2D Plane Strain Modeling of Vacuum-Consolidation with PVD

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Abstract. Prefabricated Vertical Drains (PVDs) is one of the most common methods used for improving the engineering properties of soft clayey deposits. These are used to accelerate the consolidation process of treated ground and thereby speed-up the construction activities. Different techniques can be combined with PVDs to augment the efficiency of the method. Application of vacuum is such a technique which in combination with PVDs helps to accelerate the dissipation of excess pore pressure under embankments. This paper presents the equivalent plane strain modeling of the vacuum consolidation combined with PVDs and surcharge loading, using the finite element program ABAQUS. Settlement and excess pore pressures obtained from the analyses were compared with the observed field values as mentioned in the literature. Influence of spacing of the drains on the consolidation behaviour is also studied. A comparative study is conducted between the modeling methods proposed by Indraratna and Redana(1997) and Chai et al.(2001). Also, the settlement obtained from the equivalent plane analyses is compared with the analytical solution proposed by Hansbo (1979).

Keywords: PVD; Vacuum consolidation; Equivalent Plane strain Analyses; Excess pore pressure; Settlement

1 Introduction

Marginal soils like soft clays which have poor geotechnical properties, poses problems for construction and hence require some sort of improvement to be done prior to the construction of structures. Various types of vertical drains like sand drains, wick drains, prefabricated vertical drains, stone columns, gravel piles, sand compaction piles etc. are commonly used for this purpose [17]. Prefabricated Vertical Drains (PVDs) in combination with surcharge preloading is currently widely used due to their efficiency,cost-effectiveness and easiness in installation. PVDs introduce radial drainage in the soil and hence reduce the drainage path to accelerate consolidation. PVDs evolved from the idea of cardboard wicks introduced by Walter Kjellman in 1940s. Later, Kjellman in 1952 improvised the method by combining vacuum with PVDs to form vacuum-PVD [19]. The suction effect of vacuum-PVD in addition to the radial drainage accelerates the consolidation process [4,7,17]. This method is generally employed in highly compressible and less permeable soils where the embankment height (applied as surcharge) is to be limited.

Behaviour of soils improved with vertical drains was studied theoretically by pioneers like Kjellman[19], Barron[3], Hansbo[11],etc. The initially proposed free strain hypothesis was replaced by relatively simple equal strain hypothesis as both gave same degree of consolidation [3]. Analytical solutions were developed by modifying the existing vertical drain theory [2,10,11,13,18]. The limitation of analytical solutions to represent the real situation led to the use of numerical methods for studying the performance of vacuum consolidation combined with PVDs [7,13]. Analytical, numerical and experimental studies have proven that vacuum-PVD is superior to conventional PVD in achieving consolidation [21]. Due to the nature and geometry of the PVD system, 2D plane strain condition can be applied for the numerical analyses [16]. The actual axisymmetric or 3D case is converted to equivalent plane strain analysis through either of geometric matching, permeability matching or combined matching [15]. These conversions can be incorporated in the finite element programs like ABAQUS, CRISP SAGE, etc[20,23]. The present study deals with the modeling of vacuum-PVD installed foundation soil using the finite element program ABAQUS (2016). The developed model is initially validated based on field data followed by the parametric studies such as the study of effect of drain spacing on the consolidation behaviour of foundation soil, comparison of two possible methods of modeling(proposed by Indraratna and Redana[14] and Chai et al. [7]) the case considered and the investigation of matching of the simulated results of settlement with analytically calculated settlement based on equation given by Hansbo[10].

2 Case Considered

Details of the case are given in the following section.

