The 4th International Conference on Geotechnical Engineering and Soil Mechanics,
November 2-3, 2010, Tehran, Iran

Paper No. & Code: 664 (UOSPAR)

Uncertainties of Smear Zone Characteristics in the Design of Preloading with Prefabricated Vertical Drains

A. Parsa Pajouh[1,*], B. Fatahi[1], and H. Khabbaz[1]

1- School of Civil and Environmental Engineering, Faculty of Engineering and IT, University of Technology, Sydney (UTS), Australia

*aparsapa@eng.uts.edu.au

Abstract

Installing prefabricated vertical drains using mandrels induces disturbance of the soil surrounding the drain, resulting in a smear zone with the reduced permeability. The required time for pore pressure dissipation in preloading design is strongly associated with the smear zone characteristics. In this study, the effects of smear zone properties on preloading time are numerically investigated. Parametric study is conducted to find out the range of smear zone parameters significantly influencing the consolidation period. It is observed that the characteristics of smear zone namely size and permeability have a substantial impact on the preloading design to achieve certain soil strength and stiffness satisfying both bearing capacity and settlement design criteria.

Keywords: Soft Soil, Prefabricated Vertical Drain, Preloading, Smear Zone, Permeability, Ground Improvement

1. INTRODUCTION

In the last decade, employing prefabricated vertical drains (PVDs) assisted preloading has been recognised as a very efficient method of ground improvement for sites with deep soft soil layers. In this method, a surcharge will be applied on the surface of the ground until the required settlement is obtained within the project time frame. In soft and compressible soils with a considerable thickness, due to the very low permeability of the soil, the consolidation process needs a long time to be completed. Installation of sand drains and geosynthetic vertical drains can reduce the preloading period significantly by decreasing the length of drainage path, as the consolidation time is inversely proportional to the square of drainage path. A prefabricated vertical drain (PVD) is a composite geosynthetic system consisting of a polymeric inner core with formed flow path grooves on both sides and an outer non-woven geotextile filter jacket. In comparison to the sand drains, the application of PVD systems has some advantages such as; accelerating the installation process, decreasing the adverse effects due to the lateral soil movement because of the flexibility of PVDs, and reducing the consolidation period [1]. According to Sharma and Xiao [2], installation of prefabricated vertical drains using the mandrel causes disturbance of clay surrounding the drain, resulting in a smear zone of reduced permeability adversely affecting the consolidation process as illustrated in Figure 1.

2. SMEARING EFFECTS

Soil permeability around the drain within the smear zone is decreased significantly retarding the rate of consolidation. The combined effect of permeability and compressibility within the smear zone causes a different behaviour from the undisturbed soil. Predicting soil behaviour surrounding the drain requires an accurate estimation of the smear zone properties. The parameters required to characterise the smear effect are: the extent of the smear zone (r_s), and the ratio of the horizontal coefficient of permeability in the undisturbed zone over that in the smear zone (k_h/k_s) [3] (see Figure 1). As Bergado et al. [4] explained, the PVD installation procedure, mandrel specifications and the type of soil are the factors affecting the smear zone characteristics. Both the smear zone extent and its permeability are difficult to quantify and determine from laboratory tests, and so far there is no comprehensive or standard method for measuring these characteristics. Generally, there are two main reasons and theories proposed explaining the smear zone generation; (I) the soil remoulding concept, and (II) the reconsolidation theory. Barron [5] stated that if drain wells are installed by driving cased holes which are back filled as the casing is withdrawn, driving and pulling the casing would distort and remould the adjacent soil. According to the remoulding concept restated by several other researchers [5-7], for PVD assisted preloading design, the soil surrounding the drain considered as two sections, the smear zone in the disturbed region in the immediate vicinity of the drain, and the intact or the undisturbed zone beyond the undisturbed zone. In recent years, a few researchers have used the cavity expansion theory to analyse the soil reconsolidation associated with mandrel-driven prefabricated vertical drain [2, 8, 9]. In this theory, the drain installation process is modelled as the expansion of a cylindrical cavity with a final radius equal to that of the mandrel, r_m.

