June 2006

Three-Dimensional Analysis of Soft Soil Consolidation improved by Prefabricated Vertical Drains

Cholachat Rujikiatkamjorn
University of Wollongong, cholacha@uow.edu.au

Buddhima Indraratna
University of Wollongong, indra@uow.edu.au

Three-Dimensional Numerical Modeling of Soft Soil Consolidation Improved by Prefabricated Vertical Drains

C. Rujikiatkamjorn[1] and B. Indraratna[2]

Abstract

A system of prefabricated vertical drains (PVDs) with a surcharge load is an effective method for accelerating soil consolidation by promoting radial flow. This study presents a three-dimensional (3D) finite element model for soft soil improved by a single drain. In the finite element analysis, the actual rectangular PVD cross-section is considered, and the equivalent drain diameter is then back calculated based on the consolidation curves. The numerical predictions are then compared to previous studies. The settlements observed in the laboratory are subsequently compared with the three-dimensional finite element analysis incorporating the modified Cam-Clay model and Hansbo's theory.

Introduction

A system of vertical drains with surcharge load is one of the most popular methods of soft ground improvement. Vertical sand drains having circular cross-sections were initially installed to accelerate the consolidation process by shortening the drainage path from vertical to radial direction (Nicholson and Jardine 1982). Recently, the utilisation of geosynthetic prefabricated vertical drains (PVDs) has replaced the original sand drains. This method has become an economical and viable option because of the rapid installation using simple field equipment (Indraratna et al. 1994). The PVDs are usually composed of a plastic core (protected by fabric filter) with a longitudinal channel. The most PVD sizes available in market have widths between 90-100 mm and thicknesses of 3-7 mm (Chai and Miura 1999; Bo et al. 2003).

---

[1] Doctoral Candidate, Civil Engineering, Faculty of Engineering, University of Wollongong, Wollongong City, NSW 2522, Australia, PH (61-2)4221-5886; FAX: (61-2)4221-3238, e-mail: cr27@uow.edu.au
[2] Corresponding author, Professor of Civil Engineering, Faculty of Engineering, University of Wollongong, Wollongong City, NSW 2522, Australia, PH (61-2)4221-3046, FAX (61-2)4221-3238, email: indra@uow.edu.au

The behavior of soft soil consolidation improved by PVDs has usually been analysed either by analytical theories or by two-dimensional (2D) numerical models. Based on an idealized cylindrical single unit cell with an inner cylindrical drain, theories of radial consolidation have been originally derived by Barron (1948), with subsequent modifications by Yoshikuni and Nakanodo (1974), Hansbo (1979), Chai et al. (2001) and Indraratna and Redana (2000). The average degree of radial consolidation considering smear effect based on equal strain solution can be expressed by:

$$U = 1 - \exp(-8T_h / \mu) \tag{1a}$$

in which,

$$\mu = \ln n / s + k_h / k_s \ln s - 0.75 \tag{1b}$$

where, U = average degree of consolidation due to radial drainage, μ = a group of parameters representing the geometry of the vertical drain system and smear effect, $n = d_e/d_w$, $s = d_s/d_w$, d_e = equivalent diameter of cylinder of soil around drain, d_s = diameter of smear zone, T_h is the dimensionless time factor for consolidation due to radial drainage and d_w = diameter of drain well. In Eq. (1b), k_h = average horizontal permeability in the undistrubed zone (m/s), and k_s = average horizontal permeability in the smear zone (m/s).

At a later stage, the use of an equivalent plane strain model for multi-drain simulation can be readily adapted to most field situations (Indraratna and Redana 1997; Indraratna and Redana 2000). However, the consolidation around vertical drains is truely three-dimensional (3D), hence, in the field, a large number of vertical drains will each have their own independent influence zone. The discrepancy between the measured and predicted consolidation based on the approximate 2D modelling techniques can be found from previous studies (i.e. Indraratna and Redana 1997). Therefore, the complex behaviour of the PVD system is required to be analysed as a three-dimensional problem.