2.1 General Description

The data from full-scale field study of PVD assisted ground improvement used in the expansion of Tianjin Port, Beijing, China reported by Rujikiatkamjorn et al. [20] was used for the modeling purposes. The site was divided into Sections I, II, and III of which the present study focuses only on section III where PVDs of 20 m length were installed at 1 m spacing in a square pattern and combined vacuum-surcharge loading was applied (Fig.1). The cross-sectional details are as in Fig.2. The embankment had a total base area of 28x50 m^2 beneath which these 20 m long PVDs having a discharge capacity of 100 m^3/yr were installed. Initially a vacuum pressure of 80 kPa was applied to the foundation soil for around 25 days after which the embankment construction commenced with a backfill of unit weight 17 kN/m^3 in two stages to a height of 3 m. It corresponds to a surcharge of 50 kPa. The first and bottom layer of 0.9 m height was constructed in five days and allowed to consolidate for around 22

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days followed by the top layer of 2.1 m thick with 33 days and 95 days for construction and consolidation respectively. Monitoring instruments like surface settlement plates, pore water pressure transducers, multi-level settlement gauges,

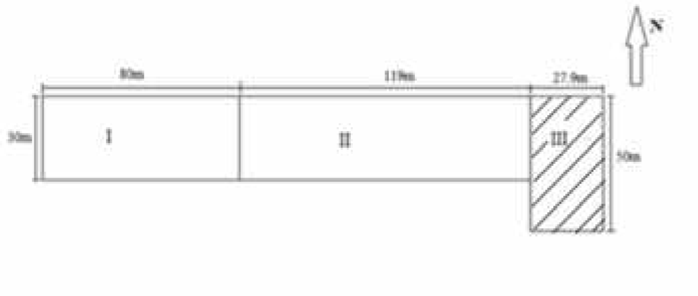

Fig.1 Site divided into three sections [20]

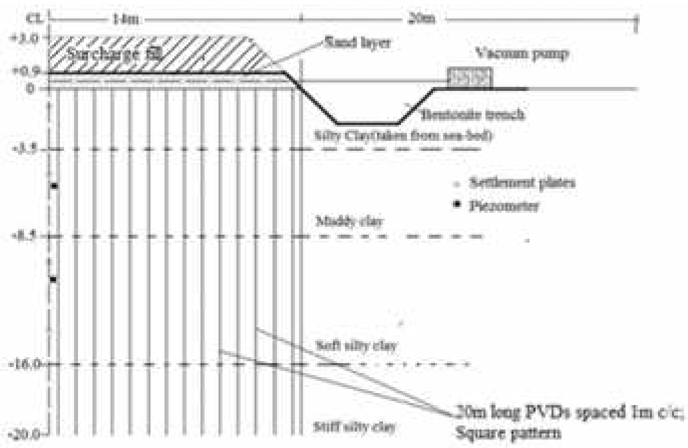

Fig.2 Cross section of test embankment with subsoil profile for Section III, Tianjin Port, Beijing [20]

standpipes and inclinometers were installed in the section. The section was monitored for around 180 days.

2.2 Description of the Finite Element Model

The numerical analyses were performed using the finite element software ABAQUS [1]. Considering the complexities associated with 3D modeling and the nearly matching results obtained from 2D analyses, equivalent plane strain model was developed for carrying out the analyses. The plane strain finite element mesh is shown in Fig.3. The area improved with vacuum-PVD is shown with finer mesh while the undisturbed area have larger mesh size. The equivalent diameter of the drains was taken to be 50 mm and the diameter of smear zone as 200 mm. Modified Cam-Clay model was used

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for the finite element analyses. Even though, 3D numerical analyses can simulate field conditions more closely, the computational time required for performing full 3D analysis is typically an order of magnitude more than the approximate approaches. In the present work, the 3D problem is converted to a 2D plane strain problem using equivalent properties and dimensions as investigated by Indraratna and Redana[14], Chai et al.[7],etc. The axisymmetric discharge capacity was given the plane strain conversion (q_{pl}) as proposed by Hird et al. [12] (Eq.1) and this converted value was used in the analyses.

$$q_{pl} = \frac{2}{\pi B} q_w \quad (1)$$

where q_w is the axisymmetric discharge capacity and B is the width of unit cell.

