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Investigation of the Consolidation Behavior of Soft Soil Improved with Vertical Drains by Finite Element Method

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Abstract

The primary consolidation may take long time due to the low permeability of clay soils in such cases soil improvement may be required to shorten the consolidation time, increase shear strength, and therefore bearing capacity. Preloading is one of the commonly used methods to consolidate soils before actual load and to strengthen weak compressible soils. In cases with time problems, the use of prefabricated vertical drains (PVD) with pre-loading shortens the drainage path and reduces the consolidation time by taking advantage of the horizontal permeability of the soils is generally higher. In this study, an embankment constructed at different load rates with constant accelerates and analyzes were performed for the non-drained and drained conditions of clay soils with PVDs are in 2m, 1m, and 0.5m intervals. In this way, the effect of load rate and PVD usage on consolidation settlement and excess pore pressures in underlying low permeable clayey soil was investigated.

Keywords: Embankment, Soft Clay, Consolidation, Load Rate, Prefabric Vertical Drain.

1. Introduction

Embankments on soft soils are one of the most common consolidation problems of soil mechanics. Primary consolidation can take a long time due to the low permeability of clay soils, and in such cases, soil improvement may be required to shorten the consolidation time and increase the shear strength and thus the bearing capacity [1]. Preloading is one of the most commonly used remediation techniques to consolidate soils and strengthen weakly compressible soils before the actual load acts. This method has been successfully applied in accelerating the settlement and strengthening of soft clays used for highway embankments, industrial and residential structures, and airport roads, and is quite suitable if sufficient time is available [2]. In cases where there is a time problem, this method can be used together with PVD, and the permeability of the soils can be greatly increased by taking advantage of the generally higher horizontal permeability and shortening the drainage length. The easy-to-manufacture PVD remediation method [3, 4] also reduces the consolidation time [1, 5–9] The theory of horizontal consolidation of vertical drains was first introduced by Barron [10] and has been modified by many researchers [11–14]. Hansbo [15] introduced the "unit cell" approach that takes into account the well resistance and the distortion effect, and then Hird et al. [16] formulated the two-dimensional planar strain situation. In addition, since the finite element solution using planar strain became widespread, Indraratna and Redana [17] extended the equivalent unit cell theory to transform parameters such as permeability.

To check the accuracy of the results of the analysis given by the finite element software of the embankments made on soft soils, Borges [18] analyzed the real embankment model that is studied by Quaresma [19] and Yeo [20] by the finite element software and compared the analysis results with the real measurements in the field. Although the results were sufficiently consistent in terms of vertical settlements and excess pore pressures, they gave qualitatively similar but quantitatively different results in terms of horizontal displacements. Shen et al. [21] analyzed two different models, one improved by using PVD and the other without drain, with the help of an equivalent vertical permeability approach in order to examine the effect of using drains on soft soils. They placed PVDs at 1.5m intervals and 19 m lengths and revealed that the permeability of soft soils increased 30 times with the use of PVD, and excess pore damping could be accelerated. Chai et al. [22] and Ong and Chai [23] investigated the effect of surcharge loading speed on the vacuum preloading method. For this purpose, they performed a series of horizontal drain consolidation tests and triaxial tests in the laboratory, and as a result, they stated that loading at low velocities causes lower horizontal displacements. In addition to these studies, Chai and Rondonuwu [24] argued in their study that the optimum load rate increases with the increase of the initial effective stress of the soil. Lo et al. [25] supported a geogrid-reinforced road embankment with PVDs and examined the long-term performance of this embankment. The authors followed the tensile stresses in the geogrid and the excess pore pressure in the field for 400 days, followed by the settlements for 9 years. They tried to estimate the measured values using unit cell finite element analysis and compared the results with the actual values. As a result, it was revealed that the measured and predicted values of the excess pore pressures were compatible, and the estimated settlements for the center of the fill were smaller than the actual measured values. Akan et al. [26] investigated the effect of using PVD on the excess pore pressures, the damping times of these pressures, and the consolidation settlement of soft clay soils under different loading conditions. It was stated that lower excess pore pressures occur in the case with the drain and the damping times are reduced by 70-85% compared to the case without the drain, and the highest values are reached when the consolidation settlement is loaded at once without waiting for the embankment. Wang et al. [27] developed a model in the laboratory to evaluate the performance of the method in which vacuum and preload are used together and examined the effect of load rate by determining the horizontal displacements, vertical displacements, undrained shear strength, percentage of consolidation, horizontal consolidation coefficient and bearing capacity occurring on the ground at 3 different load rates. The findings of the research showed that the horizontal displacement is less in the fastest loading condition, the consolidation is completed faster and it gives higher bearing capacity values due to high final consolidation settlement. However, it is stated here that it should be taken into account that the vacuum pressure can reach different values for different load rates, and therefore the possibility that this situation may have affected the results should not be ignored. Kaisarta and Ilyas [28] aimed to obtain the settlement amount and time of consolidation of the soil during the vacuum process with the lateral distance between the vertical drains placed to accelerate the consolidation process and the damping of the excess pore pressure. For this purpose, they compared the settlement results obtained from a construction project with the results obtained from the finite element model created with the help of PLAXIS 2D. Similarly, Zhafirah et al. [29] performed analyzes with the analytical method to compare the consolidation time of soft soils before and after soil improvement using PVD. Nguyen et al. [30] discussed the necessity of using the latest analytical method and numerical simulation in a soil improvement project with vacuum PVD. For this purpose, a matching scheme is presented to derive suitable soil and drainage properties that are compatible with each other in analytical solution and numerical modeling. Nguyen et al. [31] have achieved a simple solution for vacuum preloaded PVDs that can be easily incorporated into the conventional method by applying the Laplace transform technique. Syahril [32] compared the results of the experimental and the numerical analysis with the finite element method. For this purpose, plate loading tests and two different consolidation tests were performed for with and without PVD soils in the laboratory, numerical analysis with the finite element method was carried out with the help of ETABS 2016 software. In addition, the finite element method is used to perform analysis in many different areas. For instance, Tigdemir et al. [33] present a numerical model for wheel-snow interaction using the finite element method. SolidWorks and ANSYS Design modeler are used to create a tire model for this purpose. The prepared models are analyzed using ANSYS Explicit Dynamics with the Mooney- Rivilin tire model. Yaylaci et al. [34] investigate the contact problem of an elastic layer resting on a rigid foundation. Two-dimensional analysis was carried out with the help of ANSYS, which is based on the Finite Element Method (FEM). Mercan and Civalek [35] present a fast and accurate method for determining the frequencies of microwires and nanowires, which are widely used in nanosensors, nanocircuits, and a variety of other scientific fields. COMSOL software is used to investigate the modal analysis of micro and nanowires. Thirty-nine modes are calculated to obtain the first ten-mode shapes and eigenfrequencies of silicon carbide nanowire. Figures captured from the software are used to present the results.

