J. Civil Eng. Mater.App. 2022 (Jun); 6(2): 113-122

Journal of Civil Engineering and Materials Application
Journal home page: http://jcema.com

Received: 02 February 2022 • Accepted: 11 April 2022

Research

doi: 10.22034/jcema.2022.347725.1086

Numerical Study of efficiency of the Vacuum Preloading in Weak Clay Treatment (a case study)

Mohammad Mehdi Pardsouie [1]*, Mohammad Hadi Pardsouie [2], Seyed Mohammad Ali Zomorodian [3], Mehdi Mokhberi [4]

[1] PhD candidate, Department of geotechnical engineering, Estahban Branch, Islamic Azad University, Estahban, Iran.
[2] Department of geotechnical engineering, Estahban Branch, Islamic Azad University, Estahban, Iran.
[3] Associate professor, Department of Water Engineering, Faculty of Agriculture, Shiraz University, Shiraz, Iran.
[4] Assistant professor, Department of geotechnical engineering, Estahban Branch, Islamic Azad University, Estahban, Iran.

*Correspondence should be addressed to Mohammad Mehdi Pardsouie Department of geotechnical engineering, Estahban Branch, Islamic Azad University, Estahban, Iran. Tel: +987137307887; Fax: +987137307887; Email: m.m.pardsouie@gmail.com.

ABSTRACT

This paper describes the behavior of soft soil foundation under Surcharge and with and Without prefabricated vertical drains (PVDs) or Vacuum Preloading base on a trial embankment which was built in Bangkok International Airport, Thailand. An analytical solution considering the variation of soil permeability and compressibility was adopted. Three scenarios were modeled and analyzed for Bangkok airport as: Model A: Application of surcharge load alone (i.e., no vacuum and PVD installation), Model B: Application of surcharge load combined with PVD (i.e., no vacuum application), Model C: Application of surcharge load combined with PVD and 60 kpa constant vacuum preloading and Model D: Application of surcharge load combined with PVD and field vacuum that was applied on site. The associated settlements at the embankment centerline are predicted and compared with the available field measurement. The field data show that the efficiency of this soil treatment technique depends on the magnitude and distribution of vacuum pressure. The height of surcharge and consolidation time can be significantly reduced in comparison with the conventional method of surcharge alone or surcharge and pvd alone. The findings of this study are expected to be useful to design engineers involved in the construction of embankments on weak grounds.

Keywords: surcharge, soil treatment, vacuum consolidation, PVD

1. INTRODUCTION

Although the technology of vacuum preloading is highly used in many projects all over the world, it is still unknown in Iran. Due to the rapid increase in population in many countries, the construction activities have become concentrated in low-lying marshy areas and reclaimed lands, which are comprised of highly compressible weak organic and peaty soils of varying thickness. These soft deposits formed by peat or clay have very low bearing capacity and excessive settlement characteristics, affecting major infrastructure including buildings, roads, and rail tracks [1-3]; Therefore, it is necessary to stabilize the existing soft soils before commencing any construction activities in order to prevent excessive and differential settlements. The technique of installing prefabricated vertical drains (PVDs) combined with fill surcharge and vacuum preloading has been used to avoid the unfavorable stability issues relating to high surcharge embankments. The effectiveness of the PVDs combined with vacuum preloading has been discussed by [4] and [5]. In this method, the vacuum head can be distributed to a greater depth of the subsoil using the PVD system. Also, the consolidation period due to the stage construction can be minimized [6-8].

In order to predict the behavior of soft ground improved by PVDs, a unit cell theory representing a single drain enclosed by a soil within a cylindrical influence zone by assuming equal strain was proposed by [3] and [9]. The single drain analysis cannot successfully predict the overall consolidation in a large project where hundreds of drains are installed. Single drain analysis with small strain condition can only be applied at the embankment centerline where the lateral displacements are zero. Elsewhere, towards the embankment toe, the single drain analysis becomes inaccurate due to the no uniform surcharge load distribution, large strain conditions, increased lateral yield, effects of changing embankment geometry, and heave at the embankment toe [10]. Hird, Indraratna and Chai [11-13] introduced an equivalent two-dimensional (2D) plane strain approach to predict the soft clay behavior improved by the vertical drain system. The embankment loading is considered a strip load. This method can be conveniently simulated as a multidrain system in numerical finite-element modeling (FEM) modeling. In anticipation of the construction of a new airport in Bangkok, Thailand, full-scale test embankments were constructed on the soft clay at the site to study the effectiveness of prefabricated vertical drains (PVDs) for accelerating the consolidation and dissipation of the excess pore-pressures resulting from fill placement. The results of the field tests have been studied and analyzed by two different research groups: one at the Asian Institute of Technology in Thailand, the other at the University of Wollongong in Australia. The findings are presented in two papers listed in the reference section [13-15].

2. MATERIALS AND METHODS

The Bangkok Airport is situated in a wet area where there is about 10 m of soft clay under a 2 m surficial over-consolidated crust [16]. Stiff clay extending to a depth of 20 to 24 m underlies the soft clay. For analysis purposes the subsoil is divided into three layers as shown in Figure 1 and the lower stiff clay is ignored [15].