There are two schools of thought to determine the characteristics of the smear zone which are the smear zone with constant properties, and the smear zone with variable properties. In classical solutions [5, 6], the influence of the smear zone is considered with an idealised two-zone model, where the smear zone is the disturbed region in the immediate vicinity of the drain and the other zone is the intact or undisturbed region outside the smear zone that is shown in Figure 1. In order to define the extent and the permeability of smear zone base on this theory, a number of laboratory investigations have been conducted and very diverse values for the above mentioned factors have been proposed which are summerised in Table 1.

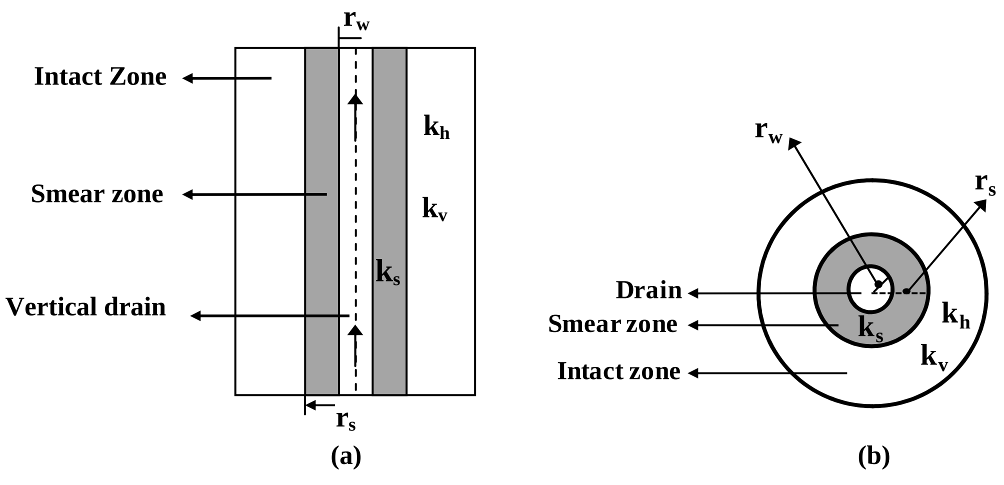

Figure 1. PVD surrounding by smear zone (a) profile, (b) cross section

According to available literature summerised in Table 1, the extent of smear zone (d_s) varies between 1.6 to 7 times of drain diameter (d_w) or, 1.5 to 5 times of mandrel equivalent diameter (d_m). Moreover, the ratio of k_h/k_s changes between 1.34 and 10.

Table 1. Proposed values for smear zone characteristics

References	d_s/d_m	k_h/k_s
Barron (1948)	1.6	3
Casagrande and Poulos (1969)	1	-
Holtz and Holm (1973)	2	-
Akagi (1976)	2	-
Hansbo (1981)	1.5	3
Hansbo et al.(1981)	2	2
Jamiolkowski et al. (1983)	2.5~3	-
Bergado et al. (1991)	2	1.5-2 (k_s=k_v)
Onoue (1991)	1.6	3
Bergado et al. (1993)	2	10
Almedia et al. (1993)	1.5~2	3~6
Hansbo (1994)	d_s/d_w=2	k_s =k_v
Mesri et al. (1994)	2-4	-
Hansbo (1997)	2	3.33-4
B. Indraratna and Redana (1998)	d_s/d_w =4~5	-
Chai and Miura (1999)	2~3	5& k_s=k_v & k_h/k_s=$(k_h/k_s)c_f$
Eriksson et al. (2000)	2	6
Hird and Moseley (2000)	d_s/d_w =1.6	3
Sharma and Xiao (2000)	4	1.3
Bo (2003)	d_s/d_w =4~7	2-10 (normally 2)
Sathananthan and Inraratna (2006)	2.5	1.34 (1.09~1.64)
Sathananthan et al. (2008)	4~6	1.61~1.92
Ghandeharioon et al. (2009)	ds = 3.1dm	-

d_s is the smear zone extent, d_w is drain diameter, d_m is mandrel equivalent diameter, k_h and k_h are horizontal and vertical permeability of intact zone respectively, k_s is permeability of smear zone, and c_f is the hydraulic conductivity ratio between field and laboratory values

