Numerical Modeling of Prefabricated Vertical Drain for Soft Clay using ABAQUS

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Abstract. Construction, buildings and infrastructure founded on soft clays are often affected by settlement problem. Therefore, Prefabricated Vertical Drain (PVD) is one of the best solutions to accelerate soil consolidation by shortening the drainage path. In this study, numerical investigation was carried out to pursue a better understanding of the consolidation of soft clay improved with PVD. The consolidation process accelerated by vertical drains was analysed using the ABAQUS to create an elastic model with surcharge of 50 kPa. The aim of this study is to compare the settlement and the time required to consolidate the soft soil at different drain spacings (1.0m, 1.5m and 2.0m) for two different lengths of PVD. The results showed that the time required to consolidate the soft soil (100 % consolidation) at 12 m and 20 m length of PVD for different spacings are in the range of 3 months to 66 months. Rate of settlements are increasing with the decreasing of drain spacing for both lengths of PVD. For the excess pore water pressure at 12 m and 20 m length of PVD with different spacings, it can be concluded that the smaller design spacing, the time required for consolidation is also decreased.

Introduction

An increasing proportion of building development takes place in areas of poor ground and this poses challenges for the geotechnical engineers to provide satisfactory foundation performance at low cost. Construction, buildings and infrastructure founded on soft clays are often affected by the stability and settlement problems. A proportion of the final settlement can be achieved prior to construction by preloading the soil, but this often takes 6 to 9 months or more to achieve [1]. The larger the preload, the less time it will take to achieve the final settlement, however great care is needed not to cause premature failure of the ground. Prefabricated Vertical Drain (PVD) with surcharge may be a cost-effective way of reducing the settlement due to lightly distributed loads from roads or residential buildings.

Prefabricated vertical drains are band shaped (rectangular cross-section) product consisting of a geotextile filter material surrounding a plastic core. The size of PVD is typically 10 cm wide by 3 to 4 mm in thickness [2]. The material consist of a plastic core to create channels which are wrapped in a geotextile filter. The main function of the filter of the vertical drain is to ensure that fine particles cannot pass through and clogging the drainage channels in the core [3]. PVD is installed vertically into the soil to let the water flow from the weak soil underground to the surface, in order to speed up the consolidation process. After the consolidation process was completed in certain period of time, the roads, dikes, runways, railways, or any structures can be safetly constructed on the ground.

The aim of vertical drain installation is to shorten the drainage paths of water and thereby reduce the time required to consolidate the soil which induced by surcharge load. The effectiveness of the vertical drain installation depends on the drain spacing and the discharge capacity of the drains [4]. In soil improvement works, vertical drains only accelerate the primary consolidation process of the subsoil and they do not reduce the secondary consolidation. Therefore, surcharging has to be used in conjunction with vertical drains to reduce post-surcharge secondary compression

Drain Properties

Diameter of influence zone. As shown in Fig. 1, the equivalent diameter of the influence zone (D_e) can be found in terms of the drain spacing (S) as follows [3]:

$$D_e = 1.13S \text{ for drains installed in a square pattern} \quad (1)$$

and

$$D_e = 1.05S \text{ for drains installed in a triangular pattern} \quad (2)$$

Drains in a square pattern may be easier to layout and control during installation in the field, but a triangular pattern usually provides a more uniform consolidation between them.

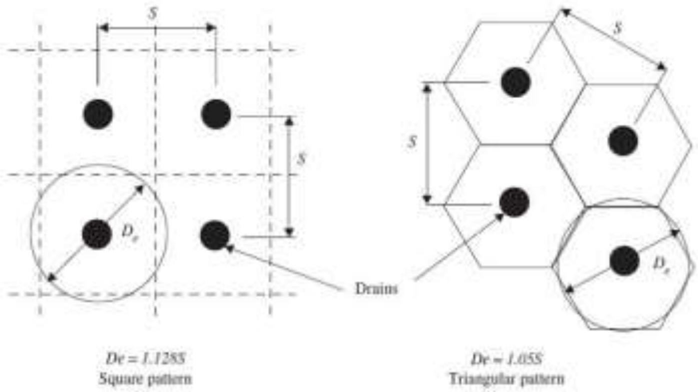


Figure 1: Typical drain installation patterns and the equivalent diameters [3].