In the design of PVD, the PVD size will vary depending on the dimensions the manufacturer will provide and the time allowed for project completion. The required optimum spacing of PVDs should be chosen considering these variables, to meet the desired degree of consolidation within the allowable project time. For this purpose, it would be correct to decide to perform a series of analyzes with traditional methods or the finite element method. Within the scope of this paper, the variation of vertical and horizontal deformations, and the excess pore pressures during the construction of a road embankment with and without PVDs and at various load rates was investigated. The constructed models were analyzed with the help of the software of Plaxis 2D v20, which utilizes the finite element method, without PVD and PVDs with the 2m, 1m, and 0.5m intervals. Analysis results are presented in figures and discussed.

2. Material and Method

The soil layers are listed from top to bottom as Ground 1 (clay), Ground 2 (sand), Ground 3 (clay), and Ground 4 (sand), and their thicknesses are 6m, 2m, 5m, and 17m, respectively. The PVDs are 13m long and extend to the Ground 4 boundary (Fig. 1).

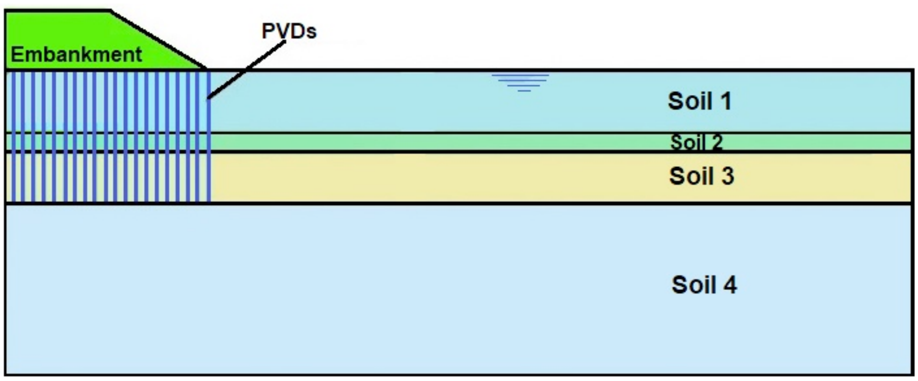

Fig. 1. Model and soil profile analyzed in Plaxis software

Soil 1 and Soil 3 are clay layers that have low permeability, while Ground 2 and Soil 4 are sand layers that have high permeability. Within the scope of the study, an embankment that has 6m of height was modeled in the Plaxis 2D v20 software, and analyzes were carried out at different load rates for different drain conditions to examine the effects of load rates and drain conditions on the consolidation behavior. Since the model is symmetrical, to reduce the analysis time, the system is divided into two parts from the center of symmetry and a solution is realized for just one part. The hardening soil model, which takes into account the assumption that the soil becomes stronger with the deformation, is preferred as the soil model. The developed model is presented in Fig. 1 and the parameters of the soil layers and embankment are shown in Table 1.