Some researchers [10, 11] introduced a three zone hypothesis to investigate the smear zone characteristics, which are the inner smear zone in the immediate vicinity of the drain, the outer smear zone (transition zone), where permeability is moderately reduced as a result of the initial reduction of void ratio during installation, and the undisturbed zone where the soil is not affected by installation (Figure 2). To estimate the extent of the smear zone based on this concept, it is necessary to define the variation of permeability in the radial direction, rather than consider it as a constant number. Walker and Indraratna [12] assumed a parabolic distribution of permeability in the smear zone, whereas Rujikiatkamjorn and Indraratna [13] considered the linear variation. Basu and Prezzi [14] has proposed analytical solutions for four different permeability distribution patterns and Chung et al. [15] applied the hyperbolic method to determine the permeability of smear zone.

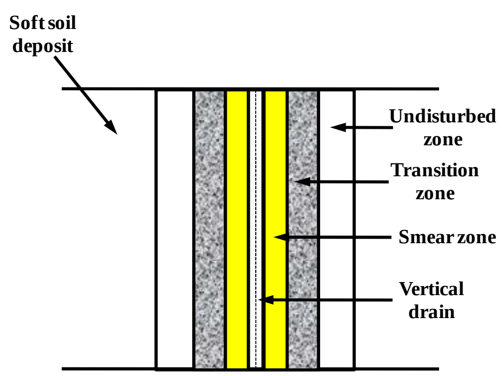

Figure 2. Three zone hypothesis for the smear zone

According to the existing literature, a wide range is proposed for the smear zone and there is no definite method that can account for the precise prediction of the extent of smear zone and its permeability. In geotechnical practices, the extent and characteristics of smear zone are estimated from available parameter ranges which are very diverse. Therefore, it is essential to study the influence of uncertainties in the smear zone size and its permeability on the preloading design. In this study, the effects of uncertainties in the smear zone parameters on the required surcharge, and preloading time are investigated numerically.

3. NUMERICAL ANALYSIS

In order to find out the influence of smear zone characteristics on the consolidation period, the finite element approach considering modified cam-clay model incorporating the variations in smear zone properties is employed. To carry out the numerical analysis a 2D finite element program (PLAXIS 2D Version 9.0) is used. Axi-symmetric model representing a single PVD condition is simulated. The 15-node triangular elements has been selected (Figure 3b). It should be noted that for more accuracy, the generated mesh has been refine in an appropriate way, specifically, in the smear zone section that is demonstrated in Figure 3c.

Required time to obtain a certain degree of consolidation is calculated. For this aim, analyses are conducted for the preloading design of a project consisting of 5m high embankment on 5m deep soft clay layer. Time duration required to achieve 90% degree of consolidation has been calculated for various smear zone properties (r_s/r_m changed between 2 to 5, and k_h/k_s varied between 3 and 10, where, r_m is the radius of mandrel). The equivalent PVD spacing is assumed to be 1.5m. Table 2 shows the properties of the soft clay used in the analysis.

