Numerical Analysis to Quantify the Influence of Smear Zone Characteristics on Preloading Design in Soft Clay

Analyses numériques pour quantifier l'influence des caractéristiques de la zone endommagée sur la conception de préchargement dans les argiles molles

Parsa-Pajouh A., Fatahi H., Khabbaz B.
School of Civil and Environmental Engineering, University of Technology Sydney (UTS), Sydney, Australia

ABSTRACT: In this paper, the effects of uncertainties of smear zone characteristics induced by installation of prefabricated vertical drains on the preloading design are numerically investigated. FLAC 2D finite difference software with additional developed subroutines has been employed to conduct the numerical simulations. The finite difference analyses have been verified using a case study. Furthermore, a comprehensive parametric study is conducted to investigate the influence of smear zone permeability and extent on the model predictions. Results of this study indicate that the assumptive properties for smear zone characteristics may result in inaccurate predictions of ground deformations and pore water pressures. This may lead to early removal of the surcharge in the construction process causing excessive post construction settlement. It is recommended to practising engineers to use results of trial preloading to back calculate the required smear zone characteristics in the early stages of embankment construction to optimize the design.

RÉSUMÉ : Dans cet article, les effets des incertitudes des caractéristiques de la zone endommagée induites par l'installation des drains verticaux préfabriqués sur la conception du préchargement sont étudiés par une méthode numérique. Le logiciel de différences finis FLAC2D avec sous-programmes additionnels a été utilisé afin de réaliser les simulations numériques. Les analyses de différences finis ont été vérifiées à l'aide d'une étude de cas. Par ailleurs, une étude paramétrique approfondie est effectuée afin d'investiguer l'influence de la perméabilité de la zone endommagé sur les prédictions du modèle. Les résultats de cette étude montrent que les propriétés supposées pour les caractéristiques de la zone endommagé peuvent entrainer des prédictions incorrectes de déformations du sol et de pressions interstitielles. Cela peut conduire à un retrait précoce de la surcharge dans le processus de construction engendrant un tassement post-construction excessive. Il est recommandé aux ingénieurs d'utiliser les résultats de l'essai de préchargement afin de calculer les caractéristiques requises de la zone endommagée pour optimiser la conception.

KEYWORDS: FLAC, numerical analysis, preloading, smear zone, vertical drain

1 INRODUCTION

Finding efficient ground improvement techniques to modify the soft soil properties, considering the project time limitation and the construction cost has been a continuous challenge for the construction companies. Various ground improvement methods have been proposed to improve the strength properties of the soft soil. In the last two decades, employing prefabricated vertical drain (PVD) assisted preloading has been recognised as a very efficient ground improvement method for sites with deep soft soil deposits (Holtz et al. 1991; Shang et al. 1998; Indraratna et al. 2005). Installation of the prefabricated vertical drains using mandrel, induces disturbance of the soil surrounding the drain, resulting in a smear zone of reduced permeability adversely affecting the consolidation process. Predicting the soil behaviour surrounding the drain requires an accurate estimation of the smear zone properties. Generally, two major parameters are proposed to characterise the smear zone; the permeability (k_s), and the extent (r_s) of the smear zone. Figure 1 illustrates the cross section of prefabricated vertical drains surrounded by smear zone, which are installed in rectangular pattern. Determining both the smear zone extent and its permeability is a challenging task. According to literature, very diverse values are reported for the permeability ratio (k_h/k_s) and extent ratio (r_s/r_m), which are illustrated in Figure 2. The proposed range shows that the extent of the smear zone (r_s) may vary between 1.6 to 7 times of the drain radius (r_w) or, 1.0 to 6 times of mandrel equivalent diameter (r_m). The proposed range for the permeability ratio (k_h/k_s) is 1.3 to 10, where k_h is the horizontal permeability of the intact soil.