Plane strain was considered as the analysis model, and the model boundaries were 100m horizontally and 30m vertically. Analyzes were carried out as phased construction, the initial conditions were analyzed in the first step, and in the second step, the embankment has 6m of height was activated and consolidation analysis was conducted.

Table 1. Material properties of embankment and soil layers

	Soil 1 (clay)	**Soil 2**	**Soil 3 (clay)**	**Soil 4**	**Embankment**
Soil model	Hardening soil	Hardening soil	Hardening soil	Hardening soil	Hardening soil
Drainage type	Undrained(A)	Drained	Undrained(A)	Drained	Drained
γ_{unsat}**(kN/m^3)**	18	18	18	17	19
γ_{sat}**(kN/m^3)**	20	20	19	18	20
E_{50}^{ref} **(kN/m^2)**	3000	30000	12000	40000	30000
c'ref (kN/m^2)	5	0.1	20	1	5
ϕ′ref (°)	25	37	28	38	40
Ψ(°)	0	7	0	8	10
k_x **(m/day)**	8.64E-6	17.28	86.4E-6	8.64	1.4
k_y **(m/day)**	8.64E-6	17.28	86.4E-6	8.64	1.4
K_0	Automatic	Automatic	Automatic	Automatic	Automatic
OCR	1.8	2.0	1.6	1.6	2.0

3. Discussion

The road embankment has 6m of height is completed at different durations at a constant rate and the excess pore pressures that occur during the loading are shown in graphs for the cases without PVD and with PVDs with 2m, 1m, and 0.5m of intervals (Figs. 2-5).

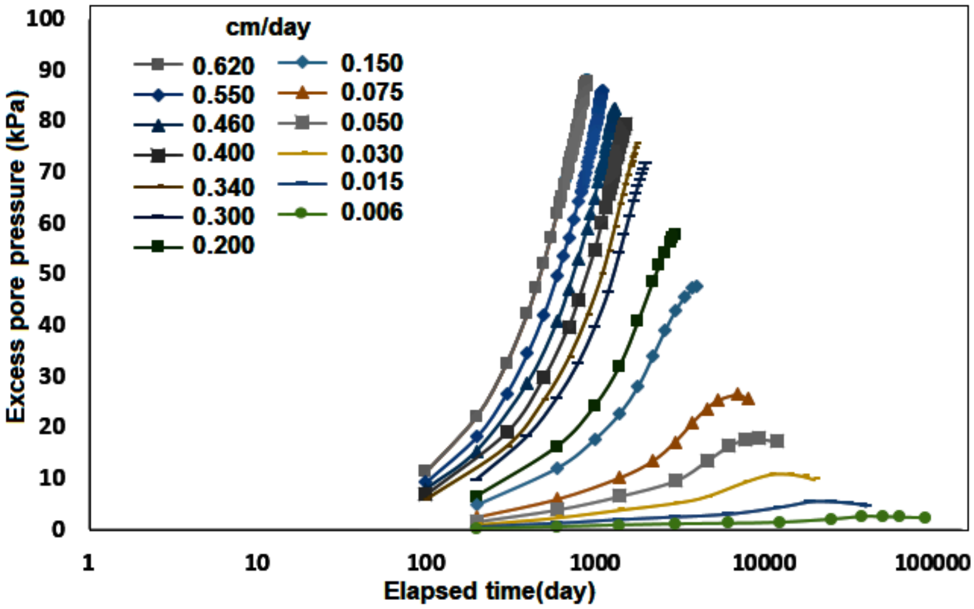

Fig. 2. Variations in the excess pore pressures below the embankment at different load rates in the case of the absence of PVD

In the case of without PVD, the excess pore pressure increases continuously till the end of the construction at load rates are more than 0.075 cm/day. In the cases that have load rates are less than 0.075 cm/day excess pore pressures increase in the first part but after a point, it starts to dampen.