The PVD drains were installed to a depth of 12 m. The embankments were constructed to a height of 4.2 m with 3H: 1V side slopes. The base areas were approximately 40 x 40 m. There were actually 1 m high berms around the base extending out 5 m but this detail is not included in the illustrative analysis presented here. A one-meter thick sand blanket was placed on the site as a construction working pad. The drains were installed from on top of the sand pad. The sand blanket was presumably also included to ensure that there would be no build-up of excess pore-pressures at the base of the embankment and to drain away water being squeezed out of the clay. The position of the drains in the two-dimensional analysis is shown in Figure 2 The horizontal spacing is 1.5 m except at the embankment toe where the spacing is 2 m (this was done purely for modeling convenience so that there is a drain at the embankment toe). Figure 2 also shows the layering used to simulate the sequential fill placement. The sand blanket is not included in the model as a separate material. The effect of the sand can be modeled by specifying a zero-pressure boundary condition along the ground surface. The physical implication is that there will be no build-up of positive pore-pressures at the ground surface. Any water arriving at the ground surface will have the opportunity to disappear through the sand somehow. The boundary condition simulates this effect. This is much simpler than trying to include the sand blanket in the model but achieves the same objective. The Modified Cam-Clay constitutive relationship is used here for the soft clay. The clay is essentially normally to slightly over-consolidated. It appears that the degree of over-consolidation varies somewhat with depth. For the illustrative analysis here the clay is treated as having an OCR of 1.5. Also, the Lambda and Kappa values were taken to be the same for the very soft and the lower soft clay. This gives settlements closer to what was measured. The weathered surficial clay is over-consolidated and consequently it is acceptable to treat this layer as behaving in a linear-elastic manner. Using a linear-elastic constitutive relationship also helps with maintaining numerical convergence near the ground surface where the stresses approach zero. The sand fill is also treated as a soft linear-elastic material and the soil parameters are viewed as being total-stress parameters. This avoids having to deal with pore-pressures in the fill. These simplifying assumptions are acceptable because we are primarily interested in using the fill as a means to apply the load. The actual stress-strain response of the sand is not of significant importance [16].

2.1. HYDRAULIC CONDUCTIVITY

The most critical parameter in an analysis like this is the hydraulic conductivity (coefficient of permeability). By the very nature of the deposition process, the conductivity can vary significantly. In addition, the stratification tends to make the conductivity somewhat higher in the horizontal direction than in the vertical direction that is shown in Figure 1 Furthermore, the insertion of the drains disturbs the soil around the drain and alters the conductivity. The disturbed zone is often called a smear zone [13]. Also, drains are installed on some kind of pattern and spacing and flow to the drains is two-dimensional in plain view. Analyses however are generally more conveniently carried out in a 2D section. Indraratna and Redana [10] have done extensive studies on how to adjust conductivities for a 2D plane-strain analysis, how to assess the smear zone thickness and conductivity and how to model the size of the drain itself. The details are in the paper reference cited at the end. A brief summary is presented here to show how these effects can be accounted. The flow is predominately horizontal to the drains and consequently most of the discussion centers around the horizontal conductivity. The vertical conductivity can be a ratio of the horizontal conductivity but this is not all that important since there is very little or no vertical flow that can be a practical and realistic assumption for FEM modeling.

2.2. DRAIN THICKNESS

The equivalent thickness of a drain for a 2D analysis can be taken as [17]:

$$d_w = \frac{2\ \ a+b}{\pi} \tag{1}$$

Where a is the thickness of the PVD drain and b is the width. So for a typical drain that is 4 mm thick and 100 mm wide, the 2D model thickness can be 66 mm or say 0.06 m. The drain can be represented with an interface element 0.06 m thick, for example.

2.3. PLANE STRAIN CONDUCTIVITY

The simplest form of converting from an axisymmetric to plane-strain conductivity is [16]:

$$\frac{K_{hp}}{K_h} = \frac{0.67}{\left[\ln\ n\ -0.75\right]} \tag{2}$$

Where n is a ratio of the drain spacing D to the equivalent drain thickness dw. If the drain spacing is 1.5 m and the equivalent drain thickness is 0.06, then n is 25. The plane-strain conductivity then is about 27 percent of the corresponding axisymmetric horizontal conductivity. This is in the absence of any well resistance and any effect of a smear zone. As an easy figure to remember, the plane-strain conductivity is about a quarter of the corresponding axisymmetric conductivity.

2.4. SMEAR ZONE

Indraratna [2] suggest that the radius of a smear zone around a drain will typically be five (5) times the equivalent radius of the mandrel. For a mandrel that is 45 mm thick and 125 mm wide the equivalent radius is about 55 mm. The radius of the smear zone then is 270 mm (0.27 m). For a 2D analysis the smear zone thickness would then be 0.54 m. Indraratna and Redana [2] have presented an equation to estimate the conductivity of the smear zone which involves various dimensional ratios and conductivity ratios. We will not go into all the details here. They are available in the [13] paper for those interested. As a broad rule the horizontal smear zone conductivity is about 10 percent of the horizontal plane-strain conductivity. For the cases presented by Indraratna and Redana [2], the ratio varies between 8 to 16 percent. Stated another way, the disturbance resulting from the insertion of the drain reduces the conductivity by about an order of magnitude in the smear zone.

2.5. GOVERNING CONDUCTIVITY

With flow across a layered system, the less permeable layer can quickly dominate the head loss and in turn govern the flow behavior. Consider the simple layered system in Figure 3. Each segment is 1 m long. A total head (H) of 10 m is applied on the left end and a total head of 1.0 m on the right end. The conductivity of the right segment is 10 times less than on the left. The head loss distribution across the system is as shown in Figure 4. Note that most of the head loss occurs in the less conductive material and also that the gradient is much higher in the less conductive material. In other words, the less conductive material on the right essentially governs the flow.