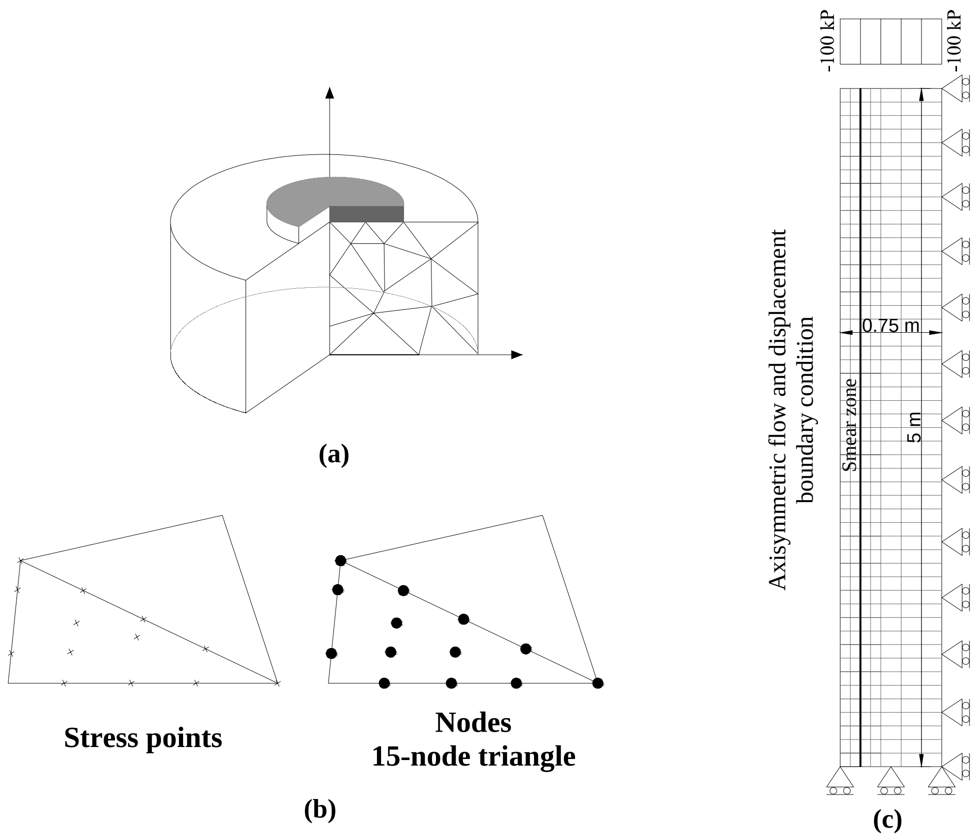

Figure 3. (a) Axi-symmetric model, (b) 15-node triangular element, (c) Numerical model of PVD

Table 1. Properties of Soft Clay [16]

Parameter	Value	remarks
γ_S	16 kN/m^3	Unit weight
k_h	1.07×10^{-9} m/s	Horizontal permeability
κ	0.035	Slope of swelling line
λ	0.35	Slope of virgin compression line
M	1.07	Slope of the critical state line
ν	0.26	Poisson ratio

It should be noted that the above soil properties has been extracted from the actual geotechnical studies by Indraratna and Redana [16]. Therefore, they have merit over the assumed parameters, which may not be completely conforming to reality

4. RESULTS

As expected, the analysis confirms that the installation of prefabricated vertical drains substantially accelerates the preloading process. PVD installation shortens the drainage path, which let the excess pore pressure to dissipate rapidly and increases the settlement rate. Figure 4 presents the vertical settlement time describing the influence of the PVD and smear zone on preloading time to obtain the required settlement. For the soil with no PVD, the required time to achieve 90% degree of consolidation is almost 1900 days (5.2 years), while, this time for the case with PVD and no smear zone is about 170 days that is approximately 11 times smaller. From Figure 4, it is clear that including the smear zone increases the required consolidation time in comparison to the case with PVD but with no smearing effect.

