Influence of the Rate of Construction on the Response of PVD Improved Soft Ground

Priyanka Talukdar and Arindam Dey

Abstract The major problem of embankment on soft soil foundations is to overcome excessive settlement, initiating undrained failure of the infrastructure, provided proper ground improvement is not planned. One of the most widely used solution to this problem is to stabilize the soft soil foundations under embankment, by the installation of prefabricated vertical drains (PVD), which is carried out throughout the world. It is observed that the installation of vertical drains highly increases the settlement rate, improves pore water pressure dissipation, and decreases the lateral deformation of the soft clay foundation. The paper presents a numerical model to analyze the response of PVD-reinforced soft soil under embankment loading to the rate of embankment construction by finite element modeling. Apart from predicting the dissipation of excess pore water pressure, lateral displacement and the resulting consolidation settlement with time, the stability factors for different rates of embankment construction have been studied. It is observed that higher stability is manifested by the embankment having a slower rate of construction.

Keywords Embankment · Soft soil · PVD · Finite element modeling · Rate of construction

1 Introduction

The exact estimation of the nature of embankments constructed on soft clay stabilized with vertical drains has posed to be a challenging problem, although significant advancement has been made in the past few years through extensive numerical modeling. Soft soil foundations can cause excessive settlement, initiating undrained failure of the infrastructure if proper ground improvement is not carried

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out (Indraratna et al. 1992). Therefore, it is imperative to apply adequate ground improvement techniques to the existing soft soils prior to the construction to prevent unacceptable excessive and differential settlement along with enhancement of the bearing capacity of the foundations. Among various methods of soft soil improvement, the installation of prefabricated vertical drains (PVD) is one of the well-established and effective techniques practiced worldwide (Wang 2009). The other forms of such hydraulic installations commonly functioning as vertical drains include stone columns and sand drains.

As reported by researchers (Guetif et al. 2007), vertical drains, such as stone columns, not only act as reinforcement, possessing greater strength and stiffness in comparison with the surrounding soil, but they also speed up the time-dependent dissipation of excess pore water pressure caused by surcharge loading due to shortening of the drainage path. Various analytical and numerical solutions have already been developed for understanding the load transfer mechanism of soft soil reinforced with stone columns. Among the most significant contributions, the studies by Wang (2009), Alamgir et al. (1996) are noteworthy.

Well-documented classical solution for vertical drains (single-drain analysis) has been carried out (Barron 1948; Hansbo 1981) and has frequently been utilized in settlement prediction, especially along the centerline of the embankment. Due to the fast development in computer capability and increasing popularity of the finite element method in geotechnical engineering, a detailed numerical analysis of the behavior of the soft soil stabilized with multiple vertical drains can now be carried out. The characteristics of vertical drains and their smear effects have been well-documented by Dey (2008). Although single-drain analysis is often sufficient to model the soil behavior along the embankment centerline (symmetric geometry), multidrain analysis is essential to incorporate the effect of changing gravity load along the embankment width to accurately predict settlements and lateral displacements. Limited case studies employing various forms of multidrain analysis have been described in the recent past (Indraratna et al. 1994; Chai et al. 1995; Indraratna and Redana 1997; Anvesh Reddy and Dey 2014). The effect of strain rate on the strength of soft cohesive soils has been extensively investigated since the early work of Terzaghi (1931) followed by Casagrande and Wilson (1951). Experimental results have consistently shown that the loading rate has an effect on the undrained shear strength and that stress–strain relations of natural soft clays are strain rate-dependent (Perloff and Osterberg 1963; Bjerrum 1972; Lo and Morin 1972; Graham et al. 1983; Kulhawy and Mayne 1990). Bjerrum (1973) attributed the time effect to the ‘interparticle creep’ along the direction of shear due to the presence of the viscous absorbed water between clay particles. The undrained creep during shear in the soil gives rise to increased pore pressures, decreased effective stresses, and decreased strengths; consequently, the undrained shear strength is rate-dependent (Ladd and Foott 1974).

In this study, a multidrain analysis has been carried out to understand the response of an embankment on PVD improved soft soil to the varying rates of construction.