For a layered system like this we can compute an equivalent conductivity as follows [2]:

$$K = \frac{d}{\left(\frac{d_1}{k_1} + \frac{d_2}{k_2}\right)} \tag{3}$$

Say d1 is 1 m, d2 is 1 m, k1 is 10 m/sec and k2 is 1 m/sec. The blended equivalent K then is 1.818 m/sec.

We can use this information to represent the conductivity of the native clay together with the smear zone rather than create separate geometric regions for the two different zones. This makes the numerical modeling easier.

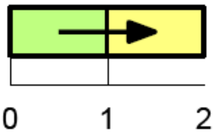


Figure 1. One element conductivity

The implication for our analysis here is that the smear zone around the drain dominates the dissipation of the excess pore-pressures and in turn the rate of consolidation.

2.6. MODELING CONDUCTIVITIES

Indraratna and Redana [2] presented a table of conductivities used in their analyses. For a 1.5 m drain spacing the conductivities are as in the following table. The blended K is computed based on drain spacing of 1.5 m (radius = 0.75 m) and a smear zone thickness of 0.54 m (radius = 0.27 m). The conductivities have been converted to m/day so that the time sequencing can be in days. For discussion and mental interpretation purposes it is worth noting that the soft clay at depth has a conductivity of about one order of magnitude less than the upper weathered clay.

2.7. CHANGES IN CONDUCTIVITY DUE TO COMPRESSION

The conductivity of soft soils can change significantly as the soil compresses and the void ratio decreases. Geostudio 2019, used in this paper has a mechanism whereby the conductivity can be adjusted as the effective stress increases in response to the dissipation of the excess pore-pressure. This is an indirect way of adjusting the conductivity resulting from a decrease in void ratio. One way to define data for such an adjustment in conductivity is from the results of an odometer test. The conductivity can be computed for each load increment in an odometer test as follows:

The average effective stress and change in void ratio for each load increment can be determined from the test results. The coefficient of compressibility is [18]:

$$a_v = \frac{e_1 - e_2}{\sigma_2' - \sigma_1'} \tag{4}$$

The average vertical effective stress is:

$$\sigma_{ave}' = \frac{\sigma'_2 + \sigma_1'}{2} \tag{5}$$

For each load increment a void ratio versus time plot is available which can be used to determine the coefficient of consolidation Cv. Once these values are known the conductivity can be computed from:

$$K = \frac{C_v \gamma_w a_v}{1 + e_o} \tag{6}$$

In this way K can be determined for the average vertical effective stress for each load increment.

2.8. 2D FIELD ANALYSIS

The commercial Geostudio 2019 FEM code coupled Stress/Pwp analysis was used in this paper. Complementary information on modelling procedure and site soil characteristic can be found in [19-21]

The following 3 models were analyzed:

Model A: Application of surcharge load alone (i.e., no vacuum and PVD installation), Model B: Application of surcharge load combined with PVD (i.e., no vacuum application),

Model C: Application of surcharge load combined with PVD and idealized 60 kpa constant vacuum preloading.

Model D: Model C: Application of surcharge load combined with PVD and in field applied vacuum pressure that is shown in fig 3b. The results are shown in fig 4.

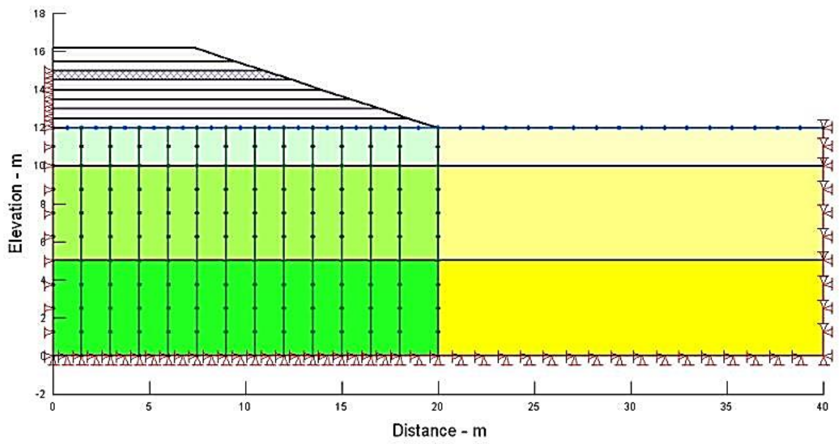
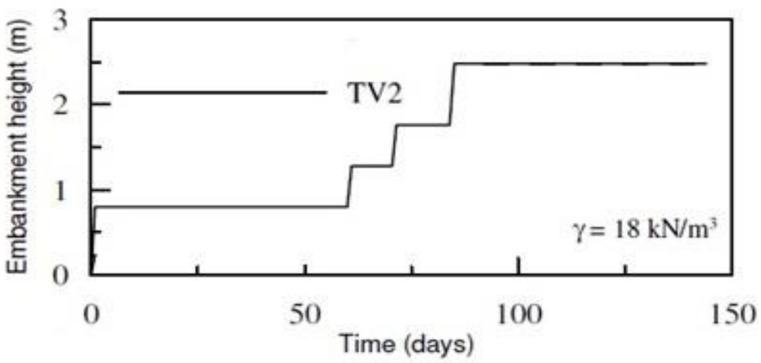
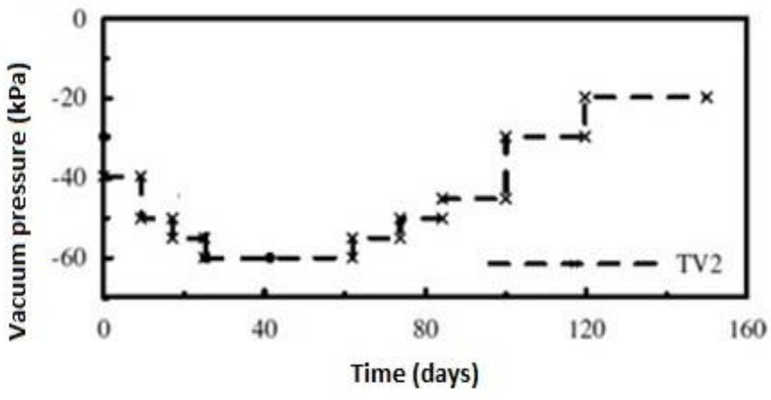