Equivalent drain diameter of band-shaped vertical drain. Most prefabricated drains have rectangular cross-section band-shaped as shown in Fig. 1, but for design purposes, the rectangular section (width a, thickness b) has to be converted into an equivalent circle with a diameter of d_w, because the conventional theory of radial consolidation assumes that drains are circular. The following typical equation is used to determine the equivalent drain diameter:

$$d_w = 2(a + b)/\pi \text{ [3]} \quad (3)$$

Smear Effect. As the installation of PVD is usually carried out by a statically or sometime vibratory driven mandrel, the degree of disturbance to the surrounding soil is related to the size and shape of the mandrel as well as to the size of the detachable shoe or anchor. The disturbed zone around the drain is called smear zone. Due to the disturbance, the permeability and the pre-consolidation pressure of the soil are reduced, and the compressibility increases. The decrease in horizontal permeability is most significant. For most of the soft clay, silt and organic soil, the ratios of k_h/k_v are generally less than 3. For marine clay with homogeneous deposit environment, the ratio of k_h/k_v is around 1 to 1.5; for lacustrine clay, varved clay and clays with discontinuous lenses and layers of more permeable materials, the ratios of $k_h/k_v$are in the range of 2 to 5 [5,6].

Methodology

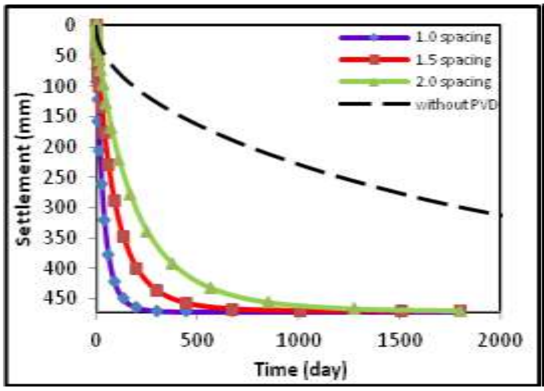
The single unit of PVD was modelled using ABAQUS software with different drain length. Due to their circular shape of influence zone, the axisymmetric model was used for analysis. The soil parameters used for modeling purposes is shown in Table 1. Three models with varying spacing (1.0m, 1.5m and 2.0m) and two models with different drain lengths (12m, 20m) have been developed. The radius of equivalent drain was calculated based on the equation proposed by Hansbo [3], while the radius of smear zone determination is based on proposed correlation as suggested by Bergado et al. [6]. A two-dimensional axisymmetric mesh was used. The element chosen was a four-node axisymmetric quadrilateral element with bilinear displacement and bilinear pore pressure variations. For the boundary condition, the vertical and horizontal displacements were fixed at the bottom part of the model. For left and right side of the model, the horizontal displacement was also fixed to simulate the frictionless interface between the soil model and adjacent soil. The geostatic command was invoked to make sure that equilibrium is satisfied within the clay layer. The consolidation pressure of 50 kPa has been selected for the model to simulate the maximum past pressure of undisturbed sample at 3 to 4 m depth.

Table 1: Properties of elastic soil model and PVD

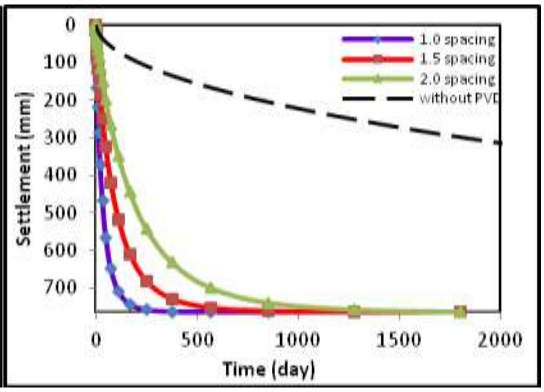
Properties	
Density, ρ	1835 kg/m^3
Young's Modulus, E	30000 kN/m^2
Poisson ratio, ν	0.25
Void ratio, e	1.2
Coefficient of permeability of the PVD, k_w	1.0×10^{-3} m/s
Coefficient of permeability of the smear zone, k_s	0.6×10^{-9} m/s
Coefficient of permeability of the undisturbed zone, k_h	1.8×10^{-9} m/s
Radius of equivalent drain, r_w	0.03 m
Radius of influence zone, r_e	0.53m, 0.79m & 1.05m
Radius of smear zone, r_s	0.09m

Results and Discussions

To investigate the effect of PVD installation pattern, three different drain spacings were considered in the analysis. Figure 2(a) and 2(b) show the rate of settlement with different drain spacings for the drain length of 12 m and 20 m respectively.



