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## An analytical model of PVD-assisted soft ground consolidation

### Abstract

Prefabricated vertical drains (PVDs) are widely used to accelerate the dissipation of excess pore pressure in soft estuarine deposits in coastal areas under fill surcharge or vacuum preloading. Vacuum preloading can also control any lateral outward movement of the embankment toe, although excessive inward movement must be avoided. An equivalent 2D numerical modelling is proposed as a predictive tool for multi-drain conditions, but unlike a 3D simulation it has a greatly reduced computation burden. A unit cell model incorporating key factors such as the smear effect, vacuum distribution, nonlinear compressibility and permeability, soil disturbance and large-strain geometry, has also been developed. This paper presents selected work at the University of Wollongong on analytical solution for PVD-assisted ground improvement. The model is applied to a case history at Tianjin Port in China and then compared with the numerical result and field measurements.

### Keywords

assisted, soft, ground, consolidation, analytical, model, pvd

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# An Analytical Model of PVD-assisted Soft Ground Consolidation

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## Abstract

Prefabricated vertical drains (PVDs) are widely used to accelerate the dissipation of excess pore pressure in soft estuarine deposits in coastal areas under fill surcharge or vacuum preloading. Vacuum preloading can also control any lateral outward movement of the embankment toe, although excessive inward movement must be avoided. An equivalent 2D numerical modelling is proposed as a predictive tool for multi-drain conditions, but unlike a 3D simulation it has a greatly reduced computation burden. A unit cell model incorporating key factors such as the smear effect, vacuum distribution, nonlinear compressibility and permeability, soil disturbance and large-strain geometry, has also been developed. This paper presents selected work at the University of Wollongong on analytical solution for PVD-assisted ground improvement. The model is applied to a case history at Tianjin Port in China and then compared with the numerical result and field measurements.

*Keywords:* large strain, nonlinearity, soft soil, soil disturbance, vertical drain, vacuum preloading,

## 1 Introduction

The world's booming population and rapid economic growth has resulted in an increasing development of highly compressible alluvial or marine deposits in many coastal areas, but their low bearing capacity and high compressibility means that these soft estuarine deposits are always impermissible for constructing infrastructure before the ground has been improved. Of the various vertical drains used to accelerate the dissipation of excess pore pressure under embankments, a prefabricated vertical drain (PVD) is the most cost effective method (Hansbo 1997, Bergado et al. 2002, Yan and Chu 2005, Chai et al. 2010, Mesri and Khan, 2012, Long et al. 2013, Indraratna 2010). Combined with fill surcharge or vacuum preloading, the radial drainage paths facilitated by PVDs stabilise the soft ground by increasing the shear strength and reducing the post-construction differential settlement. Unlike fill surcharge, vacuum preloading increases the effective stress isotropically so any corresponding lateral movement is compressive and inwards, so under a combination of fill surcharge and vacuum, lateral deformation is minimised using an appropriate

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vacuum-to-surcharge fill ratio. Unacceptable tensile stresses caused by excessive vacuum preloading with too small surcharge preloading must also be avoided. In a membrane system where a field is to be consolidated by vacuum preloading, the area is covered by an impervious membrane which ends at the edge of a peripheral trench filled with water or bentonite slurry to seal the membrane around the boundary of the treated zone. With a very large area where vacuum preloading may become cumbersome, a membraneless system where a vacuum is applied via individual PVDs with flexible tubes can be used; in this system each PVD is connected directly to the collector drain.

The unit cell approach has been developed extensively over the past decades by including some key factors that affect the behaviour of PVD-assisted consolidation such as the smear effect, vacuum distribution, nonlinear compressibility and permeability, non-Darcian flow, soil disturbance and large-strain geometry (Hansbo 1997, Geng et al. 2012, Indraratna et al. 2005b, 2005c, Walker et al. 2012, Hu et al. 2014, Rujikiatkamjorn and Indraratna 2014, and Indraratna et al. 2015). Although conventional models use a constant coefficient of consolidation under small strain assumption, their accuracy may be negatively affected by the nonlinear properties and large strain. This study presents selected work at the University of Wollongong over the past decade on the unit cell approach for PVD-assisted ground improvement that captures the void ratio-dependent compressibility and permeability, soil disturbance and large-strain geometry. The performance of the model is applied to a case history at Tianjin Port in China.