Figure 2. A schematic view of the test embankment and its boundary condition

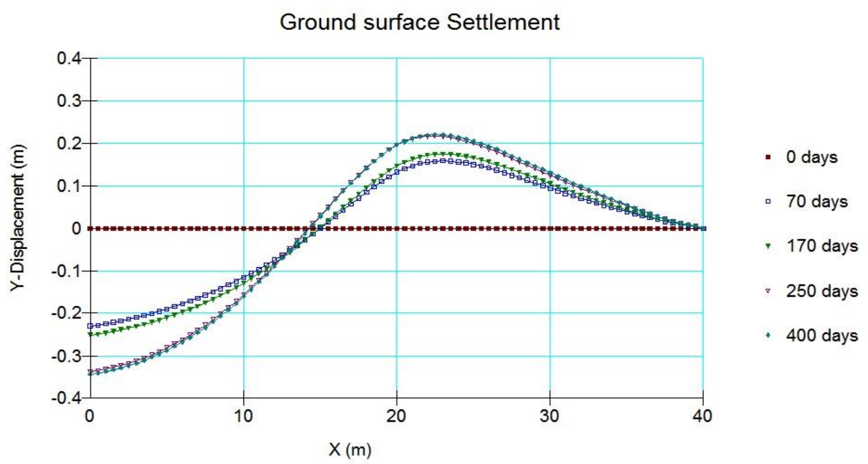


(a)

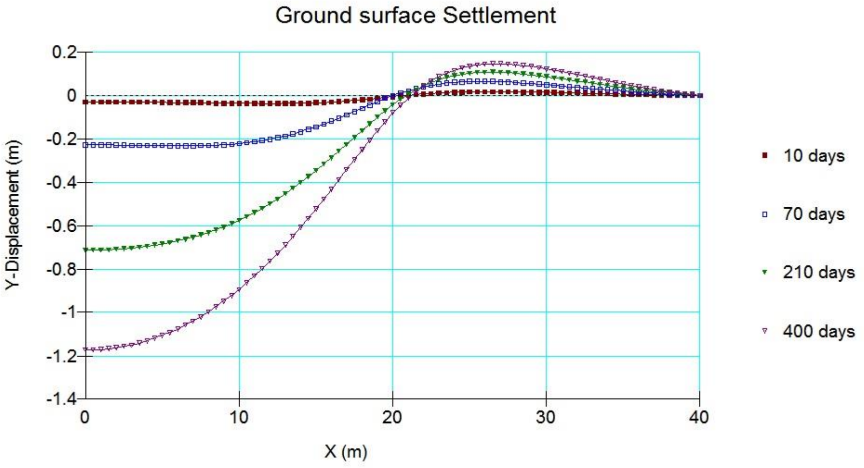


(b)

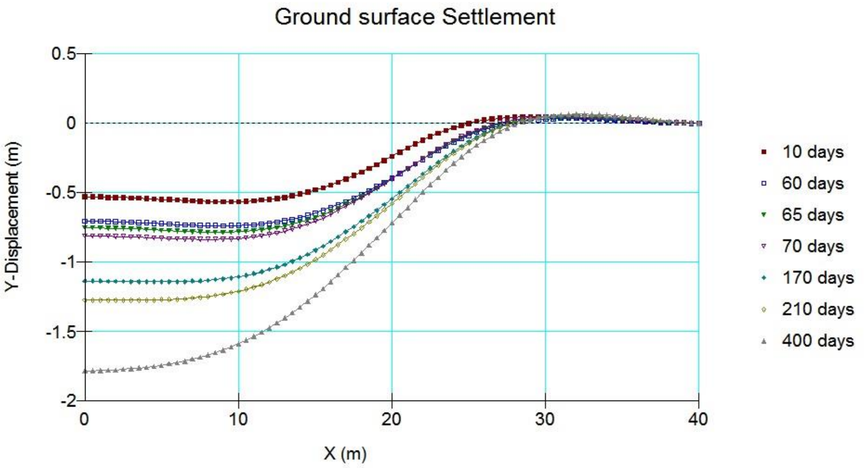
Figure 3. (a)Sequential placement of surcharge embankment vs. time (b) vacuum pressure application vs. time [22]



(a)



(b)



(c)

Figure 4. Vertical Ground Surface Displacement in a) model A b) model B c) model C

2.9. CONSTRUCTION SEQUENCE FOR EMBANKMENT

Since the embankment in Thailand was constructed in sequence according to fig 2, the same sequence has been applied in model as stage construction to reflect the real field situation.