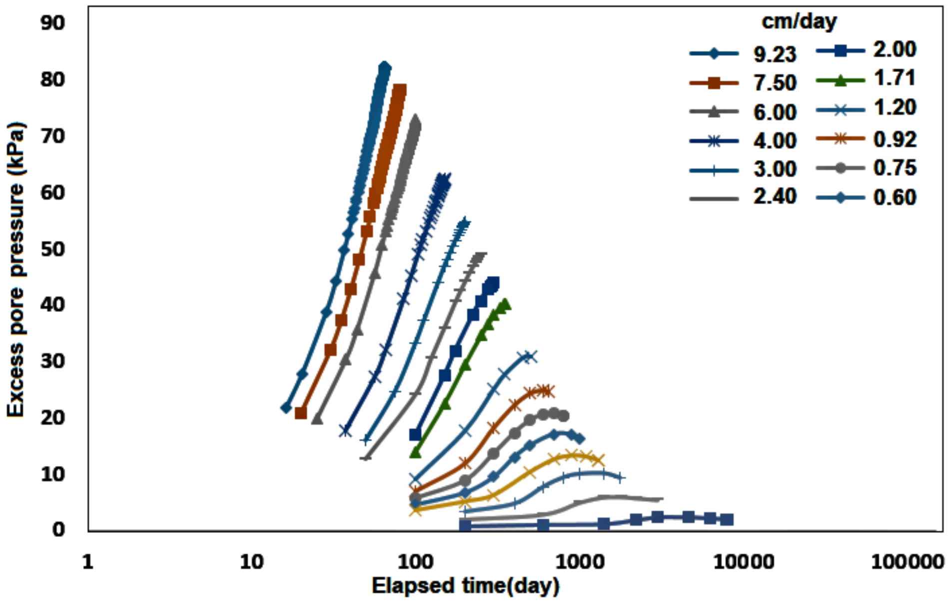

Fig. 3. Variations in the excess pore pressures below the embankment at different load rates in the case of PVDs with 2m intervals

In the case of with PVDs with 2m of intervals, the excess pore pressure increases continuously till the end of the construction at load rates are more than 0.92 cm/day. In the cases that have load rates are less than 0.92 cm/day excess pore pressures increase in the first part but after a point, it starts to dampen.

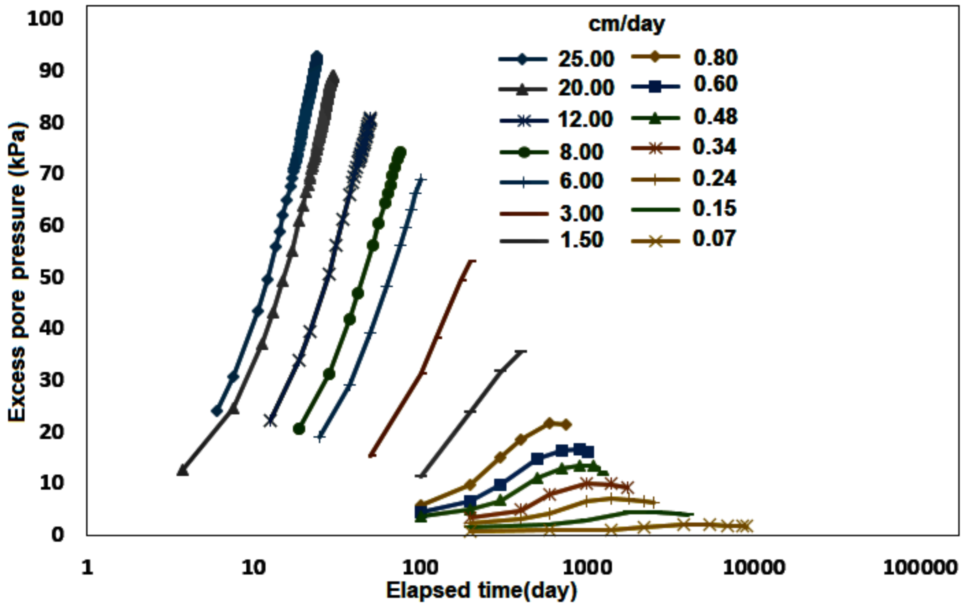

Fig. 4. Variations in the excess pore pressures below the embankment at different load rates in the case of PVDs with 1m intervals

In the case of with PVDs with 1m of intervals, the excess pore pressure increases continuously till the end of the construction at load rates are more than 0.8 cm/day. In the cases that have load rates are less than 0.8 cm/day excess pore pressures increase in the first part but after a point, it starts to dampen.