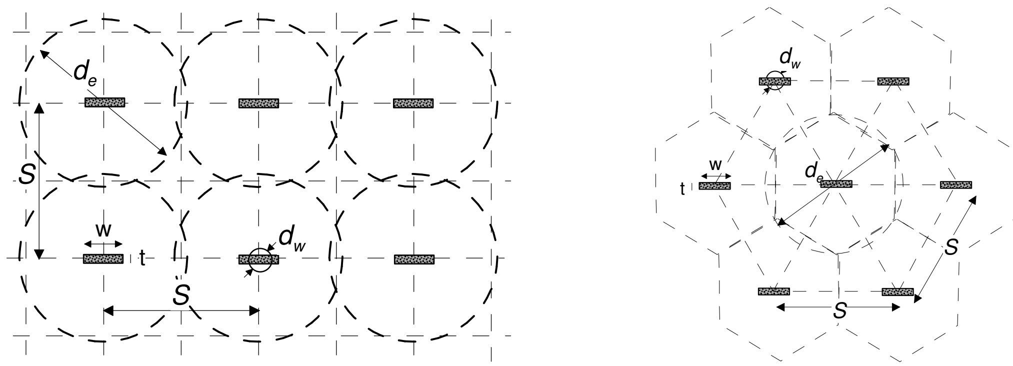
In this paper, a more complex interpretation of 3D behaviour of a vertical drain system was initially investigated by a 3D finite element code (*ABAQUS,* Hibbitt, et al., 2004). In the numerical model, the actual rectangular PVD cross-section is considered. The equivalent drain diameter is back calculated based on the consolidation curves, and the current analysis is compared to the results from previous studies. Subsequently, the 3D numerical results are compared to the Hansbo's analytical solution (1979) and laboratory observations.

Background

As illustrated in Fig. 1, rectangular PVDs are commonly installed in a square or a triangular pattern. It can be seen that shapes of PVDs are not the same as a simple circular cross-section considered in the conventional theory. Therefore, a band-shaped drain with polygon shaped outer boundary needs to be converted to an equivalent cylindrical drain with a circular influence zone (Fig. 2). In the past, the approximate equations for equivalent drain diameter have been derived with various assumptions, hence the different results were reported by various studies. None of them considered the actual 3D geometry of the PVD system. The formulations for the equivalent cylindrical drain conversion available from previous studies are highlighted below:

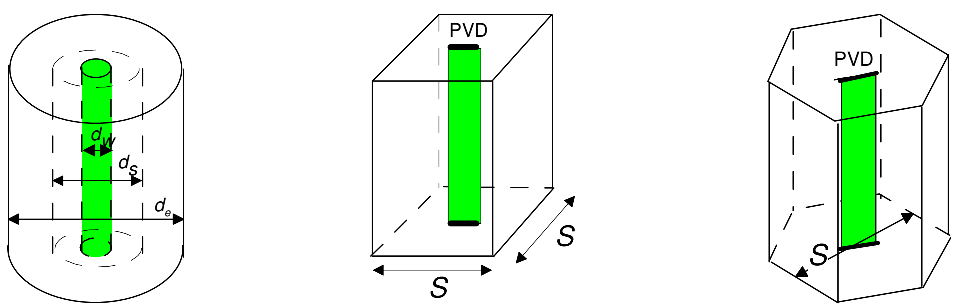
$$d_w = 2(w+t)/\pi \quad \text{(Hansbo, 1979)} \quad (2)$$
$$d_w = (w+t)/2 \quad \text{(Atkinson and Eldred, 1981)} \quad (3)$$
$$d_w = 0.5w + 0.7t \quad \text{(Long and Covo, 1994)} \quad (4)$$

where, d_w = diameter of drain well and w and t = width and thickness of the PVD, respectively.