2.10. VACUUM PRESSURE

The application of vacuum pressure was a challenge in the described project as it is clear in fig 3b. since there were a lot of leakage in sand blanket and malfunctions in system and also the flood in the construction area [23], only for a limited time the pressure of 60 kpa could be maintained.

3. RESULTS AND DISCUSSION

It is apparent that applying vacuum on PVD 's has raised the rate of ground settlement considerably as it is completely visible in fig 4. In projects with limited time, PVD – vacuum preloading system can be an idealized option to be considered. The verification of the model for Bangkok airport is shown in fig 6 that is actually the model D in this article. As it can be seen in fig 6, a good agreement between the predicted and measured settlement is obtained. If the obstacles that was mentioned in section 2.10 didn't occur, the settlement of 1.78 m was reachable that is model C in this literature.

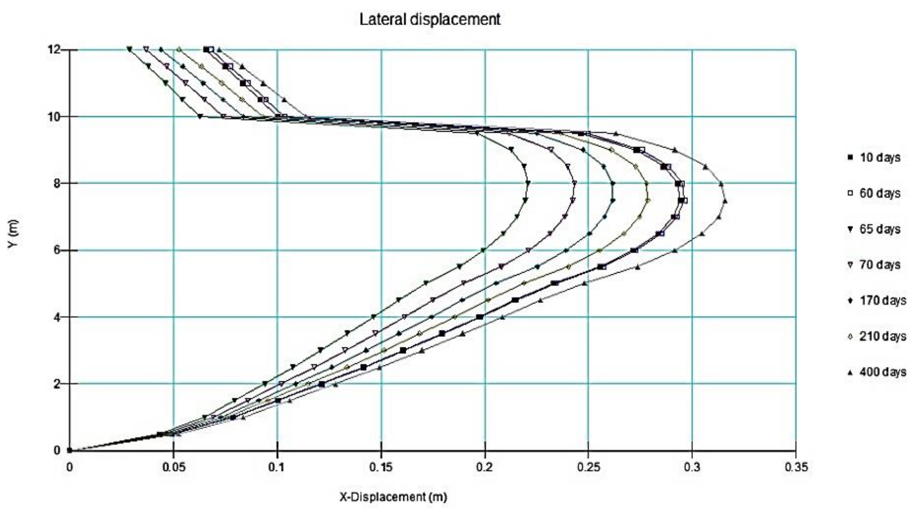
3.1. THE MODELS WITH DIFFERENT SCENARIOS

As it can be seen in figure 4 for model (a) where only the surcharge preloading alone has been used the resultant settlement after 400 days is only 33 cm but by just installing the PVDs the settlement increased to 1.19 m for

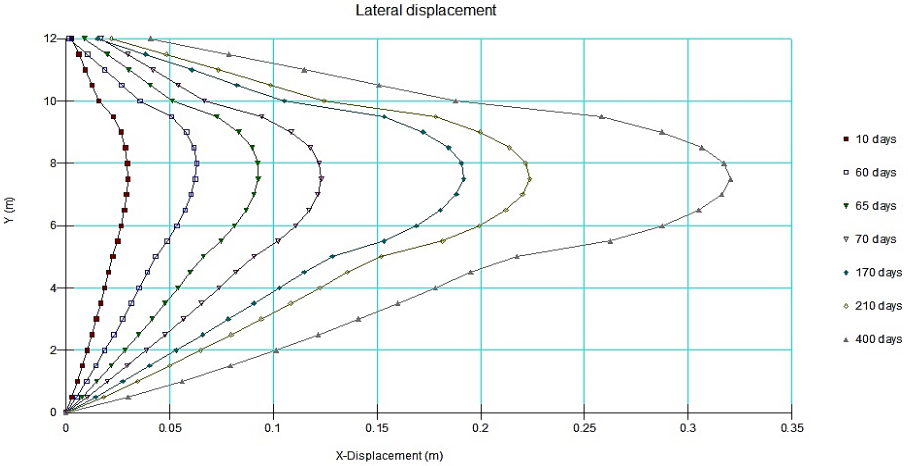
400 days. The resultant settlement is 3.6 times greater than the case where only surcharge preloading has been used. One of the obstacles in construction of embankments on weak soils, is the failure and large cracks in the toe of the embankments that are the result of excessive lateral displacement and surface heaves. Tarefde, Indraratna and Teparaksa [19, 22, 24] has investigated this problem in Bangkok airport and try to simulate the process in finite element. It can be seen in fig 4a that great heaves occurred and it is warning that the construction of embankment alone is not feasible in practice. In figure 5a it is shown that the lateral displacement is even high after 10 and 60 days of the beginning of the construction and it shows great shear forces act on the toe of the embankment that again validate that the embankment alone cannot be a good choice in designation of such soil improvement method. It should be noted that the estimated heave in the toe of the embankment is overestimated but it shows the magnitude of the problem that exist there. The same phenomena was reported by [25, 26] in different projects.

In fig 4b by installing the PVD the settlement increased to 1.19m that is the result of acceleration in radial consolidation. [27, 28] reported the effectiveness of PVD installation on acceleration of discharge from soil especially along with vacuum preloading. It can be seen in fig 5b that as a result of PVDs, the lateral displacement of the embankment at toe, has decreased considerably in 150 days after the construction of the embankment and it gradually increased to .32 m in 400 days. This gradual increase in lateral displacement prevents the sudden failures of the embankments and it also decrease the shear cracks in the vicinity of the construction site. Although it should be mentioned that even in the case of presence of PVDs, large cracks had been reported [29-31] that shows the necessity of applying a supplementary measure especially in clay with no adhesion like Bangkok clay [32, 33] that is vacuum preloading.