## 2 Unit-cell Model for PVD-assisted Consolidation

### 2.1 Governing Equation

With a unit cell model capturing the smear effect and vacuum distribution along the drain (Fig. 1), the consolidation of a soil element via radial and vertical drainage paths is governed by (Geng, et al. 2012):

$$\frac{k_h}{m_v \gamma_w} \left( \frac{1}{r} \frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial r^2} \right) + \frac{k_v}{m_v \gamma_w} \frac{\partial^2 u}{\partial z^2} = \left( \frac{\partial u}{\partial t} - \frac{dq}{dt} \right) \quad (1)$$

where  $k_h$  and  $k_v$  are the horizontal and vertical permeability of undisturbed soils, respectively,  $m_v$  is the coefficient of volume compressibility,  $\gamma_w$  is the unit weight of water,  $u$  is the excess pore pressure, and  $q$  is the surcharge loading.

By applying the vertical material coordinate  $\xi$  and spatial coordinate  $z$ , as shown in Fig. 2 (Gibson et al. 1967, 1981, Hu et al. 2014, and Indraratna, et al. 2015), the large-strain effect can be incorporated into Eq. (1), i.e.

$$\frac{k_h}{\gamma_w} \left( \frac{1}{r} \frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial r^2} \right) + \frac{k_v}{\gamma_w} \frac{\partial^2 u}{\partial \xi^2} = \frac{1}{1+e} \frac{\partial e}{\partial t} \quad (2)$$

where and  $e$  is the void ratio, and the relationship between the material coordinate and spatial coordinate is  $\frac{\partial \xi}{\partial z} = \frac{1+e}{1+e_0}$ , where  $e_0$  is the initial void ratio.

### 2.2 Void Ratio-dependent Permeability and Compressibility

Although conventional unit cell models use a constant coefficient of consolidation, its validity might be affected when the soils are highly compressible and the void ratio is reduced during consolidation. The nonlinear properties of soil compressibility and permeability can be incorporated with the relationships described by:

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

$$e = e_0 - C_c \log\left(\frac{\sigma'_r}{\sigma'_0}\right) \tag{4}$$

where  $k_0$  and  $\sigma'_0$  are the permeability and vertical effective stress corresponding to  $e_0$ .

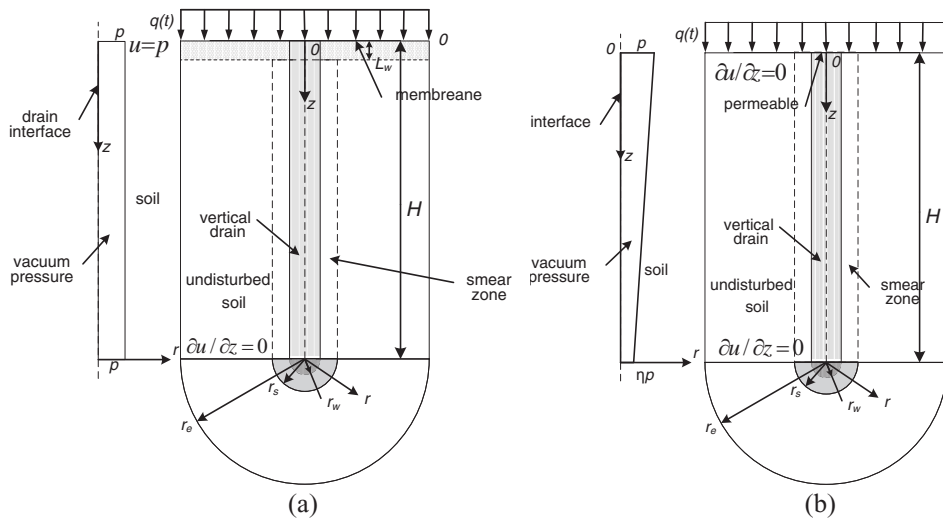


Figure 1: Unit cell model for vacuum assisted consolidation: (a) membrane system; and (b) membraneless system (Geng et al. 2012, with permission from ASCE).