Smear zone includes the soil mass in the vicinity of the vertical drain, where the soil gets densified due to installation of the drain resulting in reduction of permeability. The simulation parameters used for the model are tabulated in Table 1. λ is the slope of normal consolidation curve for loading stage after preconsolidation pressure; κ, the slope of normal consolidation curve for unloading stage ; ν represents the poisson's ratio in terms of in situ effective stress; γ is the bulk unit weight of soil;e_0 represents the initial void ratio; k_v is the coefficient of vertical permeability in the undisturbed zone; k_{h}, k'_{h} - coefficient of horizontal permeability in the undisturbed zone and smear zone respectively for axisymmetric case; k_{hp}, k'_{hp} - coefficient of horizontal permeability in the undisturbed zone and smear zone respectively for 2D plane strain analyses.

Table 1 Parameters for FEM analyses [20]

DEPTH (m)	**λ**	**κ**	**ν**	e_0	**γ (kN/m³)**	**k_v (*10⁻¹⁰ m/s)**	**k_h (*10⁻¹⁰ m/s)**	**k'_h (*10⁻¹⁰ m/s)**	**k_{hp} (*10⁻¹⁰ m/s)**	**k'_{hp} (*10⁻¹⁰ m/s)**
0.0-3.5	0.12	0.03	0.30	1.1	18.3	6.67	20	6.67	5.91	1.46
3.5-8.5	0.14	0.03	0.25	1.0	18.8	13.3	40	13.3	11.8	2.92
8.5-16	0.20	0.04	0.30	1.35	17.5	6.67	20	6.67	5.91	1.46
16.0-20.0	0.10	0.02	0.27	0.9	18.5	1.37	5	1.67	1.48	0.365

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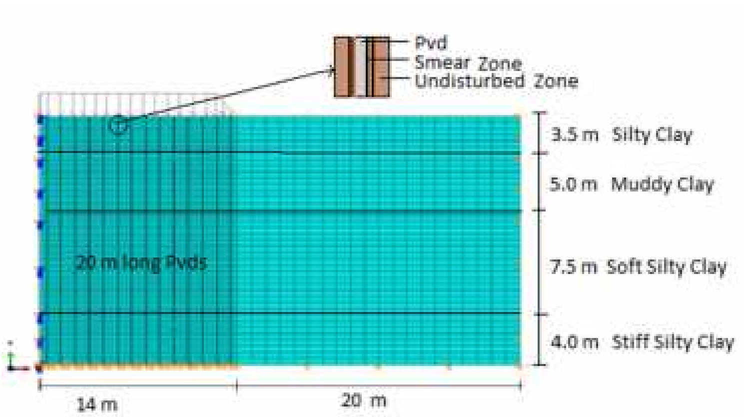

Fig.3 Finite Element mesh for equivalent plane strain analysis of foundation soil installed with 20 m long PVDs

The boundary conditions (hydraulic and displacement) used for the model can be summarized as: left and right boundaries with roller support(u=0); bottom is fixed (u=0, v=0); top face and the drain boundaries are applied with a negative pore pressure of -80kPa to simulate vacuum pressure. For carrying out consolidation analysis, coupled elements CPE8RP (8 noded displacement and pore pressure) were used.

2.3 Simulation Procedure

The first step of the analyses was to establish the initial in situ stress state and once the initial stresses were established, all nodal displacements were set to zero. To model PVDs installed in the foundation soil, three different regions were considered for each PVD viz., the drain, surrounding smear zone with reduced permeability and an undisturbed zone around the smear zone. The staged embankment construction was simulated by sequential addition of equivalent surcharge. The total embankment height of 3m was constructed in around 60days. Vacuum is simulated by applying negative pore pressure along the length of the drains and the top of the foundation soil. The monitoring period including the duration of vacuum application, construction and consolidation time of embankment is taken as 180 days.

2.4 Validation of the Model

The 2D plane strain model developed is validated based on settlement, by comparing the simulated results with the field data as reported by Rujikiatkamjorn et al. [20]. In Fig.4, the time-settlement relation obtained from the current equivalent plane strain model is compared with the field measurements. It can be observed that the current model is able to capture the general trend of measured data well.