(a) (b)

Figure 1. Drain installation pattern (a) square pattern; (b) triangular pattern



(a) (b) (c)

Figure 2. Vertical drain and its dewatered soil zone (a) theoretical cylindrical unit cell; (b) unit cell with square grid installation and (c) unit cell with triangular grid installation

Back-analysed equivalent diameter (d_w) of rectangular drains

A 3D finite element program (*ABAQUS*) was employed to simulate a unit cell with a rectangular vertical drain. In the FEM mesh, 8-node tri-linear displacement nodes with 8 pore pressure nodes (C3D8P) were employed (Fig. 3a). An elastic analysis was conducted with m_v=10^{-3} m^2/kN and Poisson's ratio of zero, to simulate the condition of zero lateral displacement in accordance with the 1-D consolidation assumed in Barron's solution. The horizontal undisturbed soil permeability (k_h) was

determined from 1-D consolidation tests to be appoximately 4×10^{-10} m/s (Indraratna et al., 2005). The dimensions of the cylindrical unit cell (see Fig. 3b) were 450 mm (influence zone diameter) and 850 mm (height). A total of 1008 3D elements were used in the finite element analysis (Fig. 3b). In the entire finite element mesh, the aspect ratio of elements was kept below 3. The top, bottom and outer boundaries were set as impermeable. The vertical loading pressure (σ_1=50 kPa) was applied at the top of the cell. The displacement boundary in *x* and *y* directions was fixed (i.e. no movement in the horizontal direction), while vertical displacement in the *z* direction was permitted. In order to simulate the perfect drain condition (infinite discharge capacity and no smear), the pore pressures at the drain boundary were set to zero and the smear zone was excluded. Only one-fourth of the influence area was used in the model because of the two axes of symmetry. The width and thickness of the rectangular drain were varied to cover the commercially available sizes of vertical drains. It is noted that the finite element model (*ABAQUS*) using a circular drain cross-section in a cylindrical unit cell has been validated with Barron's solution by Indraratna et al. (2005).

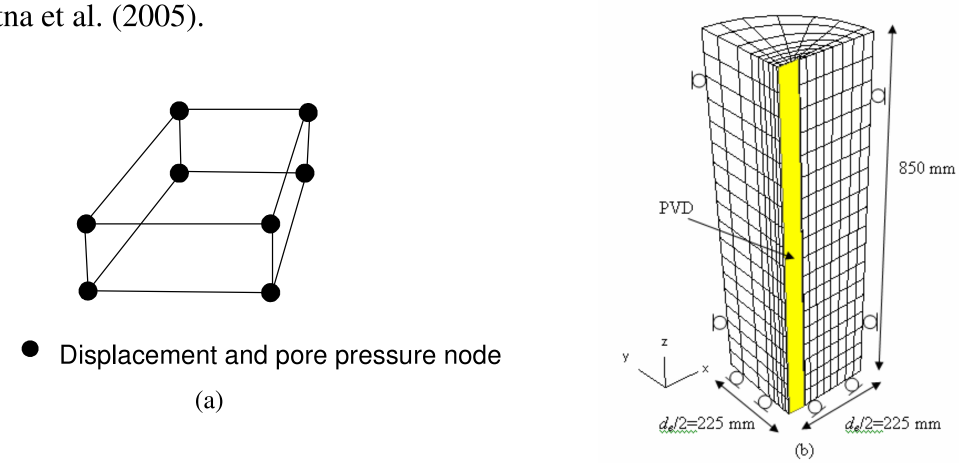


Figure 3. Finite element discretization for 3D analyses of soil in unit cell, (a) Nodes and integration points for a C3D8P element; (b) Mesh discretization.

The average degree of consolidation-time factor curves (U-T_h) based on various drain sizes by FEM are compared to Barron's solution. The equivalent drain diameter is then back-calculated using the curve fitting technique with a regression coefficient, $R^2 > 0.999$. Figure 4 summarizes the value of back calculated d_w with various drain sizes. The comparison of equivalent drain diameter obtained from 3D FEM and other methods is shown in Table 1. It can be seen that the drain diameter from 3D FEM is very close to Eq. (2), proving that the draining effectiveness of PVDs depends on the drainage perimeter.