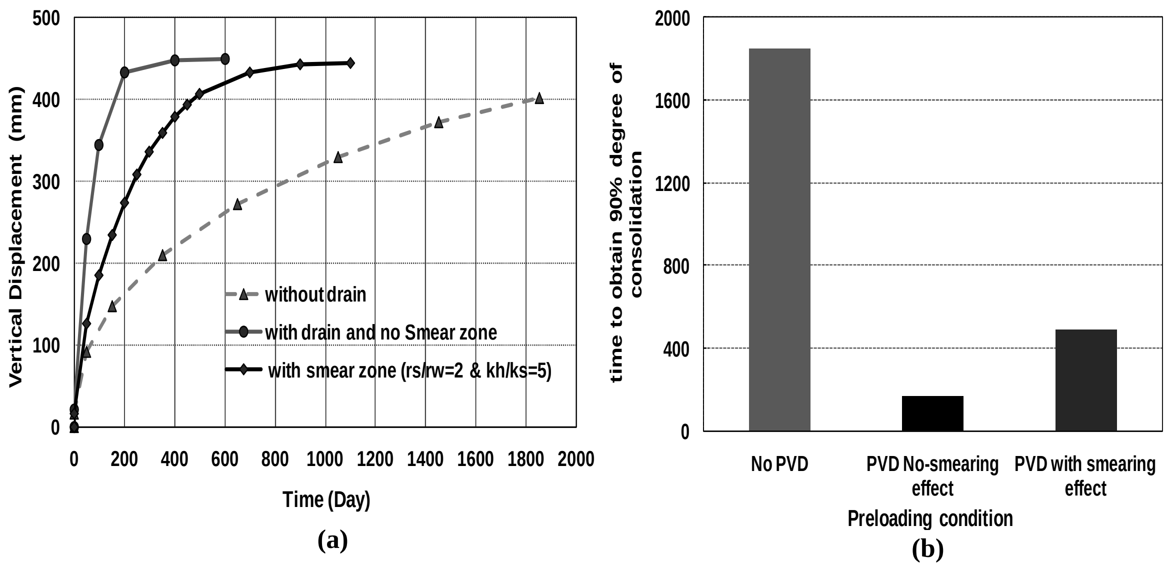

Figure 4. (a) Vertical settlement changes with time in consolidation process, and (b) required time to obtain 90% degree of consolidation

5. PARAMETRIC STUDY

To define the effect of smear zone properties on the preloading process, number of samples are analysed by varying two parameters; r_s/r_m (the smear extent over the equivalent mandrel radius) and k_h/k_s (permeability of intact zone over the permeability of smear zone). According to Figure 5, the consolidation time very much depends on the smear zone permeability, which is significantly influencing the preloading design. For example, assuming $r_s/r_m=2$, for the case with $k_h/k_s=3$, the required time to obtain 90% degree of consolidation is around 350 days, while, this time will be 750 days by increasing the ratio k_h/k_s to 10, meaning that the required time to achieve the 90% degree of consolidation for the case with $k_h/k_s=10$ is approximately two times greater than the same period for the sample with $k_h/k_s=3$.