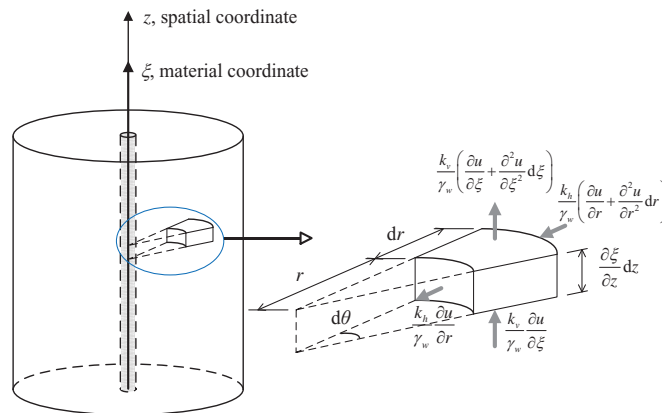


Figure 2: Large strain geometry with a spatial coordinate and a material coordinate

A laboratory test using a large-scale consolidometer with a height of 950 mm and a diameter of 450 mm was carried out at the University of Wollongong. The specimens were prepared with reconstituted alluvial clay from Moruya, in NSW, Australia. The value of  $C_c$  and  $C_k$  were 0.29 and 0.45, respectively. Two cases with different preconsolidation pressures (20 kPa and 50 kPa) were tested and the results were compared with predictions made by Indraratna et al. (2005c) and Walker et al. (2012), which considered the nonlinear permeability and compressibility, as shown in Fig. 3. A good agreement was obtained between the analytical solutions and the test data.

Figure 4 gives the impact of the ratio  $C_c/C_k$  on the consolidation rate compared to the conventional linear solution, i.e. Hansbo’s (1997) solution. While  $C_c/C_k < 1$ , actual consolidation was faster than the conventional linear solution; while for  $C_c/C_k > 1$ , actual consolidation was slower than the linear solution. There is a slight difference between the large strain curve for  $C_c/C_k = 1$  and Hansbo’s (1997) solution that was not observed by Indraratna et al. (2005c)[10] based on small strain geometry. This is the so-called large strain effect, which is attributed to inconformity between the spatial coordinate and material coordinate.

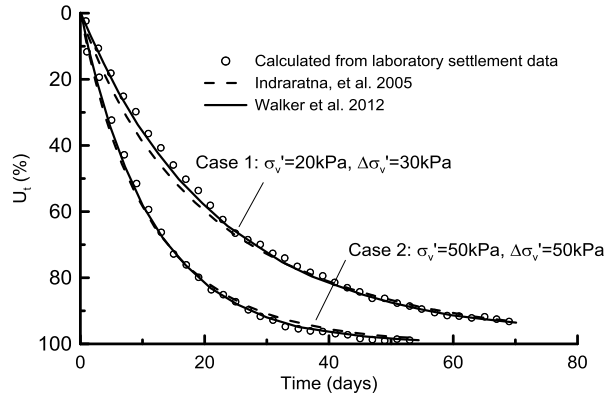


Figure 3: Comparison between test data and predictions (Walker et al. 2012).

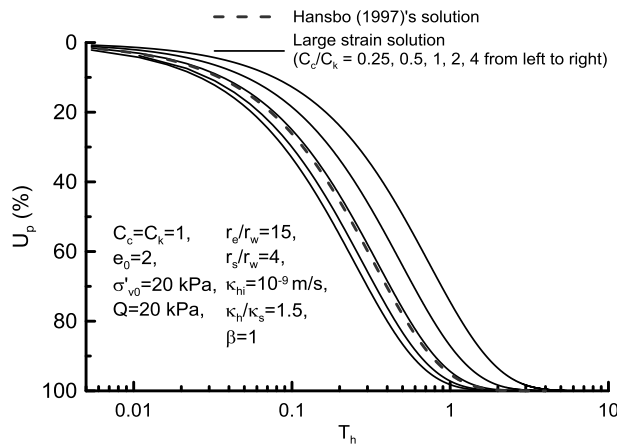


Figure 4: Impact of the ratio  $C_c/C_k$  on consolidation rate.