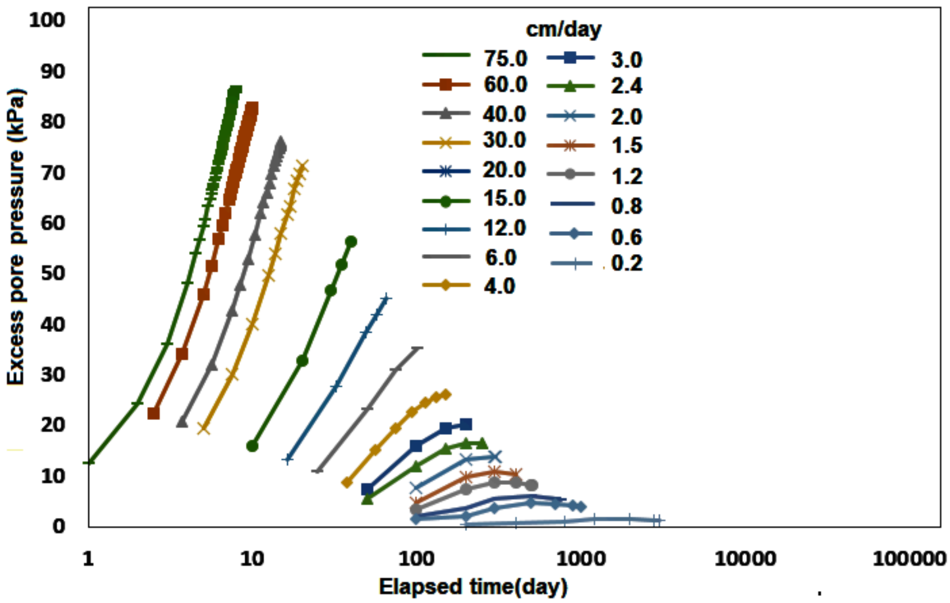

Fig. 5. Variations in the excess pore pressures below the embankment at different load rates in the case of PVDs with 0.5m intervals

In the case of with PVDs with 0.5m of intervals, the excess pore pressure increases continuously till the end of the construction at load rates are more than 2.4 cm/day. In the cases that have load rates are less than 2.4 cm/day excess pore pressures increase in the first part but after a point, it starts to dampen.

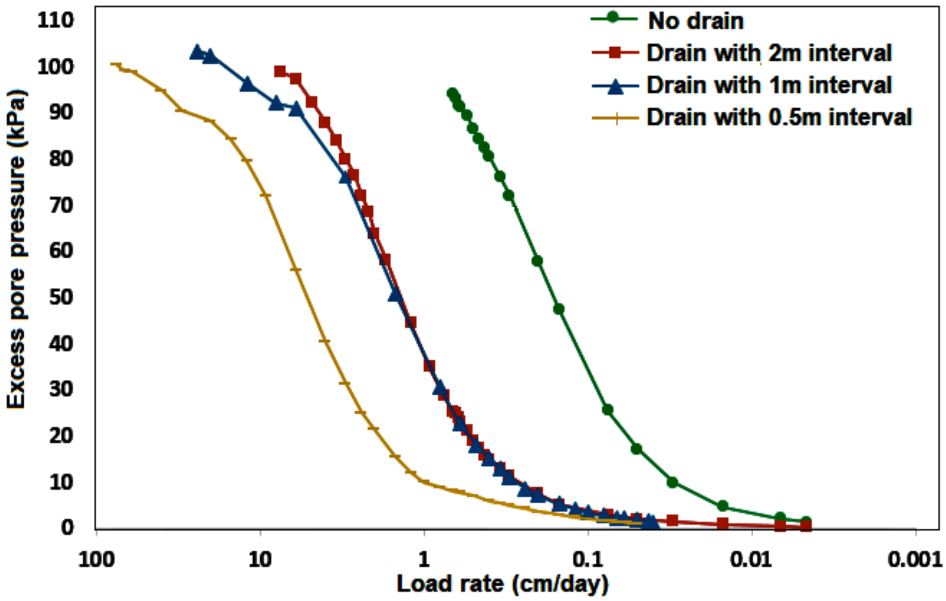

Fig. 6. The maximum excess pore pressure varies depending on the drain condition and load rate.

Maximum excess pore pressures for the cases that are with and without PVDs decrease with increasing load rates. It is observed that the behavior of the change in the excess pore pressure is similar, but similar excess pore pressures occur at, approximately 8 times for the case of 1m and 2m intervals of PVDs, and about 30 times for the case of 0.5m intervals of PVDs, faster load rates compared to the case without PVD (Fig. 6).