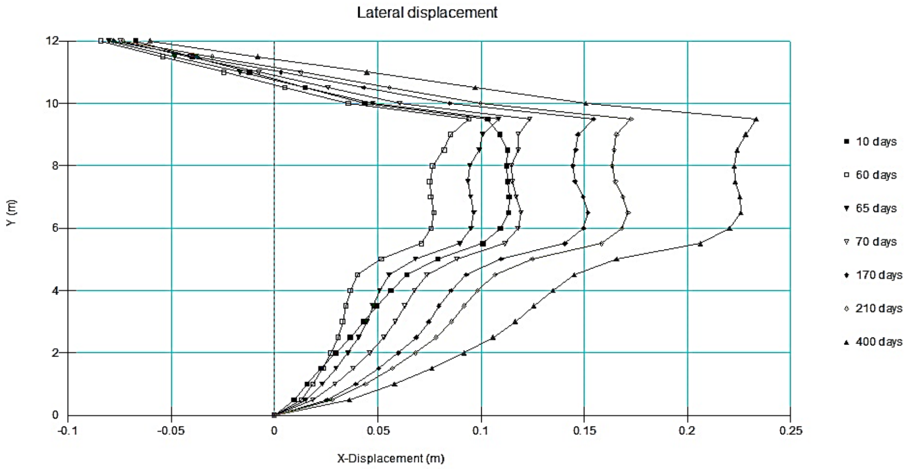
After applying the vacuum pressure the settlement increased and the lateral displacement decreased as it is shown in figure 4c and 5c respectively. The 1.99 m settlement in model B (i.e. surcharge and PVD) that has been achieved in 400 days was gained in only 170 days. The settlement reached 1.78 m in 400 days. As it can be seen in figure 5c, the lateral displacement is -0.08 cm on surface at the toe of the embankments. This inward movement that is the result of applying vacuum pressure, would be a great benefit in embankment overall stability that has been mentioned in various small scale and case histories reported by different authors [34-36]. Like the case model B, the formation and propagation of lateral displacement vs. time in underneath of the embankment is slowed (fig 5c), that allows the weak layers to be consolidated and become stiffer and as a result, the overall stability of the embankment would be increased. As mentioned by [37], after applying the vacuum pressure, the heave at the toe of the embankment would decrease, that is also demonstrated in fig 4c. Previous studies by [38, 39] confirmed that prediction of lateral movement is a difficult task compared to settlement. The errors may be numerous mainly attributed to soil anisotropy, the assumption of 2D plain strain and corner properties [20, 40]. Vacuum preloading produce an inward lateral movement of soft soil toward the embankment centerline (i.e. negative displacement in fig 5c) and minimized the risk of bearing capacity failure due to rapid embankment fill placement. However, this inward movement may cause tension cracks in adjacent areas, hence, lateral movement at the borders of the embankment and its effect on the adjacent structure should be carefully monitored [40].



(a)



(b)



(c)

Figure 5. Lateral Ground Surface Displacement in a) model A b) model B c) model C

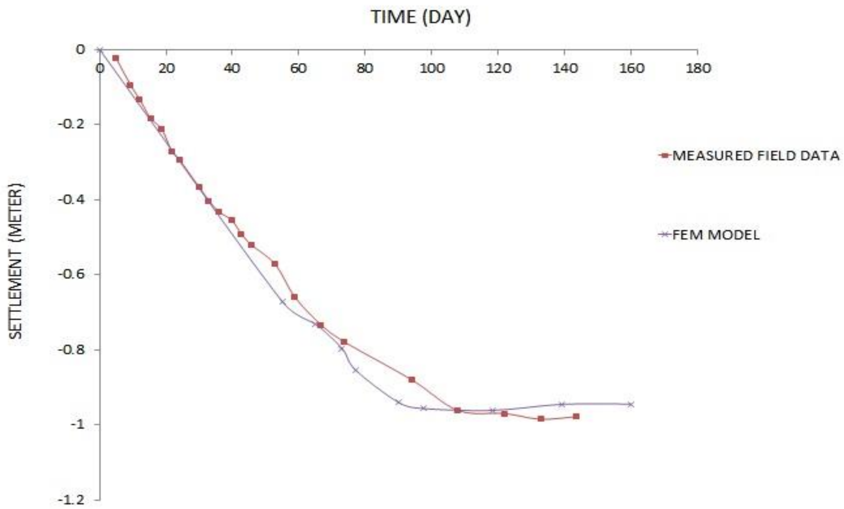


Figure 6. Comparison of Model D Results with Monitored Field Data's (field data from [16])

4. CONCLUSION

It was shown that for multi-drain simulation, plane strain finite element analysis can be readily adapted to most field situations. Nevertheless, realistic field predictions require that the axis-symmetric properties to be converted to an equivalent 2D plane strain condition, especially the permeability coefficients and drain geometry. For Bangkok airport, Model D showed that, there is a good agreement between predicted data's and field measured values except for the first 50 days that the model overestimate the values. A system of prefabricated vertical drains (PVDs) combined with vacuum preloading is an effective method for accelerating soil consolidation and avoid failures due to the rapid embankment construction because the lateral displacement decreased drastically by applying vacuum pressure. It was shown that the system of surcharge alone is not efficient and also not economical at all. Although the system that comprise of surcharge and PVDs is somehow efficient in some projects, but for this example it was shown that by just applying the vacuum pressure the time needed for 1.19 m settlement decreased by 230 days that is a great value if time is of importance in project.