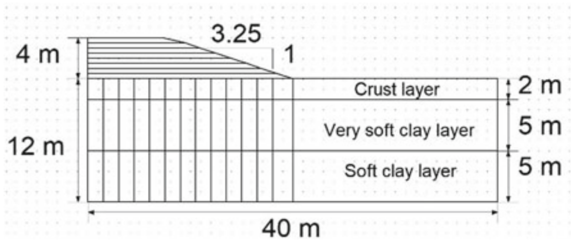

Fig. 1 Model used for the present study

2 Methodology

2.1 Model for the Present Study

In the present work, a simple FE model has been used to understand the effect of the rate of construction of the embankment on the foundation improved by PVDs. The model used in the study, along with its relevant dimensions, is shown in Fig. 1. The embankment is constructed to a height of 4 m with 3.25H:1V side slope. The embankment is constructed by eight lifts, each lift having a height of 1 m. The foundation layer consists three layers; starting from the bottom, it consists of 5 m soft clay layer, 5 m very soft clay layer, and 2 m overconsolidated crust layer.

The horizontal spacing between the vertical drains 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).

The sand blanket is not included in the model as a separate material. The effect of the sand blanket 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 sandy material. The boundary condition simulates this effect. This is much simpler than trying to include the sand blanket in the model which achieves the same objective.

2.2 Materials

The soft clay and very soft clay are characterized here by using the modified Cam-Clay (MCC) constitutive model available in Sigma/W. It is an ideal constitutive model for this case, since it can account for pore pressure changes arising from mean effective stress and deviatoric stress changes, which is an important feature in soft clay behavior. The soil properties used to represent the stress–strain behavior and strength of the soft clay and very soft clay are shown in Table 1. The stiffness of the soil is controlled by the slopes of the isotropic normal compression line (Lambda) and the unloading-reloading line (Kappa).

Table 1 Soil properties for the soft clay and very soft clay layers

Parameter	Soft clay	Very soft clay
Constitutive model	Modified clam clay	Modified clam clay
Over-consolidation ratio	1.5	1.5
Poisson's ratio (ν)	0.334	0.334
Lambda (λ)	0.5	0.5
Kappa (κ)	0.1	0.1
Initial void ratio	2.7	2.75
Friction angle (φ')	25.4	23.1
Unit weight (γ) (kN/m^3)	15	14
K_{sat} (m/day)	2.5e−005	5.67e−005

Table 2 Soil properties for the crust layer

Parameter	Soft clay
Constitutive model	Linear elastic
Young's modulus E (kPa)	10,000
Poisson's ratio (ν)	0.334
Unit weight (γ) (kN/m^3)	16
K_{sat} (m/day)	0.000248

The crust layer has been assigned a linear elastic constitutive model. This is, in part, used for numerical stability, as beyond the toe of the embankment, the in situ stresses are very small and the ground will tend to heave and go into tension. This can cause numerical convergence problems, since the elastic-plastic model, for example, cannot accommodate tension. Using a linear elastic model avoids this problem. The properties of the crust layer have been shown in Table 2.

In a Sigma/W fully coupled consolidation analysis, it is necessary to define a volumetric water content (VWC) function and a hydraulic conductivity function, even though the soil is saturated and remains saturated during the embankment loading. The volumetric water content function remains unused for saturated conditions, but is nonetheless required. An approximate estimated function is consequently adequate. As with the VWC function, an approximate hydraulic conductivity function is adequate, since only the saturated conductivity (K_{sat}) is used in the analysis. The VWC and the hydraulic conductivity functions for the soft clay, very soft clay, and the crust layers have been shown in Figs. 2 and 3, respectively.

The embankment fill is modeled using a simple linear elastic model with total stress parameters. The material used for the embankment construction is coarse sand and gravel. The pore pressure for such a material can be ignored in the numerical model. This is achieved in Sigma/W by assigning 'total stress material properties' to the fill. Hydraulic properties are consequently not required for the fill. All other relevant material properties are listed in Table 3.