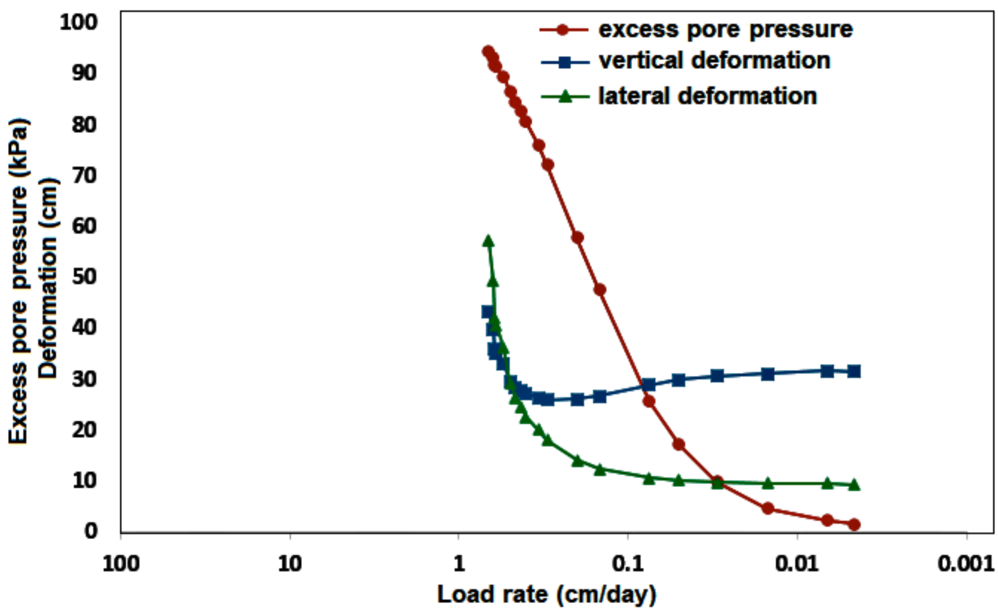

Fig. 7. In the absence of PVD, variations in the excess pore pressure, vertical and horizontal deformations are seen at various load rates.

The maximum horizontal and vertical deformations belonging to each case have different load rates are presented below as graphics (Figs. 7-10). The minimum vertical deformation in the condition that has no PVD is 26cm and the horizontal deformation is around 10cm. The minimum vertical deformation occurs at the load rate of 0.3 cm/day, and the minimum horizontal deformation occurs at the load rate of 0.08 cm/day.

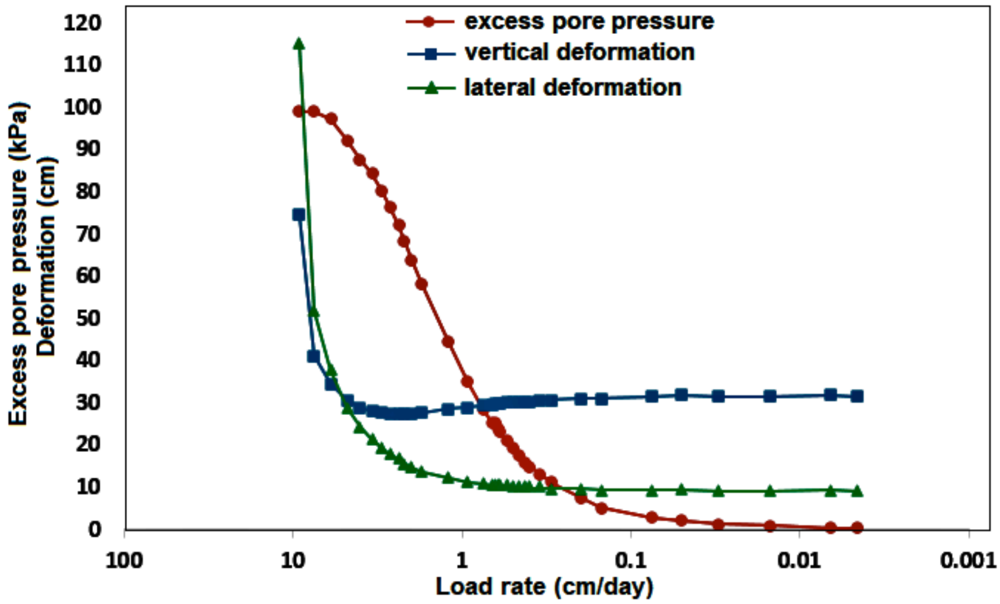

Fig. 8. Variations in the excess pore pressure, vertical and horizontal deformations in the case of PVDs with 2m intervals at varied load rates

The minimum vertical deformation that occurs in the case of drains with 2m intervals is 27cm and the horizontal deformation is around 10cm. The minimum vertical deformation occurs at the load rate of 2.4 cm/day, and the minimum horizontal deformation occurs at the load rate of 0.75 cm/day.