### 2.3 Characteristics of Soil Structure

Although nonlinear properties are more appropriate than the linear relationship used in conventional models, it is surely valid for reconstituted soils because the in-situ behaviour of soft clays might differ from laboratorial investigations due to the soil structure. Rujikiatkamjorn and Indraratna (2014) developed an analytical solution for radial consolidation that considers the characteristics of soil structure. The conceptual model for soils disturbed by driving a mandrel (Rujikiatkamjorn et al. 2013) was utilised, as shown in Fig. 5.

With the field data from the Ballina bypass project, this analytical solution was validated and compared with a previous solution that did not consider any disturbance of the soil structure, i.e. Walker and Indraratna (2007). The site of Ballina bypass project contains highly compressible

estuarine and alluvial clays, hence PVDs with vacuum and fill surcharge were used to accelerate consolidation. The measurement of settlement is given in Fig. 6 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 but did not address the effect of soil disturbance on compressibility, 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 used to capture the effect of soil disturbance on permeability and compressibility can result in a better agreement with the field data, and show the importance of soil structure characteristics in in-situ cases.

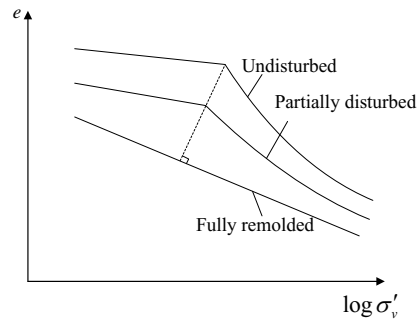


Figure 5: Conceptual compression behaviour with soil disturbance (modified from Rujikiatkamjorn et al. 2013, 2014).

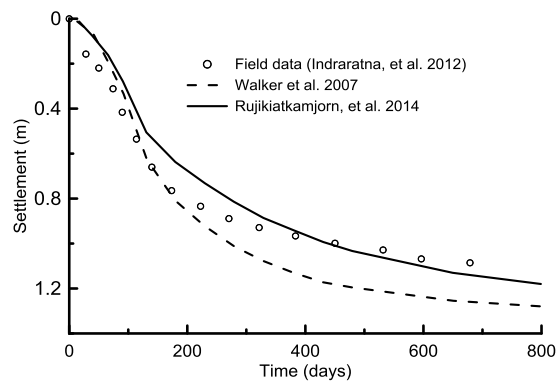


Figure 6: Predicted and measured settlement at SP1, Ballia bypass (adopted from Rujikiatkamjorn, et al. 2014).

### 3 Case History at Tianjin Port

Tianjin Port is situated about 100 km from Beijing, China (Yan and Chu, 2005). During its expansion a new pier was constructed on reclaimed land for a new storage facility. As per Indraratna et al. (2005a), at the site of Tianjin Port, the top layer (thickness of 3-4 m) was mainly dredged marine clay, underlain by a 16-19 m of original seabed clay which is normally consolidated. Vertical band drains with a cross section of  $100 \times 3 \text{ mm}^2$  and length of 20 metres were installed in a  $1 \text{ m} \times 1 \text{ m}$  square pattern. Given these relatively long drains, only radial consolidation was considered and vertical consolidation was omitted. Ground improvement in Sections 1, II, and III with a combination of PVDs has been studied by Rujikiatkamjorn et al. (2008) through 2D and 3D finite element modelling. The in-situ soil properties are given in Table 1, and the dimensions of Section I, II, and III are  $80 \text{ m} \times 30$

m, 119 m × 30 m, and 50 m × 27.9 m, respectively. Due to the large number of drains under these embankments, full 3D finite element modelling might be cumbersome here, but with the proper method, full 3D finite modelling can be converted into plane strain modelling by converting the axisymmetric properties into equivalent 2D properties. This markedly reduces the computation burden while maintaining the accuracy required for most field situations (e.g. Indraratna et al. 2005b). Indraratna et al. (2005d) proposed an equivalent plane strain approach to simulate vacuum assisted consolidation by modifying the original theory proposed by Indraratna and Redana (1997).

Settlement and excess pore pressure at Section II were also calculated by the unit cell model based on large strain and small strain geometrical assumption. Figure 7 presents the surface settlement, determined from the unit cell model, field measurement, and numerical simulation by Rujikiatkamjorn et al. (2008). A good agreement is found between the prediction and the field measurement. There is a slight difference between the large strain curve and small strain curve that shows how the large strain solution lags behind the small strain solution. The dissipation of excess pore pressure at depths of 5.5 m and 11 m below the ground surface is given in Fig. 8, and indicates a good agreement between the unit cell model, numerical simulation, and the field data. The excess pore pressure is mainly negative throughout the entire period of consolidation because of vacuum preloading. An applied vacuum pressure of -80 kPa is maintained, but the maximum negative pressure at 11 m deep is about -70 kPa, showing how the vacuum decreases as it propagates into deep depths through the PVDs.