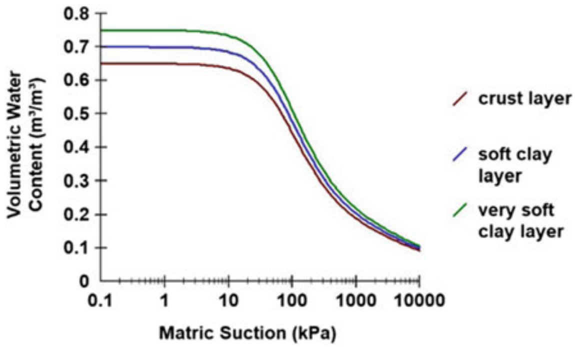

Fig. 2 Volumetric water content functions

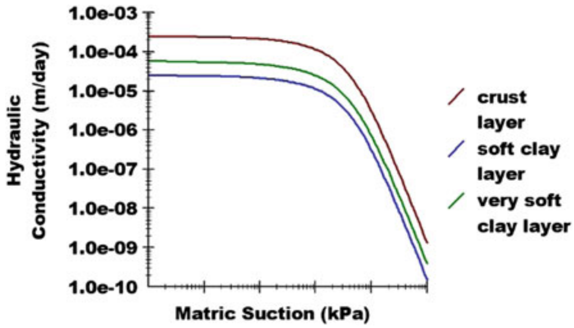

Fig. 3 Hydraulic conductivity functions

Table 3 Soil properties for the embankment fill

Parameter	Soft clay
Constitutive model	Linear elastic
Young's modulus E (kPa)	10,000
Poisson's ratio (ν)	0.334
Unit weight (γ) (kN/m^3)	18

2.3 Analyses Techniques

An initial in situ analysis has been carried out in Sigma/W to establish the initial ground stresses. The K_o condition in Sigma/W is specified through Poisson's ratio. The specified unit weights are used to apply the self-weight of the material. An initial water table has been specified along the ground surface during the in situ analysis. The subsequent sequential loading process carried out on the foundation, in the form of addition of embankment lifts, which has been modeled stage-wise using the 'coupled stress pore water pressure (PWP) analysis' approach. The embankment was constructed in eight different lifts, each lift having a height of 1 m. Three different rates (0.5, 0.05, and 0.005 m/day) have been used to construct the embankment. A stress-based stability analysis had been performed after the end of construction, with the aid of the Slope/W module in order to obtain the corresponding stability values. The entry–exit specification had been used to define a wide range of circular slip surfaces in the Slope/W. The boundary conditions are, in essence, the driving force which results in the solutions of the numerical problems. In the present simulation, the horizontal displacements along the left and the right sides of the foundation have been fixed, whereas the displacement of the bottom has been fixed in both horizontal and vertical directions. A zero-pressure boundary condition has been used along the ground surface to model the effect of a sand blanket.

3 Results and Discussions

3.1 Stability Analysis (With and Without PVDs)

Stress-based stability analysis was performed for the models to check the variation of the FoS with the different rates of construction. The factor of safety values for the different rates has been shown in Figs. 4a–c and 5a–c. The figures show the stability values for the three different rates for two different cases: without the installation of the PVDs and with the installation of PVDs.

These results demonstrate significant variation in stability of the embankment with the rate of construction. The stability factors for very rapid construction rates, which will lead to undrained behavior of the foundation soil, are very less as compared to the stability values for slow construction rates which permit complete drainage of the foundation soil. The analysis also indicates that installation of the PVDs results in higher stability values.

3.2 Seepage and Deformation Analysis (With PVDs)

The build-up of excess pore water pressure in the foundation at the end of construction of the embankment, near its centerline, for the three different rates has been shown in Fig. 6.

Figure 6 clearly indicates that the rise of excess PWP in the soft soil for rapid rates is higher when compared to the excess PWP values for slow rate of construction. The maximum value of excess PWP for 0.005 m/day is 29.02 kPa, whereas it is 75.4 kPa and 110.7 kPa for the construction rates of 0.05 m/day and 0.5 m/day, respectively.