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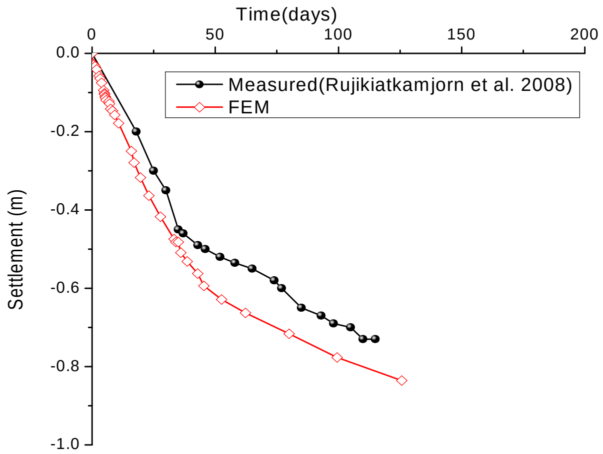

Fig.4 Comparison of field data and FEM results for settlement at a depth of 1 m along the embankment centerline

2.5 Parametric Studies

The equivalent plane strain model developed is subjected to studies considering the effect of spacing of drains. Models were developed considering different drain spacings viz., 1 m, 1.5 m, 2 m and 3 m. In all the studies conducted with the model, consolidation behavior was studied based on settlement and pore pressure analyses.

An analytical study was performed using Hansbo's [10] equation for degree of radial consolidation given by Eq.2

$$U_h = \frac{S_t}{S_f} = 1 - \exp[\frac{-8T_h}{F}] \tag{2}$$

where, S_t and S_f represents the measured settlement at any time and the final settlement respectively. T_h is the time factor for horizontal consolidation; F is the PVD geometry factor given by Eq. 3a-d

$$F = F(n) + F_s + F_r \tag{3a}$$

$$F(n) = \ln[\frac{D_e}{d_w}] - \frac{3}{4} \tag{3b}$$

$$F_s = [\frac{k_h}{k_s} - 1]\ln[\frac{d_s}{d_w}] \tag{3c}$$

$$F_r = \frac{2}{3}\pi L^2 \frac{k_h}{q_w} \tag{3d}$$

$$T_h = \frac{C_h t}{D_e^2} \tag{4}$$

where, C_h is the coefficient of horizontal consolidation, D_e is the diameter of the equivalent soil cylinder, k_h and k_s are the horizontal permeabilities in undisturbed zone and smear zone respectively, d_w is the equivalent drain diameter, d_s is the smear zone diameter, L is the drainage length for PVD improved zone, q_w is the discharge capacity of the drain. The final settlement can be calculated based on the analytical method proposed by Zeng and Xie [25] given by Eq.5

$$S_f = \frac{S_3(S_2-S_1)-S_2(S_3-S_2)}{(S_2-S_1)-(S_3-S_2)} \quad (5)$$

where, S_1, S_2 and S_3 are the measured settlements at time t_1, t_2, and t_3. The time intervals are chosen such that $t_2 - t_1 = t_3 - t_2$.

The study also attempts to compare two different approaches of modeling namely, the method proposed by Indraratna and Redana[14], in which the drain, smear zone and the undisturbed zones are considered separately and the simplified method proposed by Chai et al.[7] in which the PVD installed zone is considered as the improved zone having an equivalent vertical permeability (Eq.6) different from the remaining undisturbed zone.

$$k_{ve} = \left(1 + \frac{2.5l^2}{\mu D_e^2}\frac{k_h}{k_v}\right)k_v \quad (6)$$

where, 'l' is the drainage length; 'l' is equal to thickness of soil stratum(H) for the case of one-way drainage and l= H/2 for the case of double drainage. k_h and k_v are the permeabilities in horizontal and vertical directions respectively. D_e is the diameter of influence zone of the PVD.