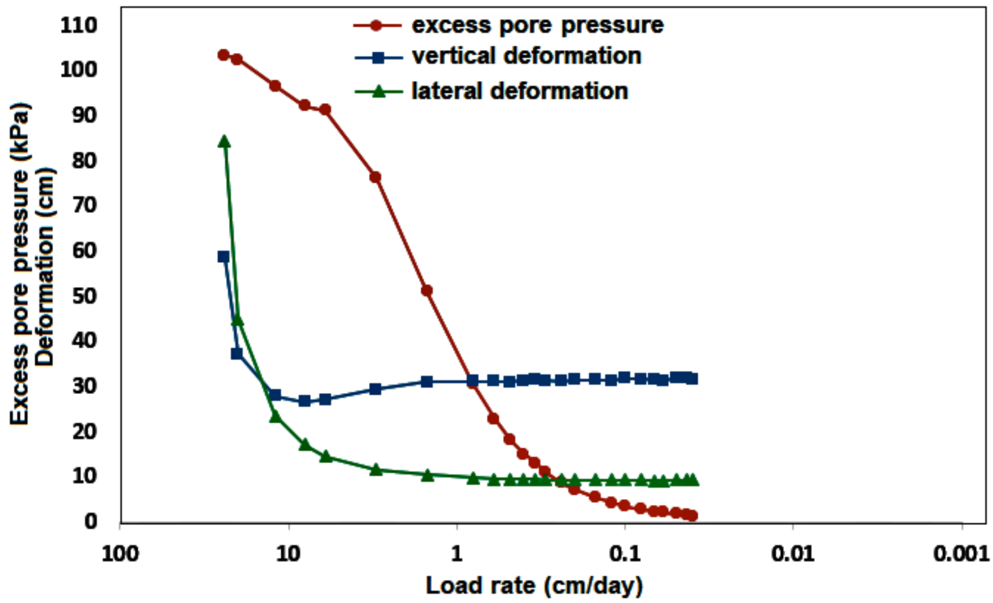

Fig. 9. Variations in the excess pore pressure, vertical and horizontal deformations in the case of PVDs with 1m intervals at varied load rates

The minimum vertical deformation that occurs in the case of drains with 1m intervals is 26cm and the horizontal deformation is around 10cm. The minimum vertical deformation occurs at the load rate of 8 cm/day, and the minimum horizontal deformation occurs at the load rate of 1.5 cm/day.

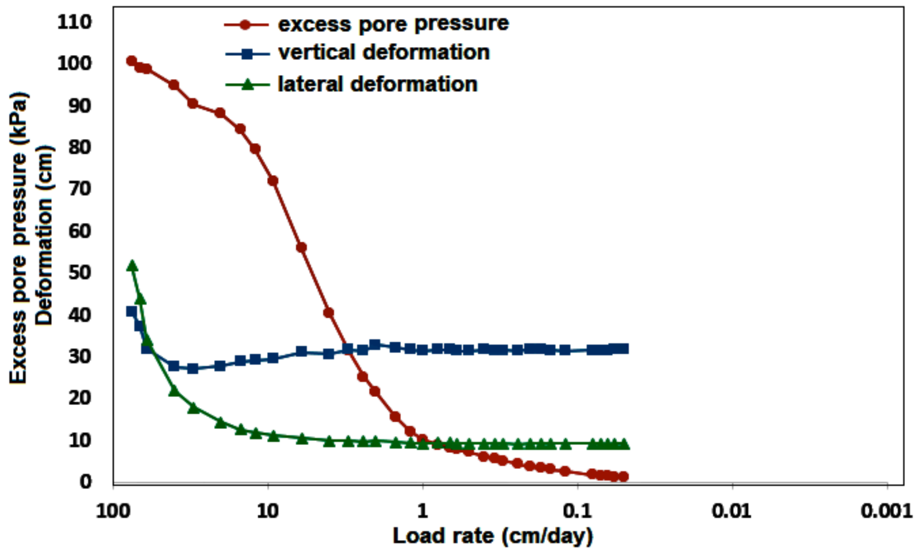

Fig. 10. Variations in the excess pore pressure, vertical and horizontal deformations in the case of PVDs with 0.5m intervals at varied load rates

The minimum vertical deformation that occurs in the case of drains with 0.5m intervals is 27cm and the horizontal deformation is around 10cm. The minimum vertical deformation occurs at the load rate of 30 cm/day, and the minimum horizontal deformation occurs at the load rate of 6 cm/day.

The maximum excess pore pressure decreases with the decrease of the load rate in both cases with and without PVD. Maximum horizontal and vertical deformations, decrease with the decrease in load rate to a limit but do not continue to decrease in slower load rates and remain almost constant.

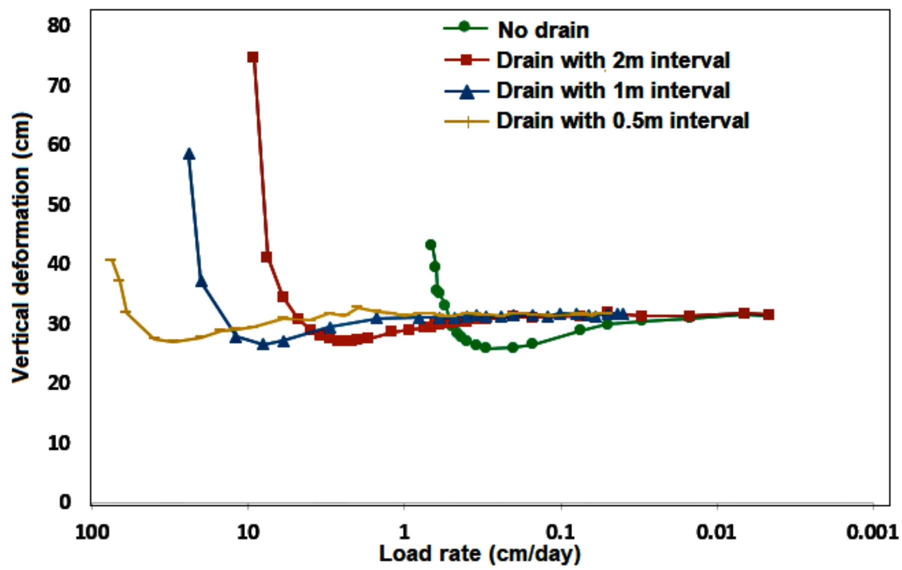

Fig. 11. Maximum vertical deformations in different drain conditions and at various load rates