Depth (m)	$C_r$	$C_r$	$\gamma$ (kN/m <sup>3</sup> )	$e_0$	$\frac{k_{h0}}{10^{-10}}$ (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

**Table 1:** Basic soil properties at Tianjin Port

## 4 Conclusion

PVDs combined with a fill surcharge or vacuum preloading were used to stabilise soft ground by increasing the shear strength and reducing post-construction settlement. Lateral outward movement can be controlled by vacuum preloading because it increases the effective stress isotropically, although significant inward movement and tensile stresses caused by excessive vacuum preloading must be avoided. Membrane and membraneless systems can be used to ensure the effectiveness of vacuum preloading. The equivalent 2D model, after validation by rigorous mathematical and numerical modelling, can be used as a predictive tool for multi-drain conditions under large embankments with acceptable accuracy but a much lower computational burden than full 3D simulation. A unit cell model is a simplified model that analyses the behaviour of PVD-assisted consolidation; it was used to study key factors such as the smear effect, vacuum distribution, nonlinear compressibility and permeability, non-Darcian flow, soil disturbance and large-strain geometry. This paper presents selected work carried out at the University of Wollongong over the past decade on the unit cell approach for PVD-assisted ground improvement that captures the void ratio-dependent compressibility and permeability, soil disturbance and large-strain geometry. The performance of the model was applied to a case history at Tianjin Port in China, and gave a good agreement between the numerical and analytical predictions, as well as the field measurements.



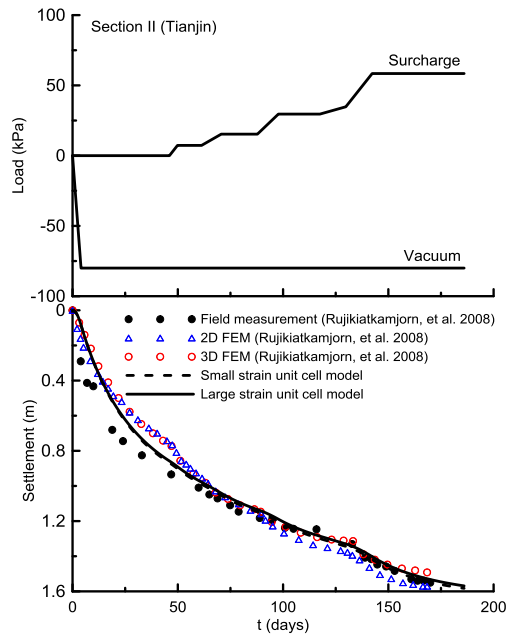


Figure 7: Predicted and measured settlement in Section II at Tianjin Port.

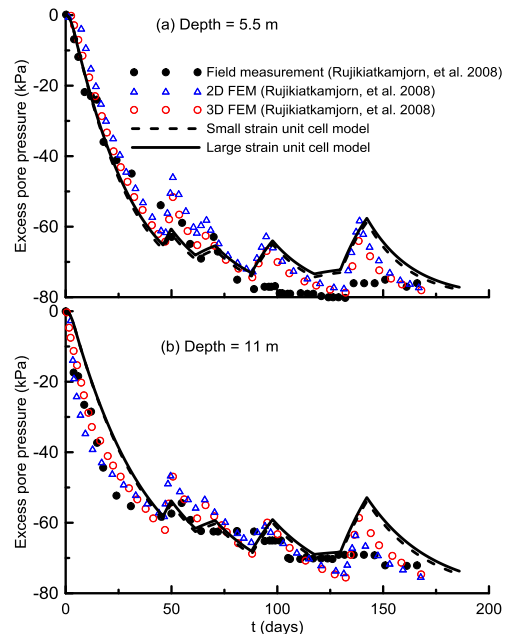


Figure 8: Predicted and measured excess pore pressure in Section II at Tianjin Port.

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