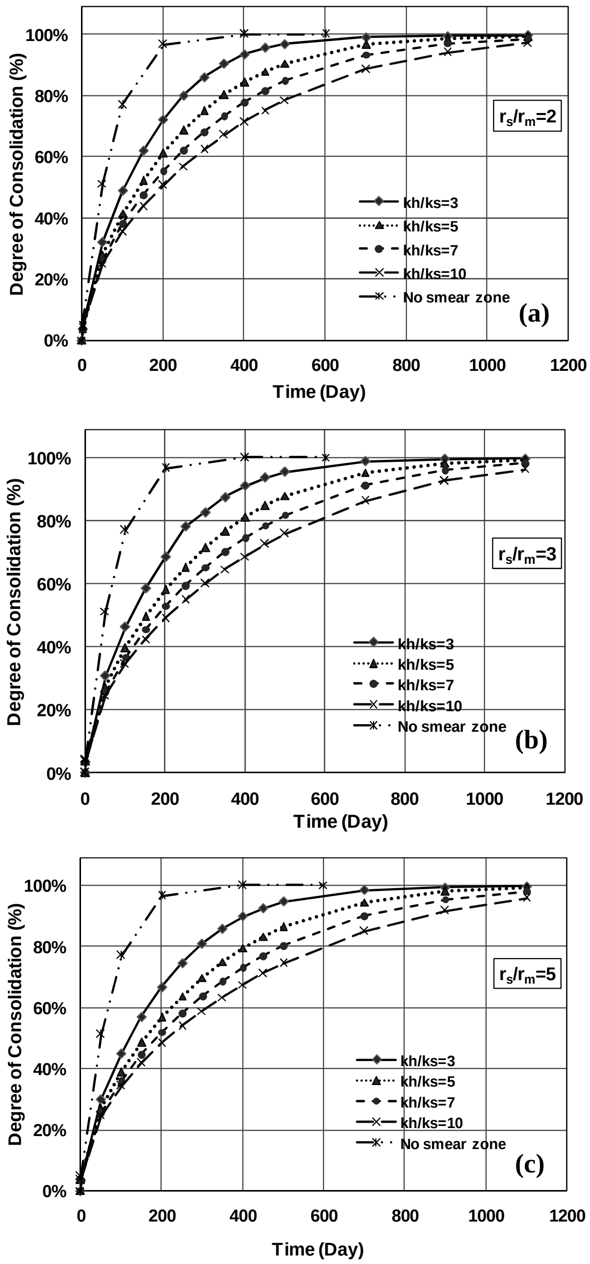

Figure 5. Effect of smear zone permeability on consolidation process; (a) r_s/r_m=2, (b) r_s/r_m=3, and (c) r_s/r_m=5

Figure 6 shows required time to achieve 90% degree of consolidation for various smear zone properties. It is observed that time for 90% degree of consolidation considerably increases by decreasing smear zone permeability. The minimum required time for 90% degree of consolidation is approximately 350 days belong to the case with $r_s/r_m=2$ and $k_h/k_s=3$, whereas, the maximum time is almost 850 days corresponding to the case with $r_s/r_m=5$ and $k_h/k_s=10$. These results clearly show that smear zone extent is also an important factor influencing the consolidation period.

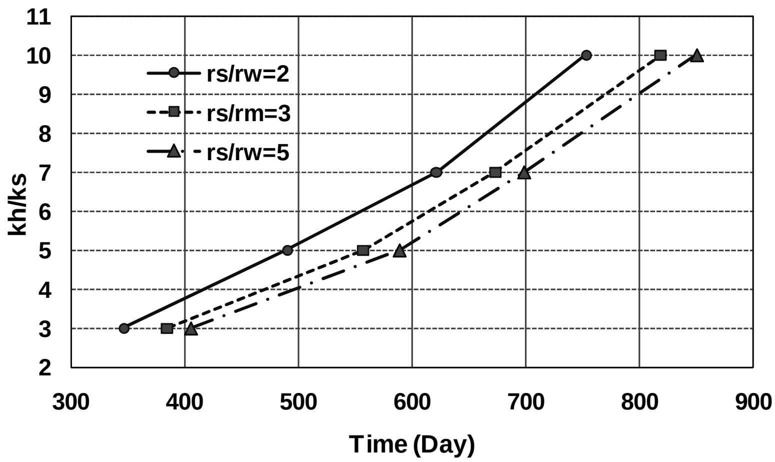

Figure 6. Required time to obtain 90% degree of consolidation

Figure 6 also shows the significance of smear zone extent on the required time to rich to the 90% degree of consolidation. It is observed that the effect of smear zone variation is more considerable in the low ranges (between 2 and 3) comparing to the higher values. Clearly, the growth in consolidation time for higher values of r_s/r_m is still remarkable and should not be neglected. Table 2 summerises the required time for 90% degree of consolidation for the case with $k_h/k_s=5$. It can be seen that the consolidation time is grown by about 20% by increasing the smear ratio from 2 to 5.

Table 2. Required time to obtain 90% degree of consolidation for the case of $k_h/k_s=5$

r_s/r_m	2	3	5
Time (day)	490	558	589

6. CONCLUSIONS

The numerical investigation confirms that the installation of the vertical drain reduces the consolidation time substantially, whereas, incorporating the smear zone around the PVD in the analysis, affect the consolidation process adversely. Furthermore, the permeability of the smear zone is a key factor in preloading design, and has a significant effect on required time to obtain 90% degree of consolidation. Varying the k_h/k_s between the ranges of 3 to 10, while r_s/r_m is constant, can increase preloading time by about 200%. Additionally, the consolidation time depends on the smear zone extent and the changes in this parameter have a direct effect on the required preloading time. By increasing the smear zone extent ratio (r_s/r_m) from 2 to 5, the required time to achieve a certain consolidation degree can increase up to 20%.

According to the results, it is observed that the properties of the smear zone have a key role on the required consolidation time to achieve certain soil strength and stiffness satisfying both bearing capacity and settlement design criteria. Therefore, accurate estimation of the properties of smear zone based on soil type and installation method is vital for ground improvement projects using preloading and PVDs. The current available research indicates that further research should be conducted to quantify the properties of smear zone based on influencing factors, helping design engineers and clients to optimise the design and minimise construction costs, respectively.