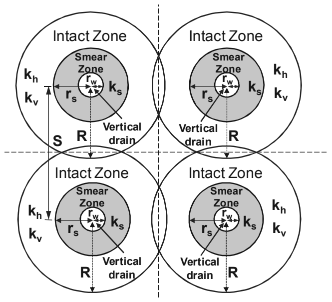


Figure 1. Cross section of PVD surrounding by smear zone

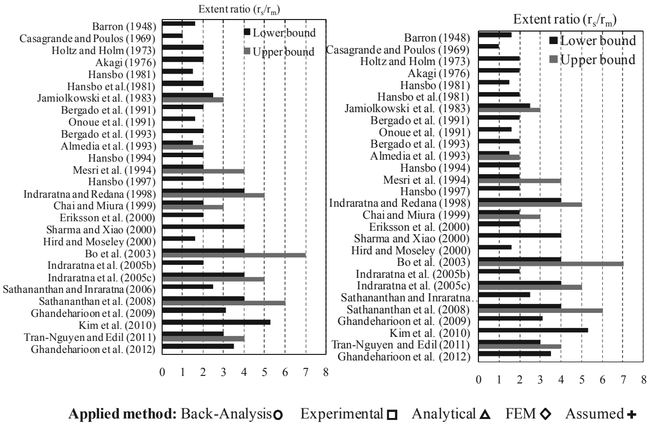


Figure 2. Proposed values for smear zone characteristics

It can be observed that wide ranges are proposed for k_h/k_s and r_s/r_m and there is no definite method to predict these parameters precisely to be used by practising engineers. The assumptive properties for smear zone characteristics may result in inaccurate predictions of the ground behaviour. This can lead to early removal of surcharge in construction process resulting in excessive post construction settlement. Therefore, it is essential to study the influence of the uncertainties in the smear zone size and its permeability on the preloading design to improve the performance of soft deposits. Thus, a numerical code using FLAC 2D has been developed in this study to investigate the uncertainties of PVD smear zone characteristics on the preloading design which can be used to back calculate smear zone characteristics for actual preloading projects.

2 NUMERICAL MODELLING

In the present study, FLAC 2D v6.0 has been employed to model the PVD assisted preloading process focusing on smear zone uncertainties. Required new subroutines have been written using the built-in programming language FISH (FLACish) to tailor analyses to suit specific needs for the parametric study, giving the following unique advantages to the developed code for this study; (i) automatic mesh generation process by entering the required parameters to modify the grid pattern inside and outside the smear zone; (ii) ability to change different parameters such as the model dimensions, vertical drain properties, subsoil profile, smear zone characteristics and preloading conditions; (iii) the option to define the exact location of desired points to generate and plot any future history graphs; and (iv) automatic solving process based on the modified input data. Chittagong Sea Port in Bangladesh with 3.0 m high embankment on 9 m deep soft clay, has been selected for the numerical simulations and verification of the developed code and subroutines.

2.1. *Case Study: Chittagong Sea Port in Bangladesh*

According to Dhar et al. (2011), a container yard has been constructed at Chittagong Port, the largest sea port in Bangladesh, for handling loaded containers. The site is located on the bank of Karnafully river beside the Bay of Bengal in the Indian Ocean. The yard covers an area of 60,700 m^2 and was designed to support a container load producing a contact pressure of approximately 56 kPa. Geotechnical investigations revealed the presence of a soft to very soft clayey silt/silty clay deposit with a thickness of approximately 7 m (Figure 3).

Preloading with prefabricated vertical drains was adopted to preconsolidate the compressible soft deposits, which was followed by the field monitoring. Vertical drains were installed down to the depth of approximately 9 m below the ground level in square patter to cover the full depth of the soft clay. A surcharge load consisting of 3.0 m high fill of sand was placed for preloading. Surcharge material was placed in two layers of approximately equal thickness. The sides of the surcharge load were kept vertical along the boundaries of the area using sand bags and brick stacks. Figure 3 shows a profile detailing the ground improvement work schematically. In addition, Figure 4 shows the construction history of the embankment.