3 Results and Discussion

3.1 Effect of Spacing of Drains

The spacing of drains has direct influence over the permeability of the surrounding soil and thereby on the settlement and pore pressure dissipation. FEM analyses with PVD center to center spacings of 1 m, 1.5 m, 2 m and 3 m were conducted to provide an indication of the effects of PVD spacing on the settlement of vaccum treated ground. The settlement behaviour of soil when the spacing of the drains is varied is shown in Fig.5. It can be seen that the settlement rate decreases with increasing the spacing. At any time during the initial stages of loading, the settlement for 1 m spacing is more compared to larger spacings. For example, considering an arbitrary time of 30 days, the surface settlement achieved in the cases of 1 m, 1.5 m, 2 m and 3 m spacing are 0.68 m, 0.52 m, 0.38 m and 0.25 m respectively. There is an increase of 172% in settlement of soil for 1 m spaced PVD compared to 3 m spaced ones. But the increase in settlement between the adjacent values of spacing is only marginal. As the spacing decreases there is a corresponding increase in the number of drains that can be installed in the given area and hence the total area of smear zone also increases. Smear zone introduces a hardening effect in the foundation soil, by the reduction in void ratio which leads to a reduction in the long-term settlement. Similar result was reported by Borges [4] by comparing the case of vertical drains with and without smear zone. In the case of closely spaced drains, the overall areal extent of smear zone is more compared to widely spaced drains. Hence, the hardening effect will be more in the former case leading to lesser ultimate settlement than the soil stabilized with widely spaced drains. As a result, the ultimate settlement obtained for PVD spacing of 1 m is less than that for the widely spaced PVDs. After 2000 days from com-

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mencement of vacuum application, the settlement obtained for the cases of 1 m, 1.5 m, 2 m and 3 m are 1.18 m, 1.3 m, 1.4 m and 1.55 m respectively.

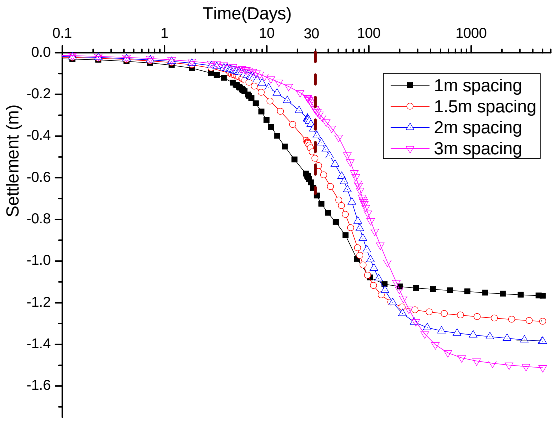

Fig. 5 Comparison of surface settlements for different PVD spacings

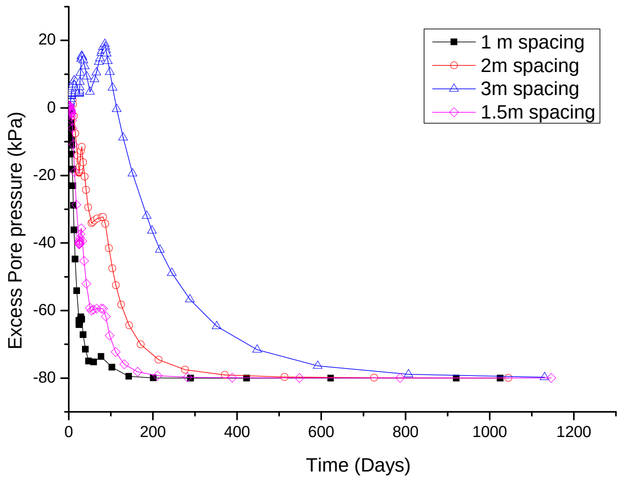

Fig. 6 Excess pore pressure variation for different PVD spacings

Fig.6 shows the variations in excess pore pressure with time in the foundation soil at 5.5 m depth below the embankment center for different spacings of PVD. The excess pore pressure dissipation is accelerated by reducing the drain spacing. Though the final pore pressure in all the cases reaches the value of the applied vacuum, the rate at which it is attained varies depending on the spacing. The time at which final pore pressure is achieved in the cases of 1 m, 1.5 m, 2 m and 3 m are 150, 265, 450 and 825 days respectively (Fig.6). The requirement of much higher duration when

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PVDs of 3 m spacing are provided compared to 1 m spacing signifies the influence of drain spacing in the consolidation behavior of treated ground.