The development of lateral displacements in soft clay foundations during and after the construction of embankments has been the subject of numerous studies in recent years. The observations of the detrimental effect of lateral displacements on the behavior of adjacent structures have resulted in the need for such studies. For example, in the particular case of piles installed close to or within embankments, lateral displacements have been found to produce bending moments (Heyman

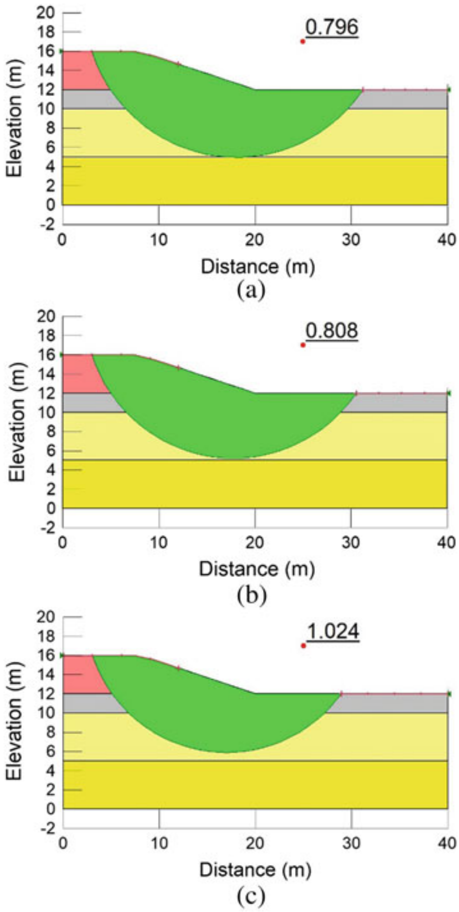

Fig. 4 Stability of embankment on soft soil without PVDs **a** rate 0.5 m/day **b** 0.05 m/day **c** 0.005 m/day

and Boersma 1961), resulting in undesirable movements of piled bridge abutments (Marche and Chapuis 1974), and can even lead to the structural failure of the piles (Marche and Lacroix 1972). On the other hand, there has been a suggestion that lateral displacements can be considered as a good indicator of the stability of embankment foundations (Franx and Boonstrag 1948). The variation of the lateral displacements of the soft soil foundation, at the end of construction time, just below the toe region has been shown in Fig. 7.

Figure 7 indicates that varying the rates of construction did not pronounce much variation in the lateral displacements. The lateral displacements for all the rates give similar trend, and the variation in their magnitudes is not substantial. This can be attributed to the fact that the variation of excess PWP in the foundation for different

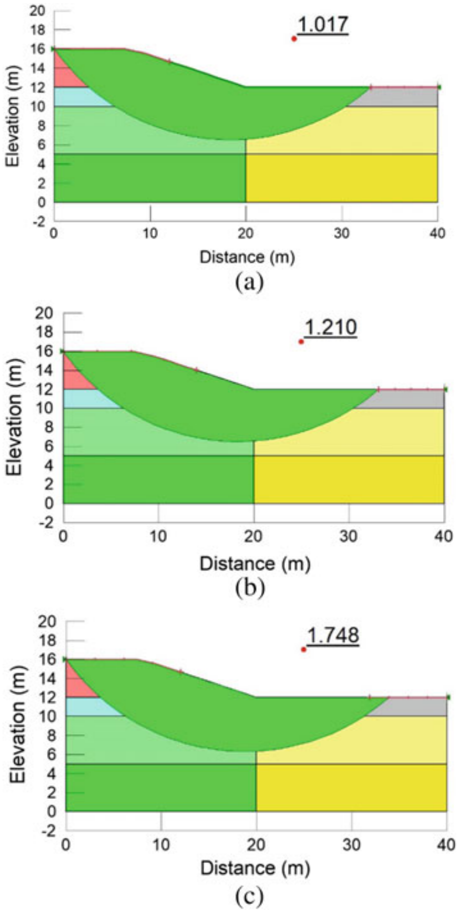

Fig. 5 Stability of embankment on soft soil with PVDs **a** rate 0.5 m/day **b** 0.05 m/day **c** 0.005 m/day

rates of construction is high below the embankment, and it reduces near and beyond the toe region as shown in Fig. 8.

In Fig. 8, the excess PWP was calculated at an elevation of 8 m along the distance from the centerline of the embankment. It is very clearly understood that the excess PWP values below the embankment is very high, and it reduces as it is measured toward the toe. This nature is consistent for all the three different rates of construction. The excess PWP is being negligible near the toe region irrespective of the different rates; these rates will not pronounce any significant variation in the lateral displacement of the soft soil foundation near the toe region.