REFERENCES

1. Indraratna, B., Rujikiatkamjorn, C., Kelly , R., and Buys, H., 2010, *"Sustainable Soil Improvement Via Vacuum Preloading,"* Proc. of the ICE - Ground Improvement, 163(1), pp. 31~42;

2. Sharma, J. S., and Xiao, D., 2000, *"Characterization of a Smear Zone around Vertical Drains by Large-Scale Laboratory Tests,"* Can. Geotech. J., 37(6), pp. 1265~1271;

3. Chai, J., and Miura, N., 1999, *"Investigation of Factors Affecting Vertical Drain Behavior,"* J. of Geotech. and Geoenvir. Eng., 125(3), pp. 216~226;

4. Bergado, D. T., Asakami, H., Alfaro, M. C., and Balasubramaniam, A. S., 1991, *"Smear Effects of Vertical Drains on Soft Bangkok Clay,"* J. of Geotech. Eng., 117(10), pp. 1509~1530;

5. Barron, R. A., 1948, *"Consolidation of Fine-Grained Soils by Drain Wells,"* Trans. Am. Soc. Civ Eng., 113(pp. 718~754;

6. Hansbo, S., 1981, *"Consolidation of Fine-Grained Soils by Prefabricated Drains,"* Proc. Proc. No. 18, Swedish Geotechnical Institute, Stockholm, Sweden;

7. Indraratna, B., and Redana, I. W., 1997, *"Plane-Strain Modeling of Smear Effects Associated with Vertical Drains,"* Journal of Geotechnical and Geoenvironmental Engineering, 123(5), pp. 474~478;

8. Sathananthan, I., Indraratna, B., and Rujikiatkamjorn, C., 2008, *"Evaluation of Smear Zone Extent Surrounding Mandrel Driven Vertical Drains Using the Cavity Expansion Theory,"* Int. J. of Geomech., 8(6), pp. 355~365;

9. Ghandeharioon, A., Indraratna, B., and Rujikiatkamjorn, C., 2010, *"Analysis of Soil Disturbance Associated with Mandrel-Driven Prefabricated Vertical Drains Using an Elliptical Cavity Expansion Theory,"* Int. J. of Geomech., 10(2), pp. 53~64;

10. Basu, P., Basu, D., and Prezzi, M., 2008, *"Equal-Strain Analysis of Pvd-Enhanced Consolidation Considering Soil Disturbance,"* Goa, India;

11. Basu, D., Prezzi, M., and Madhav, M. R., 2010, *"Effect of Soil Disturbance on Consolidation by Prefabricated Vertical Drains Installed in a Rectangular Pattern,"* Geotech. and Geolog. Eng., 28(1), pp. 61~77;

12. Walker, R., and Indraratna, B., 2006, *"Vertical Drain Consolidation with Parabolic Distribution of Permeability in Smear Zone,"* J. of Geotech. and Geoenvir. Eng., 132(7), pp. 937~941;

13. Rujikiatkamjorn, C., and Indraratna, B., 2009, *"Design Procedure for Vertical Drains Considering a Linear Variation of Lateral Permeability within the Smear Zone,"* Can. Geotech. J., 46(3), pp. 270~280;

14. Basu, D., and Prezzi, M., 2007, *"Effect of the Smear and Transition Zones around Prefabricated Vertical Drains Installed in a Triangular Pattern on the Rate of Soil Consolidation,"* International Journal of Geomechanics, 7(1), pp. 34~43;

15. Chung, S. G., Lee, N. K., and Kim, T. H., 2009, *"Hyperbolic Method for Prediction of Prefabricated Vertical Drains Performance,"* J. OF Geotech. & Geoenvir. Eng., 135(10), pp. 1519~1528;

16. Indraratna, B., and Redana, I. W., 2000, *"Numerical Modeling of Vertical Drains with Smear and Well Resistance Installed in Soft Clay,"* Can. Geotech. J., 37(1), pp. 132~145;