FUNDING/SUPPORT

Not mentioned any Funding/Support by authors.

ACKNOWLEDGMENT

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

5. REFERENCES

[1] Holtz RD, Jamiolkowski MB, Lancellotta R, Pedroni R. Prefabricated vertical drains: design and performance. 1991. [View at Google Scholar]; [View at Publisher].

[2] Indraratna B, Redana IW. Numerical modeling of vertical drains with smear and well resistance installed in soft clay. Canadian Geotechnical Journal. 2000 Feb 1;37(1):132-45. [View at Google Scholar]; [View at Publisher].

[3] Barron RA. Consolidation of fine-grained soils by drain wells by drain wells. Transactions of the American Society of Civil Engineers. 1948 Jan;113(1):718-42. [View at Google Scholar]; [View at Publisher].

[4] Chu J, Yan SW, Yang H. Soil improvement by the vacuum preloading method for an oil storage station. Geotechnique. 2000 Dec;50(6):625-32. [View at Google Scholar]; [View at Publisher].

[5] Chai JC, Carter JP, Hayashi S. Ground deformation induced by vacuum consolidation. Journal of geotechnical and geoenvironmental engineering. 2005 Dec 1;131(12):1552-61. [View at Google Scholar]; [View at Publisher].

[6] Shang JQ, Tang M, Miao Z. Vacuum preloading consolidation of reclaimed land: a case study. Canadian Geotechnical Journal. 1998 Oct 1;35(5):740-9. [View at Google Scholar]; [View at Publisher].

[7] Yan SW, Chu J. Soil improvement for a road using the vacuum preloading method. Proceedings of the Institution of Civil Engineers-Ground Improvement. 2003 Oct;7(4):165-72. [View at Google Scholar]; [View at Publisher].

[8] Cognon JM, Juran I, Thevanayagam S. Vacuum consolidation technology-principles and field experience. InProceedings of the Conference on Vertical and Horizontal Deformations of Foundations and Embankments. Part 2 (of 2) 1994 (pp. 1237-1248). Publ by ASCE. [View at Google Scholar]; [View at Publisher].

[9] Richart Jr FE. A review of the theories for sand drains. Journal of the soil mechanics and foundations division. 1957 Jul;83(3):1301-. [View at Google Scholar]; [View at Publisher].

[10] Indraratna B, Redana IW. Laboratory determination of smear zone due to vertical drain installation. Journal of geotechnical and geoenvironmental engineering. 1998 Feb;124(2):180-4. [View at Google Scholar]; [View at Publisher].

[11] Hird CC, Pyrah IC, Russell D, Cinicioglu F. Modelling the effect of vertical drains in two-dimensional finite element analyses of embankments on soft ground. Canadian Geotechnical Journal. 1995 Oct 1;32(5):795-807. [View at Google Scholar]; [View at Publisher].

[12] Chai J, Bergado DT, Shen SL. Modelling prefabricated vertical drain improved ground in plane strain analysis. Proceedings of the Institution of Civil Engineers-Ground Improvement. 2013 May;166(2):65-77. [View at Google Scholar]; [View at Publisher].

[13] Indraratna B, Rujikiatkamjorn C, Sathananthan I. Analytical and numerical solutions for a single vertical drain including the effects of vacuum preloading. Canadian Geotechnical Journal. 2005 Aug 1;42(4):994-1014. [View at Google Scholar]; [View at Publisher].

[14] Lam LG, Bergado DT, Hino T. PVD improvement of soft Bangkok clay with and without vacuum preloading using analytical and numerical analyses. Geotextiles and Geomembranes. 2015 Nov 1;43(6):547-57. [View at Google Scholar]; [View at Publisher].

[15] Rujikiatkamjorn C, Indraratna B, Chu J. 2D and 3D numerical modeling of combined surcharge and vacuum preloading with vertical drains. [View at Google Scholar]; [View at Publisher].

[16] Indraratna B, Sathananthan I, Rujikiatkamjorn C, Balasubramaniam AS. Analytical and Numerical Modeling of Soft Soil Stabilized by Prefabricated Vertical Drains Incorporating Vacuum reloading. [View at Google Scholar]; [View at Publisher].

[17] Indraratna B, Sathananthan I, Bamunawita C, Balasubramaniam AS. Theoretical and numerical perspectives and field observations for the design and performance evaluation of embankments constructed on soft marine clay. InElsevier geo-engineering book series 2005 Jan 1 (Vol. 3, pp. 51-89). Elsevier. [View at Google Scholar]; [View at Publisher].

[18] B.M. Das, Principles of geotechnical engineering, Cengage learning, 2021. [View at Google Scholar]; [View at Publisher].

[19] Das BM. Principles of geotechnical engineering. Cengage learning; 2021. [View at Google Scholar]; [View at Publisher].

[20] Pardsouie MM, Pardsouie MH. The effect of PVDs length on the lateral displacement of embankments. Geotechnical Geology. 2022 Jun 1;18(1):655-8. [View at Google Scholar]; [View at Publisher].