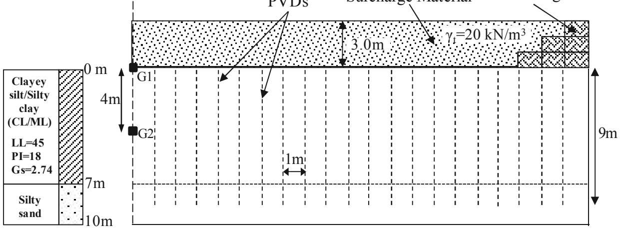


Figure 3. Cross section of constructed embankment

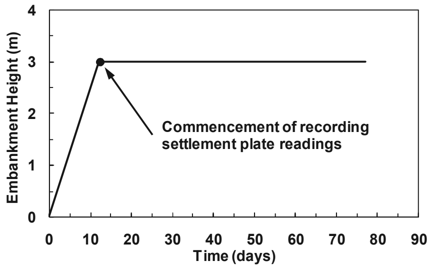


Figure 4. Construction history (Chittagong Port embankment)

FLAC 2D numerical code incorporating modified Cam-Clay constitutive soil model has been employed to simulate Chittagong Port preloading process applying plane strain conditions. The zero excess pore water pressure has been considered along the vertical drains and the ground surface boundary to model the PVD and surface drainage, respectively. Adopted soil properties in the numerical analysis are summerised in Table 1.

Table 1. Adopted soil properties (after Dhar et al. 2011)

Layer	Soil type	M	λ	κ	ν	e_o	γ_s kN/m^3	k_h 10^{-9}m/s	k_h/ k_v
Clayey Silt	Soft soil	0.94	0.13	0.026	0.3	1.28	14.0	2.31	1.5

The equivalent plane-strain permeability (k_{hp}) proposed by Indraratna and Redana (2000) has been used in the numerical analysis.

$$(k_{hp}/k_h) = 0.67 / [(\ln(n)-0.75] \quad (1)$$

$$(k_{sp}/k_{hp}) = \beta / [(k_{hp}/k_h) [(\ln(n/s)+(k_h/k_s) \ln(s)-0.75]-\alpha] \quad (2)$$

$$\alpha = 2(n-s)^3 / [3(n-1)n^2] \quad (3)$$

$$\beta = [2(s-1) / (n-1)n^2] * [n(n -s-1)+1/3\ (s^2+s+1)] \quad (4)$$

where, k_h and k_{hp} are axisymmetric and plane-strain horizontal permeability values of intact zone respectively, k_s and k_{sp} are axisymmetric and plane-strain permeability values of smear zone, respectively, α and β are geometric coefficients, n is the spacing ratio equal to B/b_w where B and b_w are equivalent plane-strain radius of the influence zone and radius of the drain respectively, and $s=r_s/r_w$. The value of k_h needs to be determined first (laboratory or field), then k_{hp} can be calculated using Equation (1). When k_{hp} is known, k_{sp} can be obtained from Equation (2). The discretised plane- strain finite-difference mesh composed of quadrilateral elements is shown in Figure 5, where only half of the trial embankment is considered by exploiting symmetry.

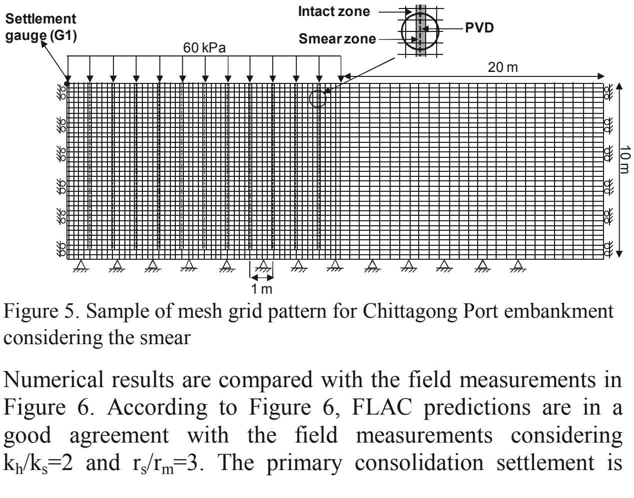


Figure 5. Sample of mesh grid pattern for Chittagong Port embankment considering the smear

Numerical results are compared with the field measurements in Figure 6. According to Figure 6, FLAC predictions are in a good agreement with the field measurements considering k_h/k_s=2 and r_s/r_m=3. The primary consolidation settlement is predicted to be approximately 258 mm. As illustrated in Figures 4 and 6, the field settlement is measured immediately after placing the surcharge to the full height of 3 m (after 12 days).