Laboratory simulation

Large-scale laboratory consolidation tests were conducted to compare the laboratory results with the 3D numerical predictions.

Experimental Setup. The schematic illustration of a large-scale radial drainage consolidation apparatus is shown in Fig. 5a. The details of the unit cell have been explained elsewhere by Indraratna and Redana (1997). The diameter and height of the

soil sample are 450 and 850 mm, respectively. The remolded alluvial clay was mixed and placed in the apparatus under vacuum condition to ensure full saturation. Two separate series of tests were conducted in the large-scale consolidation apparatus: one for obtaining the initial variation of soil permeability along the radial distance (Test A) and the other for obtaining the associated consolidation settlement (Test B). In Test A, an initial preconsolidation pressure (p'_c) of 20 kPa on top of the rigid plate was applied for 5 days. At the end of the preconsolidation stage, a prefabricated vertical band drain (PVD) of cross section 100 mm × 4 mm was installed using a specially designed rectangular close-ended mandrel. After drain installation, the mandrel was withdrawn by the hoist system, and a vertical preconsolidation pressure of 20 kPa was then reapplied until no further settlement. After installation of the vertical drain, horizontal specimens were collected from different locations within the cell at known radii (i.e. Sections A-A and B-B in Fig. 5b). Standard oedometer tests were conducted on these samples to establish the variation of soil permeability close to and away from the central drain. Figure 6 shows the variation of the horizontal and vertical permeability at different radii. In Test B, following the preconsolidation stage and drain installation, the subsequent surcharge load was applied instantaneously in two stages (50 and 100 kPa), with a duration of 15 days between each stage. The corresponding settlement behavior was recorded and plotted.

Table 1. Comparison of equivalent drain diameters

Drain size		Drain diameter (mm, d_w)			
w (mm)	t (mm)	Eq. (2)	Eq. (3)	Eq. (4)	3D FEM
95	5	63.6	50.0	51.0	64
98	4	64.9	51.0	51.8	65
98	5	65.5	51.5	52.5	66
94	4	62.3	49.0	49.8	63
93	4	61.7	48.5	49.3	62