3.2 Modeling by Equivalent Permeability

The results obtained from the simplified method proposed by Chai et al. [7] is compared with those from the model in which smear zone is considered separately (Fig.7,8). From the settlement and pore pressure curves, it can be seen that Chai's method of modeling overestimates the degree of consolidation. The estimated settlement by this method at 120 days is around 47% higher than the measured value.

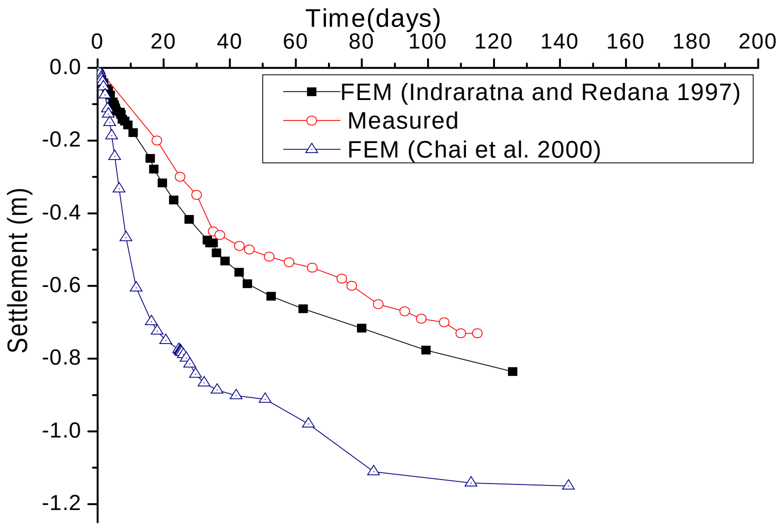

Fig. 7 Settlement comparison of the results from models based on equivalent vertical permeability (Chai et al. [7]) and explicit method (Indraratna and Redana [14]) with measured values

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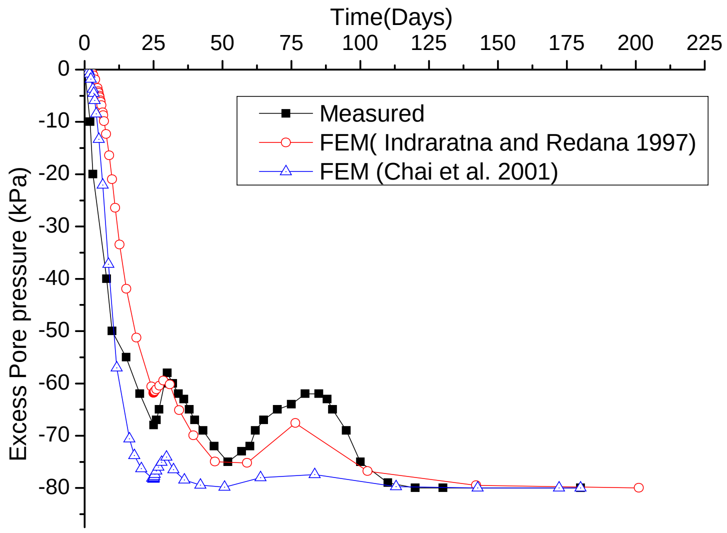

Fig.8 Comparison of excess pore pressure from models based on equivalent vertical permeability (Chai et al. [7]) and explicit method (Indraratna and Redana [14]) with measured values

3.3 Settlement Comparison using Hansbo's Solution

The settlement of the foundation soil obtained from the numerical model is compared with the analytical solution proposed by Hansbo [10]. Applying Eq.5, the final settlement $S_{f\ could}$ be obtained $_{as}$ 1.184m. The Finite element analysis shows a long-term settlement of 0.98m (Fig.9) which is close to the analytical solution. Using the measured settlement values, the coefficient of radial consolidation (C_h) can be back-calculated from Eqs.2-4. The value corresponding to 50% consolidation (ie, 0.59 m) is obtained as 0.021 m^2/day. Taking this as the average value of C_h, time-dependent settlements were plotted for long term (Fig.9) based on Eq.2. On comparing the analytical results thus obtained with the simulated results, it can be seen that considerable matching is existing between the solution. This again emphasizes the validity of the model developed.