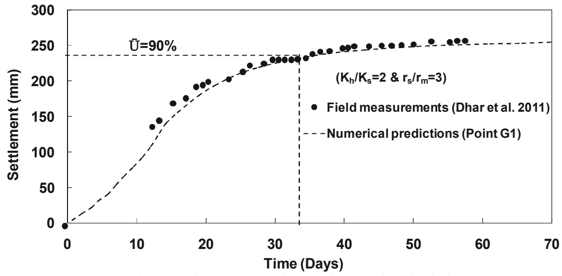


Figure 6.Comparison of numerical results with filed data

3 PARAMETRIC STUDY AND DISCUSSION

Parametric studies have been conducted to investigate the influence of the smear zone characteristics on the preloading design simulating Chittagong Port case study with the details presented in the previous section. For this purpose, k_h/k_s (permeability ratio) and r_s/r_m (extent ratio) have been changed from 2 to 5. Figure 7 illustrates the parametric study results for settlement-time relationships.

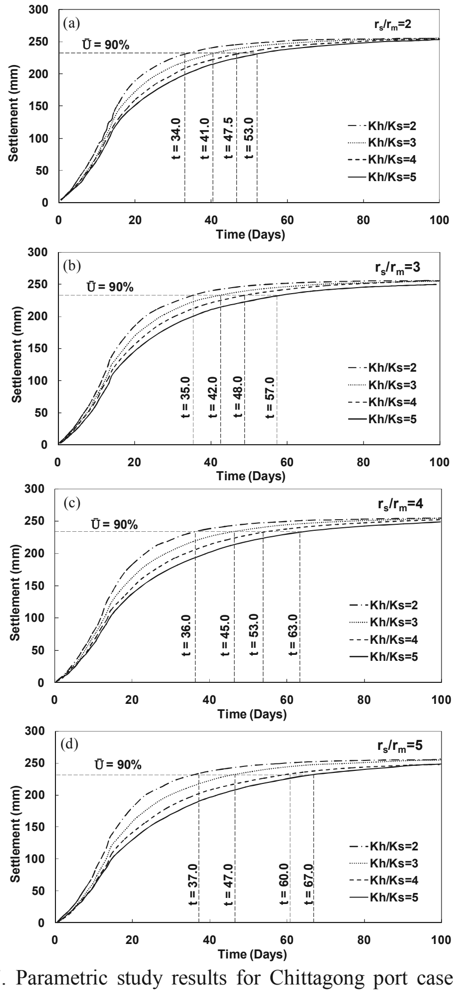


Figure 7. Parametric study results for Chittagong port case history at point G1; (a) r_s/r_m=2; (b) r_s/r_m=3; (c) r_s/r_m=4; and (d) r_s/r_m=5

According to Figure 7, the settlement curves are converged to a unique value of approximately 258 mm, which is the primary consolidation settlement. The required time to obtain 90% of primary consolidation settlement (232 mm) has been considered to investigate the effect of smear zone properties on consolidation process. According to Figure 7a, the minimum time of 34 days is needed to achieve 90% degree of consolidation, considering k_h/k_s=2 and r_s/r_m=2. When smear zone properties are k_h/k_s=5 and r_s/r_m=5, the required time would be the maximum and equal to 67 days, which is approximately twice longer than the minimum (see Figure 7d). According to the settlement curves in Figure 7, the influence of smear zone permeability variations is more critical when the smear zone extent ratio is larger. For instance the required time to obtain 90% degree of consolidation has been increased by 56% (from 34 days to 53 days) changing the permeability ratio from 2 to 5 considering the extent ratio equal to 2, while this boost is 80% (from 37 days to 67 days) for extent ratio of 5.

The general trend in Figures 7(a)-7(d) shows that changing the permeability ratio in a smaller range results in large variations of the required time to obtain 90% degree of consolidation considering a constant extent ratio. According to Figure 7(a), the consolidation time is increased by 23% by varying the permeability ratio from 2 to 3, while this change is 17% and 12% when the permeability ratio is changed from 3 to 4 and 4 to 5, respectively.