(a)

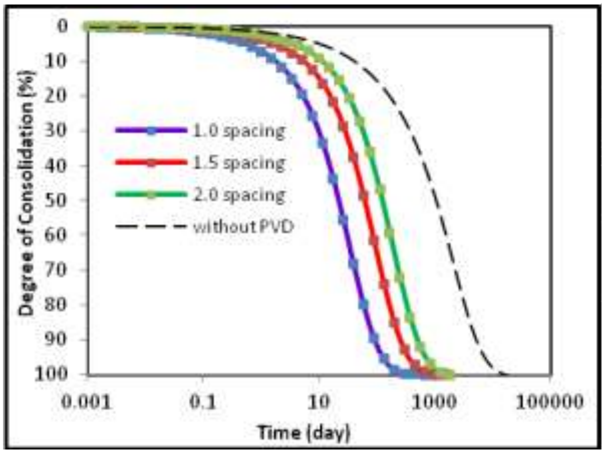


(b)

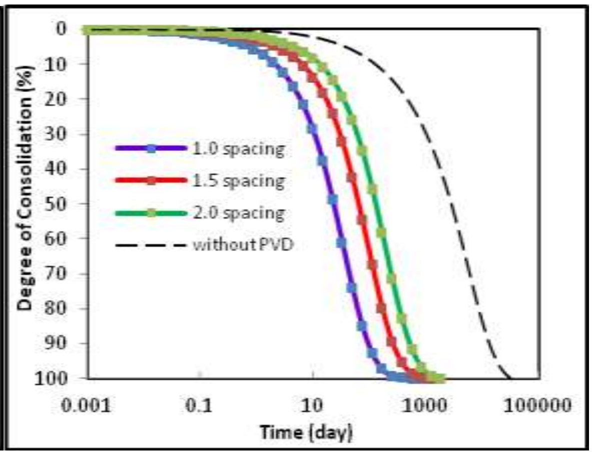
Figure 2: (a) Settlement for 12 m length with different spacing (b) Settlement for 20 m length with different spacing.

The primary settlement for the model with 1.0 m spacing end within a short period of time compared with 1.5 m and 2.0 m spacing for both lengths as shown in Fig. 2. In addition, the rates of settlements are increasing with the decreasing of drain spacing for both length of PVD due to the decreasing of the horizontal drainage path. In term of the drain length, the rate of settlements for 12 and 20 m of the drain length were also compared with the settlement without PVD. It can be seen that from the graph, the rate of settlements without PVD for both lengths were smaller than those with PVD at different spacings. The final magnitude of settlements with PVD at different spacings are considerably faster than the model without PVD. For all different spacings with PVD of 12 m length, the final magnitude of settlements are almost the same which are approximately 480 mm, while for 20 m length are 770 mm. However, in the early stage of settlement for 12 m and 20 m length, the rate of settlements are greater when the spacing were reduced.

As shown in Fig. 3, the degree of consolidation without PVD for 12 m and 20 m lengths take approximately more than 9000 days (300 months) to complete which is longer than the model with PVD installation. Degree of consolidations are also completed (100 %) at a short period of time for both lengths when drainage spacings were reduced. The degree of consolidation for all spacings are same between 12 m and 20 m length of PVD. Therefore, the length of PVD has little or no effect on the consolidation time for all spacings. The magnitude of settlement at the smaller spacing could attribute to the smear effect [7]. Thus, this has caused greater disturbance to the soil when PVDs were installed at the closer spacing. The greater settlement observed in the zone with smaller drain spacing could also be due to the secondary compression. The soil would reach the virgin consolidation range earlier when the rate of consolidation increased which caused the secondary compression to develop earlier at a higher rate [8]. If the completion time is the most important design consideration, another way to reduce the consolidation time is to use a larger than required surcharge to consolidate the soil.