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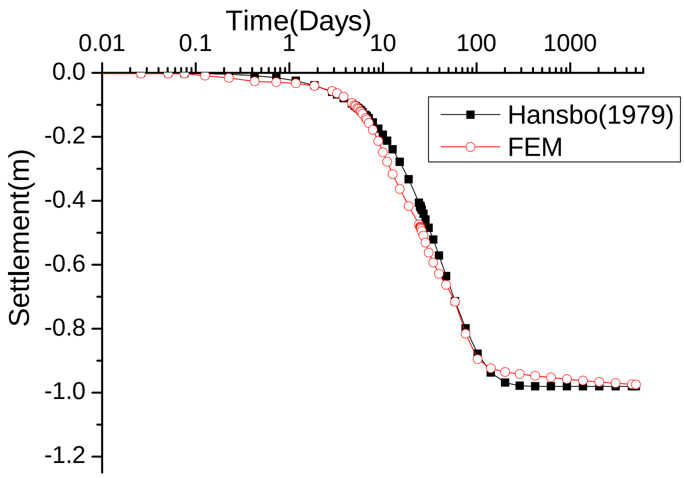

Fig.9 Comparison of Hansbo's solution with simulated results of settlement

4 Conclusions

A 2D equivalent plane strain model was developed to study the behavior of foundation soil improved with vacuum-PVDs using the finite element program ABAQUS. The following conclusions were made based on the numerical results:

i. From the spacing study, it was observed that during the initial stages, the smaller spacings produce more settlement at a given time. At an arbitrary time (30 days), the surface settlement achieved in the cases of 1 m, 1.5 m, 2 m, and 3 m spacing are 0.68 m, 0.52 m, 0.38 m and 0.25 m respectively. It shows an increase of 172% in settlement of soil for 1 m spaced PVD compared to 3 m spaced PVDs. However, the final settlement shows an opposite trend due the increased area of smear zone (hence reduced permeability) in the closely spaced drains. The effect of spacing is observed as the longer duration for pore pressure dissipation in case of larger spacing. 1 m, 1.5 m, 2 m and 3 m spaced drains require 150, 265, 450 and 825 days respectively for attaining complete dissipation of pore pressure.

ii. On comparing the results of two methods of modeling namely those proposed by Indraratna and Redana[14] and Chai et al.[7] with the measured values , it was observed that Chai's model overestimates the degree of consolidation based on both settlement and pore pressure. The estimated settlement by Chai's method at 120 days is around 47% higher than the measured value.

iii. The results of settlement from equivalent 2D plane strain analyses and Hansob's [10] method was similar showing that the simplified 2D model can be used to study the behaviour of PVD assisted vacuum consolidation instead of full 3D simulation which lowers the computational burden.

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Acknowledgment

The authors wish to acknowledge Science Engineering Research Board (SERB), India for the financial support for this research work through the grant ECR/2017/000445.