Figure 8 illustrates the numerical parametric study results investigating the influence of the smear zone properties on the excess pore water pressure (EPWP) dissipation. Graphs are plotted for point G2 located at the depth of 4 m (see Figure 3). Figure 8 confirms that increasing the permeability and extent ratios prolongs the pore water pressure dissipation process considerably. According to Figure 8, the permeability ratio is more critical parameter than the extent ratio, although the influence of extent ratio variation on the consolidation time can not be neglected. For example, according to Figure 8b, there is 160% difference between the predicted excess pore pressure values after 34 days (90% of the field degree of consolidation) for k_h/k_s=2 (EPWP=13 kPa) and k_h/k_s=5 (EPWP=34 kPa), while keeping r_s/r_m=3.

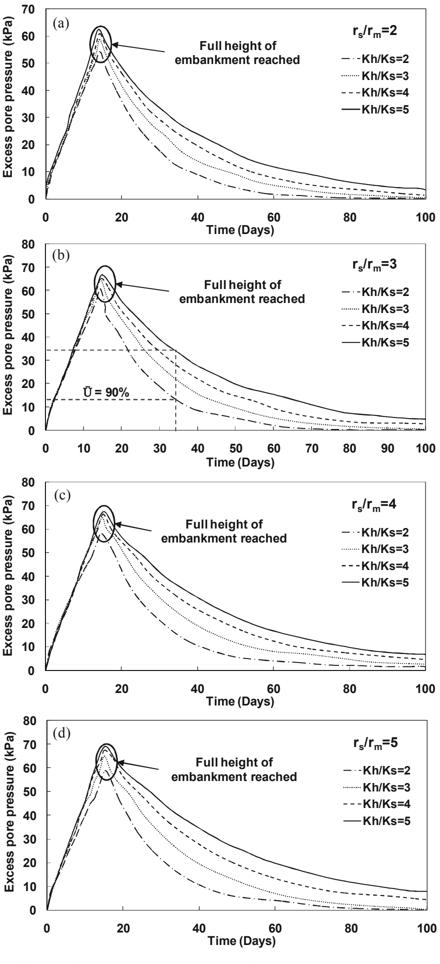


Figure 8. Effect of smear zone properties on excess pore water pressure dissipation for Chittagong port case history at point G2

The required time to obtain 90% degree of consolidation for different smear zone properties is illustrated in Figure 9 using parametric study results, which presents a better interpretation of the effects of the smear zone properties on consolidation time. According to Figure 9, the consolidation time significantly depends on the smear zone permeability and extent. For example, assuming r_s/r_m=2, for the case with k_h/k_s=2 and k_h/k_s=5, the required times to obtain 90% degree of consolidation are approximately 33 days and 53 days, respectively, indicating 60% difference. It can be noted that the difference is more significant for larger values of r_s/r_m.

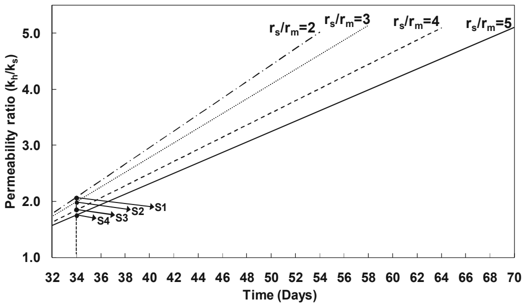


Figure 9. Predicted time to obtain 90% degree of consolidation

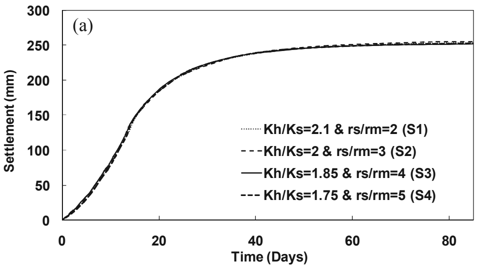
Figure 9 clearly indicates that the smear zone extent ratio (r_s/r_m) is an important parameter influencing the consolidation time and cannot be neglected. Varying r_s/r_m in the range of 2 to 5, assuming k_h/k_s as a constant parameter can influence the required consolidation time by more than 25%. Combined effects of uncertainties in the smear zone extent and permeability will result in momentous changes of consolidation time. Results presented in Figure 9 indicate that the influence of uncertainties in r_s/r_m becomes more important when permeability of smear zone decreases.