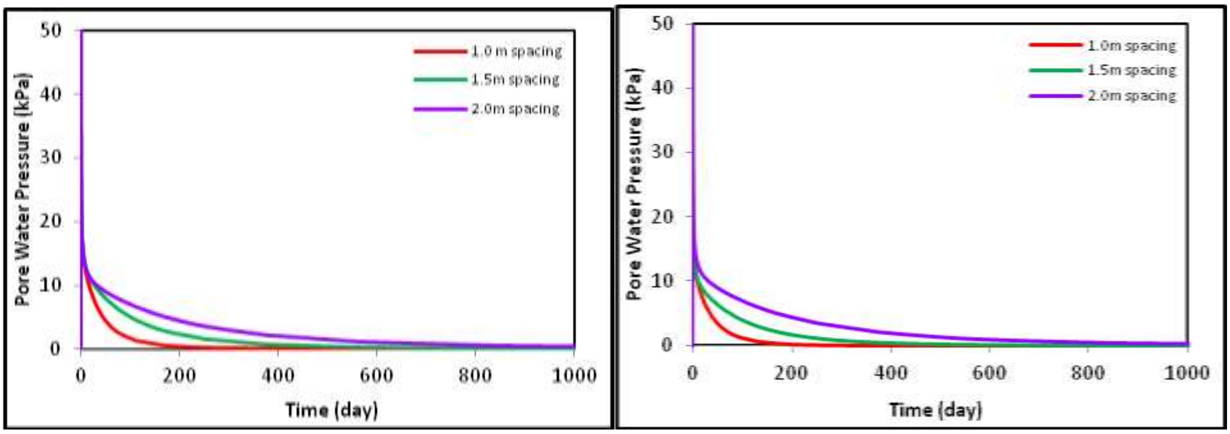
(a)



(b)

Figure 3: (a) Degree of Consolidation Graph for 12 m Length of PVD at three Different Spacing and Without PVD (b) Degree of Consolidation Graph for 20 m Length of PVD at three Different Spacing and Without PVD.

The 1.0, 1.5 m and 2 m spacing had achieved 100% degree of consolidation in the range of 100 days (3 months) to 2000 days (66 months) for both lengths of PVD as compared to without PVD which has about more than 9000 days (approximately 300 months). It clearly shows that the time required to reach 100% degree of consolidation is much shorter if the PVD is being used as compared to without PVD. The water flows of this model are one-way drainage which is the top of the drain boundary. The different value of *k* at drain, smear and undisturbed clay are related to the water flows on consolidation process out of this model. Movement of water from the model become slower and take a longer time, particularly at the bottom of the model, where the water flows above the drain boundary(top of the model). Fig. 4 illustrates that at three different spacings, the excess pore pressures were decreased with time and the length of drains.The excess pore water pressure has increased between 10 to 20 kPa initially and decreased at 0 kPa after certain periods of time. The 1.0 m, 1.5 m and 2.0 m spacings were decreased at 0 kPa for about 200 days, 400 days and 800 days respectively for both lengths. Therefore, it clearly shows that the both lengths of PVD have no effect in term of the excess pore water pressure trend.



(a) (b)

Figure 4: (a) Pore Water Pressure Graph for 12 m Length at three Different Spacing(b) Pore Water Pressure Graph for 20 m Length at three Different Spacing.

Conclusions

In this paper, a numerical design and analysis for vertical drains incorporating with 50 kPa surcharge was developed for axisymmetric modeling in different length (12 and 20 m) and with different spacing (1.0 m, 1.5 m and 2.0 m) and also compared with and without PVD. After the analysis, the settlement, degree of consolidation and excess pore water pressure are reliable and comparable with past studies. Installation of the PVD significantly increased the rate of settlements with the decreased of drain spacing for 12 and 20 m length of PVD. For the excess pore water pressure at 12 and 20 m length with different spacings, it can be concluded that the smaller design spacing, the time required for water to dissipate are also decreased. Therefore, an effective drainage system and proper design are the key for success of ground improvement by surcharge with PVD installation.

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