References

1. Abaqus (2016) Documentation. Dassault Syste`mes, Ve´lizy-Villacoublay, France
2. Akagi, T.: Consolidation caused by Mandrel-Driven Sand-drains. Proceedings of the 6th Asian Regional Conference on Soil Mechanics and Foundation Engineering,1, July, Singapore (1979).
3. Barron, R. A.: Consolidation of fine-grained soils by drain wells, Transactions of the American Society of Civil Engineers,113, 718–742 (1948).
4. Bergado, D.T., Long, P.V., Chaiyaput, S., Balasubramaniam, A.S.: Prefabricated Vertical Drain (PVD) and Deep Cement Mixing (DCM) / Stiffened DCM (SDCM) techniques for soft ground Improvement. IOP Conf. Series: Earth and Environmental Science 143 (2018).
5. Borges J.L.,: Three-Dimensional Analysis of Embankments on Soft Soils Incorporating Vertical Drains by Finite Element Method, Computers and Geotechnics Vol 31,665–676 (2004),
6. Chai J.C., Miura N.: A design method for soft subsoil improvement with prefabricated vertical drain (2000).
7. Chai J., Shen S.,Miura N., Bergado D.T.: Simple Method of Modeling PVD Improved Subsoil. Journal of Geotechnical and Geoenvironmental Engineering, 127(11), 965-972 (2001).
8. Chai J., Hong Z., Shen S.: Vacuum-drain consolidation induced pressure distribution and ground deformation. Geotextiles and Geomembranes,28,525-535 (2010).
9. Chu, J., Yan, S. W., Yang, H.: Soil Improvement by the Vacuum Preloading Method for an Oil Storage Station. Geotechnique 50(6) 625-632 (2000).
10. Hansbo, S.: Consolidation of Clay by Band-shaped Prefabricated Drains.Ground Engineering, 12(5) (1979).
11. Hansbo, S.: Consolidation of Fine-Grained Soils by Prefabricated Drains.Proceedings of 10th International Conference, SMFE., Stockholm, Vol.3,677-682 (1981)
12. Hird C.C., Pyrah I.C., Russell D.: Finite element modeling of vertical drains beneath embankments on soft ground. Geotechnique 42, No. 3, 499-511, (1992)
13. Hird, C.C, Pyrah, I.C., Russell, D., Cinicioglu, F.: Modeling the Effect of Vertical Drains in Two-Dimensional Finite Element Analyses of Embankments on Soft Ground. Canadian Geotechnical Journal Vol 32: 795-807, (1995)
14. Indraratna, B. and Redana, I.W.: Plane Strain Modeling of Smear Effects Associated with Vertical Drains. Journal of Geotechnical and Geoenvironmental Engineering,123(5), 474-478 (1997)
15. Indraratna B., Bamunawita C., Redana I., McIntosh G., : Modeling of prefabricated vertical drains in soft clay and evaluation of their effectiveness in practice.Journal of Ground Improvement,7(3), 127-138 (2003)

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16. Indraratna B., Sathananthan I., Rujikiatkamjorn C., Balasubramaniam A.S.: Analytical and Numerical Modeling of Soft Soil Stabilized by Prefabricated Vertical Drains Incorporating Vacuum Preloading. International Journal of Geomechanics, ASCE 5 (2), 114–124, (2005).
17. Indraratna B.: Recent Advances in Vertical Drains and Vacuum Preloading for Soft Ground Stabilisation. Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul, pp 141-166, (2017)
18. Kim, T.Y., Ngyuen, B.P., Yun, D.H.,: Analysis of consolidation behavior of PV-improved ground considering a varied discharge capacity. Engineering Computations, (2017).
19. Kjellman W.: Consolidation of Clay Soil by Means of Atmospheric Pressure. Proceedings on Soil Stabilization Conference. Boston USA 1 pp. 258-263 (1952).
20. Rujuikiatkamjorn, C., Indraratna, B., Chu, J.: 2D and 3D Numerical Modeling of Combined Surcharge and Vacuum Preloading with Vertical Drains. International Journal of Geomechanics, ASCE,8(2),144-156 (2008).
21. Rujikiatkamjorn C.: Physical Modeling of Soft Clay Consolidation using Vacuum-Surcharge Method. Australian Geomechanics Journal, 47 (3), 27-34, (2012).
22. Tarefder R., Zaman M., Lin D., Bergado D.T.: Finite element modeling of soft ground with PVD under vacuum and embankment preloading. International Journal of Geotechnical Engineering, 3(2), 233-249, (2009).
23. Witasse R., Racinais J., Maucotel F., Galavi V., Brinkgreve R., Plomteux C.: Finite Element Modeling of Vacuum Consolidation using Drain Elements and Unsaturated Soil Conditions. International Symposium on Ground Improvement IS-GI Brussels 31 May & 1 June 2012
24. Yoshikuni H., Nakanodo H.: Consolidation of soils by Vertical Drain Wells with Finite Permeability. Soils and Foundations, 14(2), Japanese Society of Soil Mechanics and Foundation Engineering, (1974)
25. Zeng G. X., Xie K. H.: New Development of the Vertical Drain Theories. Proceedings of the 12th International Conference on Soil Mechanics and Foundation Engineering, Rio de Janeiro, 2, 1435–1438, (1989)

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