According to the back calculation results presented in Figure 6, the predicted settlement curve is in the best agreement with the field measurements considering smear zone properties of k_h/k_s=2 and r_s/r_m=3. The required time to obtain 90% degree of consolidation for this condition is equal to 34 days, which is highlighted as point S2 in Figure 9. A vertical line is plotted from $t_{90\%}$= 34 days, which intersects the set of lines at points S1, S2, S3 and S4. Smear zone properties at these points are summarised in Table 2.

Table 2. Back calculated smear zone properties to achieve $t_{90\%}$= 34 days

Point	S1	S2	S3	S4
k_h/k_s	2.10	2.0	1.85	1.75
r_s/r_m	2	3	4	5

Numerical analyses applying developed FLAC code have been conducted to compare the settlement and excess pore water pressure variations against the consolidation time. Different combinations of smear zone extent and permeability may result in the same $t_{90\%}$= 34 days and predictions are presented in Figure 10.



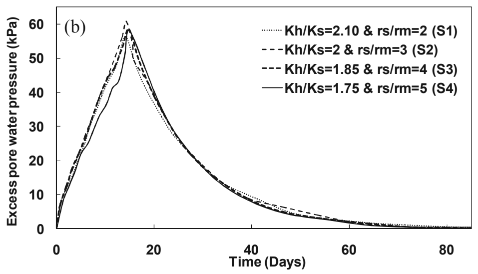


Figure 10. FLAC analysis results for points in Table 2 (a) Settlement variation; (b) Excess pore water pressure dissipation

Figure 10 shows that the curves for the settlement variations and the excess pore water pressure dissipations with time follow the same trend for points S1, S2, S3 and S4. Therefore, smear zone properties of any of these points can be adopted for the practical design purposes.

4 CONCLUSIONS

Preloading time during consolidation process can significantly be affected by formation of the smear zone in the vicinity of the prefabricated vertical drains (PVDs). Smear zone is a reduced permeability area induced by mandrel insertion that halts the consolidation process. Available literature proposes a wide range for the smear zone extent and permeability and yet there is no definite prediction method that can be used to estimate the extent of smear zone and its permeability to be used in the design procedure. In this study, numerical analyses have been employed to investigate the effects of uncertainties of smear zone characteristics on the preloading design. FLAC 2D software has been employed to develop a numerical code assisting with the parametric study and back calculating smear zone properties. The verification exercise on Chittagong port case history confirms the validity of the developed numerical code. According to the parametric study results the properties of the smear zone have key roles on the required consolidation time to achieve a certain soil strength and stiffness satisfying both bearing capacity and settlement design criteria. Therefore, accurate estimation of the properties of smear zone based on the soil type and the installation method is vital for the ground improvement projects adopting PVD assisted preloading. Results of this study indicate that assumptive properties for smear zone characteristics may result in inaccurate predictions of ground deformations and pore water pressures. This can lead to early removal of surcharge in construction process resulting excessive post construction settlement. Thus, it is recommended to practising geotechnical engineers to back calculate the smear zone properties using a trial construction similar to the future construction procedure.

5 REFERENCES

Dhar, A. S., Siddique, A. and Ameen, S. F. 2011. Ground improvement using pre-loading with prefabricated vertical drains. *International Journal of Geoengineering Case Histories*, 2(2), 86-104.

Holtz, R.D., Jamiolkowski, M.B., Lancellotta, R. and Pedroni, R. 1991. Prefabricated vertical drains: design and performance. *CIRIA, Butterworth-Heinemann*, London.

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(1), 132-145.

Indraratna, B., Rujikiatkamjorn, C. and Sathananthan, I. 2005. Analytical and numerical solutions for a single vertical drain including the effects of vacuum preloading. *Canadian Geotechnical Journal*, 42(4), 994-1014.

Shang, J.Q., Tang, M. and Miao, Z. 1998. Vacuum preloading consolidation of reclaimed land: a case study. *Canadian Geotechnical Journal*, 35(5), 740-749.