Maximum vertical deformations occur in cases with different drain conditions that are similar in behavior and the minimum vertical deformations that occur for conditions with or without PVD is around 26 cm. It is seen that the load rates that cause minimum vertical deformation are 8, 27, and 100 times faster in the situations with PVDs with 2m, 1m, and 0.5m of intervals compared to the situation without PVD, respectively (Fig. 11).

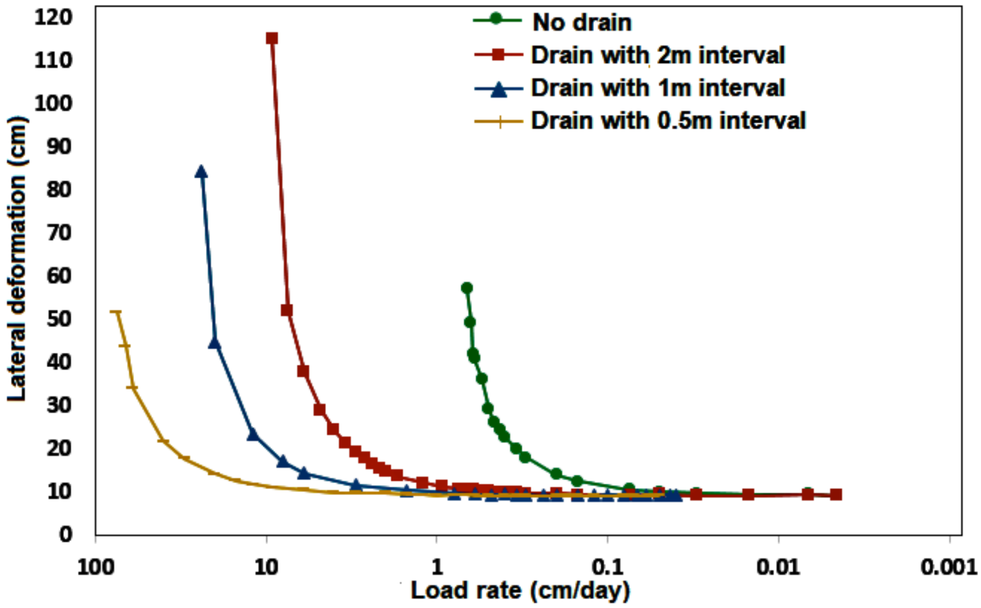

Fig. 12. Maximum lateral deformations in different drain conditions and at various load rates

Maximum lateral deformations occur in cases with different drain conditions that are similar in behavior and the minimum lateral deformations that occur for conditions with or without PVD is around 10cm. It is seen that the load rates that cause minimum lateral deformation are 9, 19, and 75 times faster in the situations with PVDs with 2m, 1m, and 0.5m of intervals compared to the situation without PVD, respectively (Fig. 12).

4. Conclusions

Within the scope of the study, excess pore pressures and deformations that will occur in the clay soil layers due to the filling sitting on the soil section containing low permeability clay soils were investigated. In this context, an embankment model with a height of 6 m has been analyzed for different vertical drain spacing situations and at different constant speeds, where the 6 m loading will be completed at different times. The effects of loading speed, vertical drain usage, and spacing on consolidation speed, deformations, and excess pore pressures were investigated as a result of the analyzes performed in the cases without PVD, and with PVDs having 2m, 1m, and 0.5m of intervals. The following results have been achieved:

- Maximum excess pore pressures, vertical deformations, and horizontal deformations that occur as a result of the embankment load at different rates are similar in behavior.

- Both with and without PVDs, the maximum excess pore pressures decrease with the increase in load rate.

- Maximum lateral and vertical deformations, decrease with the decrease in load rate to a limit but do not continue to decrease in slower load rates and remain almost constant.
- The minimum vertical deformations and lateral occur for conditions with or without PVD is around 26 cm and 10cm, respectively.
- Similar maximum excess pore pressures occur at, approximately 8 times for the case of 1m and 2m intervals of PVDs, and about 30 times for the case of 0.5m intervals of PVDs, faster load rates compared to the case without PVD.
- The load rates that cause minimum vertical deformation are 8, 27, and 100 times faster in the situations with PVDs with 2m, 1m, and 0.5m of intervals compared to the situation without PVD, respectively.
- The load rates that cause minimum lateral deformation are 9, 19, and 75 times faster in the situations with PVDs with 2m, 1m, and 0.5m of intervals compared to the situation without PVD, respectively.

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