[21] M.M. Pardsouie, M. Momeni, S.A. Nasehi, M.H. Pardsouie, 2D Numerical Investigation of the Effectiveness of Surcharge and Vacuum Preloading Along with PVDs, in: 13th National Congress on Civil Engineering Isfahan University of Technology, Isfahan, IranAt: Isfahan , Iran, Esfahan,Iran, 2022.5.22.

[22] Indraratna B. Recent advances in the application of vertical drains and vacuum preloading in soft soil stabilisation. [View at Google Scholar]; [View at Publisher].

[23] D.T. Bergado, A. Balasubramaniam, R.J. Fannin, R.D.J.C.G.J. Holtz, Prefabricated vertical drains (PVDs) in soft Bangkok clay: a case study of the new Bangkok International Airport project, 39(2) (2002) 304-315. [View at Google Scholar]; [View at Publisher].

[24] Teparaksa W. Prediction versus performance on lateral displacements in soft Bangkok clay under embankment loading. InInternational Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts 1995 (Vol. 3, No. 32, p. 130A). [View at Google Scholar]; [View at Publisher].

[25] López-Acosta NP, Espinosa-Santiago AL, Pineda-Núñez VM, Ossa A, Mendoza MJ, Ovando-Shelley E, Botero E. Performance of a test embankment on very soft clayey soil improved with drain-to-drain vacuum preloading technology. Geotextiles and Geomembranes. 2019 Oct 1;47(5):618-31. [View at Google Scholar]; [View at Publisher].

[26] Bahsan E, Liao HJ, Ching J, Lee SW. Statistics for the calculated safety factors of undrained failure slopes. Engineering Geology. 2014 Apr 8;172:85-94. [View at Google Scholar]; [View at Publisher].

[27] Saowapakpiboon J, Bergado DT, Youwai S, Chai JC, Wanthong P, Voottipruex P. Measured and predicted performance of prefabricated vertical drains (PVDs) with and without vacuum preloading. Geotextiles and Geomembranes. 2010 Feb 1;28(1):1-1. [View at Google Scholar]; [View at Publisher].

[28] Wu J, Ouyang C, Dai M, Gao Z, Fu H, Wang J. Effect of surcharge loading rate on the performance of surcharge–vacuum preloading with prefabricated horizontal drains. Marine Georesources & Geotechnology. 2022 Jul 15:1-9. [View at Google Scholar]; [View at Publisher].

[29] Stark TD, Ricciardi PJ, Sisk RD. Case study: Vertical drain and stability analyses for a compacted embankment on soft soils. Journal of geotechnical and geoenvironmental engineering. 2018 Feb 1;144(2):05017007. [View at Google Scholar]; [View at Publisher].

[30] Bergado DT, Jamsawang P, Jongpradist P, Likitlersuang S, Pantaeng C, Kovittayanun N, Baez F. Case study and numerical simulation of PVD improved soft Bangkok clay with surcharge and vacuum preloading using a modified air-water separation system. Geotextiles and Geomembranes. 2022 Feb 1;50(1):137-53. [View at Google Scholar]; [View at Publisher].

[31] Putu Tantri K Sari IB. A case study on causation of the landslide in Porong-Sidoarjo for road construction with high embankments elevation. Journal of Southwest Jiaotong University. 2021;56(4). [View at Google Scholar]; [View at Publisher].

[32] Horpibulsuk S, Rachan R, Suddeepong A. Assessment of strength development in blended cement admixed Bangkok clay. Construction and Building Materials. 2011 Apr 1;25(4):1521-31. [View at Google Scholar]; [View at Publisher].

[33] Teachavorasinskun S, Amornwithayalax T. Elastic shear modulus of Bangkok clay during undrained triaxial compression. Géotechnique. 2002 Sep;52(7):537-40. [View at Google Scholar]; [View at Publisher].

[34] Chai J, Ong CY, Carter JP, Bergado DT. Lateral displacement under combined vacuum pressure and embankment loading. Géotechnique. 2013 Aug;63(10):842-56. [View at Google Scholar]; [View at Publisher].

[35] Ong CY, Chai JC. Lateral displacement of soft ground under vacuum pressure and surcharge load. Frontiers of Architecture and Civil Engineering in China. 2011 Jun;5(2):239-48. [View at Google Scholar]; [View at Publisher].

[36] Chai J, Rondonuwu SG. Surcharge loading rate for minimizing lateral displacement of PVD improved deposit with vacuum pressure. Geotextiles and Geomembranes. 2015 Nov 1;43(6):558-66. [View at Google Scholar]; [View at Publisher].

[37] Indraratna B, Rujikiatkamjorn C, Wijeyakulasuriya V, McIntosh G, Kelly R. Soft soils improved by prefabricated vertical drains: performance and prediction. [View at Google Scholar]; [View at Publisher].

[38] Ni J, Geng XY. Radial consolidation of prefabricated vertical drain-reinforced soft clays under cyclic loading. Transportation Geotechnics. 2022 Aug 17:100840. [View at Google Scholar]; [View at Publisher].

[39] B. Indraratna, I. Gasson, R.J.C.G.J. Chowdhury, Utilization of compacted coal tailings as a structural fill, 31(5) (1994) 614-623. [View at Google Scholar]; [View at Publisher].

[40] Wang P, Han Y, Wang J, Cai Y, Geng X. Deformation characteristics of soil between prefabricated vertical drains under vacuum preloading. Geotextiles and Geomembranes. 2019 Dec 1;47(6):798-802. [View at Google Scholar]; [View at Publisher].