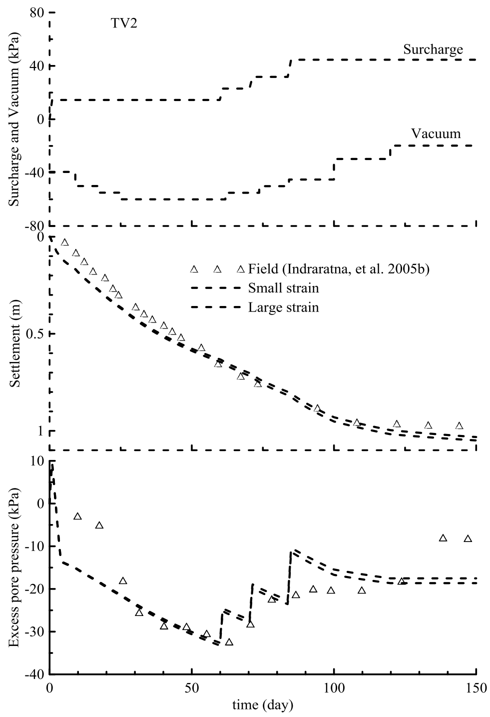

Figure 6 Prediction and field measurement of settlement and excess pore pressure (3 m depth) at TV2 of SBIA.

4 CONCLUSIONS

PVDs combined with a fill surcharge or vacuum preloading have been used to stabilise soft ground by increasing the shear strength and reducing post-construction settlement. The application of vacuum can not only expedite the consolidation rate but also increase the factor of safety for the ground stability. Membrane and membraneless systems can be used to ensure the effectiveness of vacuum pressure. A unit cell model is a simplified model that analyses the behaviour of PVD-assisted consolidation, and it normally addresses the factors such as the smear effect, vacuum magnitude, and coefficient of consolidation. For most cases, traditional unit cell model based on constant coefficient of consolidation is practical enough to predict the settlement and excess pore pressure. However, for very large deformation, a model that captures the nonlinear compressibility and permeability, non-Darcian flow, and large-strain geometry becomes necessary. Soil disturbance due to mandrel driving also has a significant influence on the consolidation performance. This paper introduced a unit cell approach based on large-strain assumption, and was applied to analyse two case histories at Tianjin Port in China, and the Second Bangkok International Airport in Thailand.

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