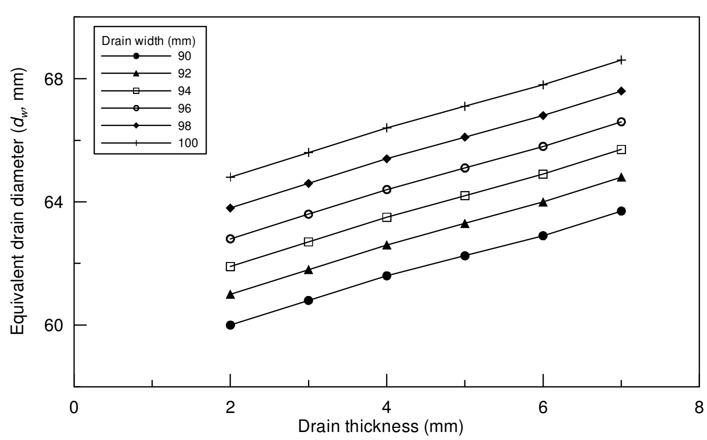


Figure 4. Equivalent drain diameter back-calculated from 3D FEM

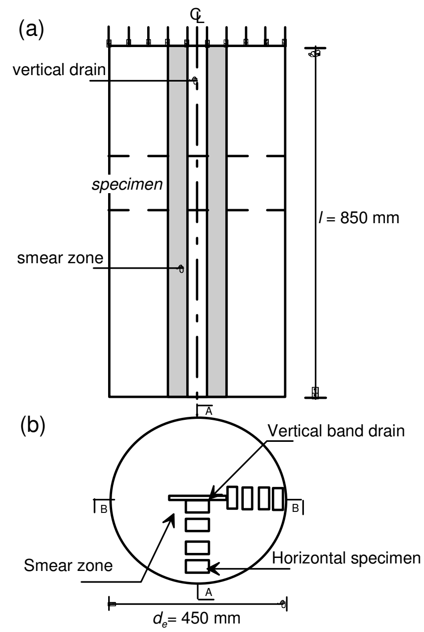


Figure 5. Schematic Diagram: (a) section of test equipment showing central drain and associated smear; (b) locations of specimens to determine permeability characteristics (Modified after Indraratna and Rujikiatkamjorn, 2004)

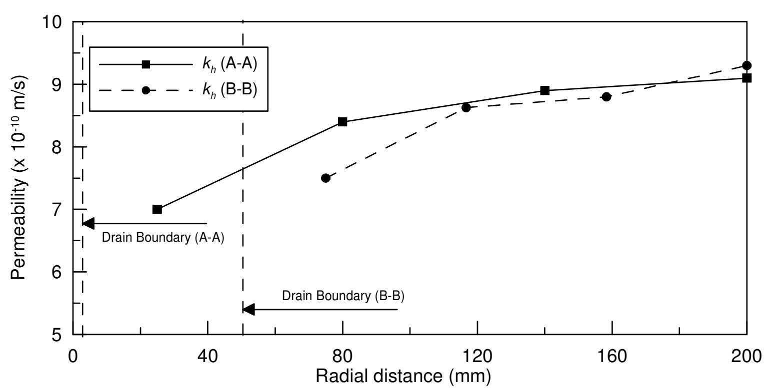


Figure 6. Lateral permeability along radial distance at 20 kPa vertical effective preconsolidation pressure (after Indraratna and Rujikiatkamjorn, 2004)

3D Numerical modeling of the large-scale consolidation cell.

The 3D finite element analysis employed to predict the settlement behavior of the soil was based on the modified Cam-clay model (Roscoe and Burland, 1968) The discretized finite element mesh of the soil cell was illustrated earlier in Fig. 3b. The modified Cam–Clay properties of the soft clay are given in Table 2. The variation of permeability shown in Fig. 6 and the correct void ratio-permeability relationship (e-logk_h) that has slope of c_k,were incorporated in the numerical analysis. The finite element predictions are compared with Hansbo's equation (Eq. 1), using d_w = 0.0664m, d_s = 0.20m, d_e = 0.45m, k_h/k_s = 1.5 and c_h = 0.60m^2/year (Fig. 7). The effect of well resistance was ignored, as the discharge capacity of the drain was sufficiently large and also it was still enough to prevent 'kinking'. As shown in Fig. 7, the

settlement prediction from Equation (1) slightly underestimates the laboratory results, whereas the finite element prediction incorporating the radial variation of permeability (Fig. 6) agrees very well with the laboratory measurements.

Table 2. Modified Cam–Clay parameters used in consolidation analysis.

Soil Properties	Value
κ	0.05
λ	0.14
Permeability change index (c_k)	0.45
Critical state line slope, M	1.1
Initial void ratio, e_0	0.9
Poisson's ratio, ν	0.25

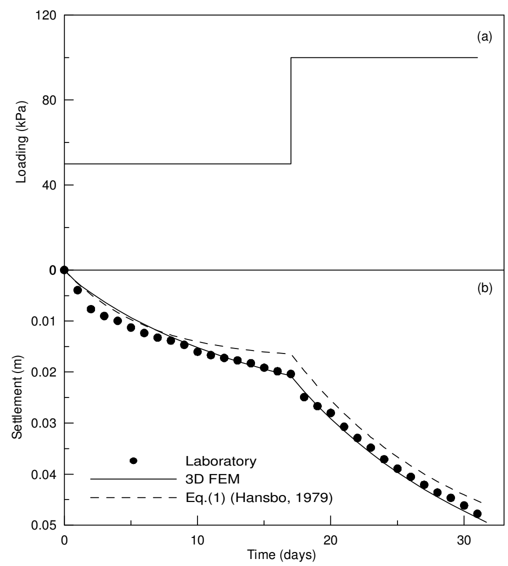


Figure 7. Comparison between measured and predicted results from 3D FEM and Equation (1); (a) stages of loading; (b) surface settlements

Conclusion

In this paper, a numerical model based on three-dimensional finite element model (FEM) was introduced to analyze the soft soil consolidation improved by prefabricated vertical drains (PVDs). The actual rectangular PVD cross-section was considered in the numerical simulation. The equivalent drain diameter was back calculated and compared to the results of previous studies based on the consolidation behavior. The study confirms that the equivalent drain diameter calculated on the basis of a drain perimeter is similar to that obtained from the FEM numerical results.

The predictions from the 3D numerical model agree well with the laboratory measurements, obtained using large-scale consolidation testing. In the analysis which adopts the modified Cam-clay theory, the inclusion of smear effect, the actual variation of horizontal permeability along the radial direction and the void ratio-permeability relationship significantly improved the accuracy of settlement prediction.

However, the predictions based on the conventional analysis (Hansbo, 1979) slightly underestimated the laboratory data. By using the 3D FEM analysis, one is able to analyse the time-dependent consolidation behavior of PVDs installed in soft clays considering the actual cross-sectional shape of band drains and the associated non-cylindrical smear zone.

References

Atkinson, M.S. and Eldred, P. (1981). "Consolidation of soil using vertical drains." *Geotechnique*, 31(1), 33-43.

Chai, J.C. and Miura, N. (1999). "Investigation on some factors affecting vertical drain behavior." *J. of Geot. and Geoenvi. Eng*., ASCE, 125(3), 216-226.

Chai, J. C., Shen, S. L., Miura, N. and Bergado, D. T. (2001) "Simple method of modeling PVD improved subsoil." *J. of Geot. and Geoenvi. Eng*, ASCE, 127(11), 965-972.

Bo, M.W., Chu, J., Low, B.K. and Choa, V. (2003). Soil improvement; prefabricated vertical drain techniques. Thomson Learning, Singapore, 341p.

Hansbo, S., (1979). "Conslidation of clay by band-shaped prefabricated drains." *Ground Eng*., 12(5), 16-25.

Hibbitt, Karlsson and Sorensen (2004). *ABAQUS/Standard User's Manual*, Published by HKS Inc.

Indraratna, B. and Redana, I W., (1997), "Plane strain modeling of smear effects associated with vertical drains." *J. Geotech. Eng., ASCE,* 123(5), 474-478.

Indraratna, B. and Redana, I W. (2000). "Numerical modeling of vertical drains with smear and well resistance installed in soft clay." *Canadian Geotechnical Journal,* 37, 132-145.

Indraratna, B. and Rujikiatkamjorn C**.**, (2004). "Laboratory Determination of Efficiency of Prefabricated Vertical Drains Incorporating Vacuum Preloading." *The 15th Southeast Asian Geotechnical Conference*. 1: 453-456.

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., Rujikiatkamjorn C., and Sathananthan, I., (2005). "Analytical and numerical solutions for a single vertical drain including the effects of vacuum preloading." *Canadian Geotechinical Journal*, 42: 994-1014.

Long, R. and Covo, A. (1994). "Equivalent diameter of vertical drains with an oblong cross section. Journal of Geotechnical Engineering," 120(9), 1625-1630.

Nicholson D.P. and Jardine R.J. (1982). "Performance of vertical drains at Queenborough bypass." *Vertical Drains*, the Institution of Civil Engineers: London, 67-90.

Yoshikuni, H. and Nakanodo, H., (1974). "Consolidation of Fine-Grained Soils by Drain Wells with Finite Permeability." *Japan Soc. Soil Mech. and Found. Eng*. 14(2), 35-46.