The ground surface settlement profiles for the three different rates at the end of the construction are shown in Fig. 9. The figure indicates that dissipation of excess PWP at slow rates results in higher settlements below the embankment as compared to the settlements at rapid rates.

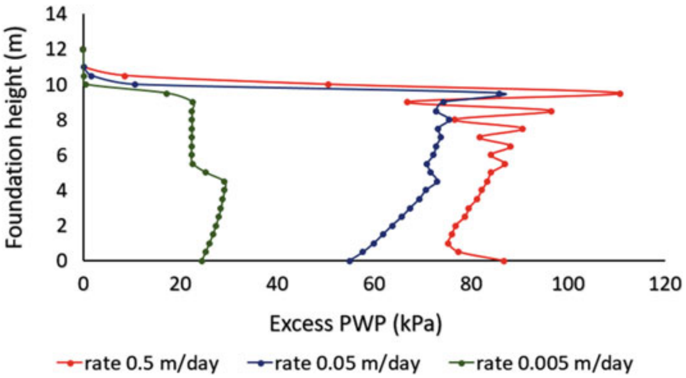

Fig. 6 Variation of excess PWP at the centerline of the embankment for different rates of construction

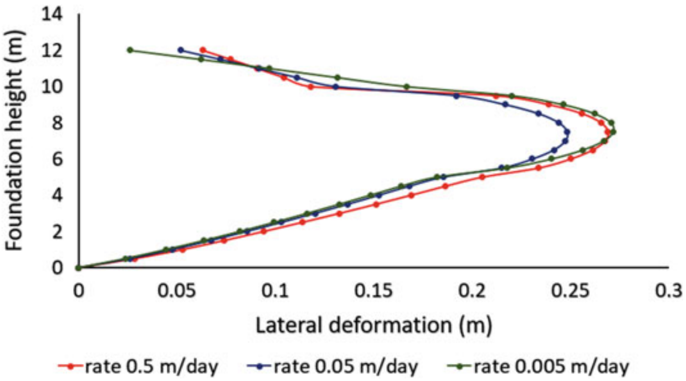

Fig. 7 Variation of lateral displacement below embankment toe for different rates of construction

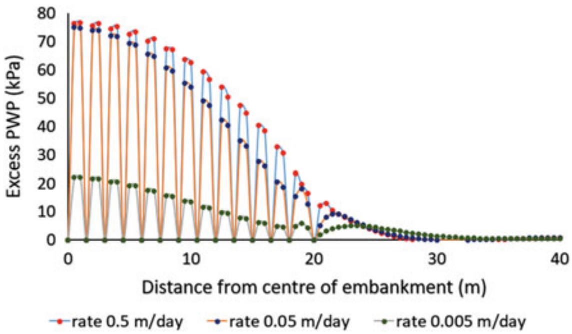

Fig. 8 Variation of excess PWP in the foundation from the center of embankment

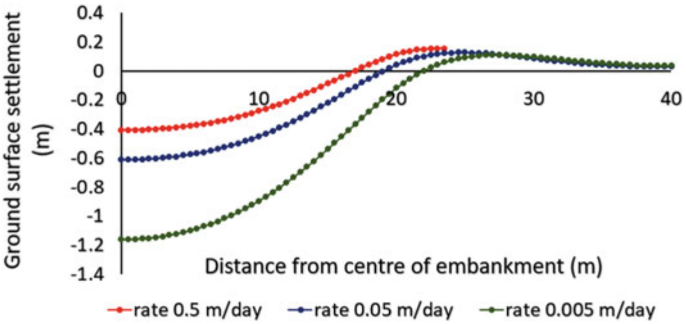

Fig. 9 Ground surface settlement for different rates of construction

In Fig. 9, the maximum settlement of 1.2 m is observed for 0.005 m/day, while the same is noted as 0.6 m and 0.4 m for the construction rates 0.05 m/day and 0.5 m/day, respectively. Beyond the toe region, the in situ stresses are small and the ground has a tendency to go into tension, which is manifested as a heave for all the different rates.

The settlements for the different rates have been presented in Fig. 10a, showing the deformed mesh, along with the vertical displacement contours at the end of construction (8, 80, 800 days).

Figure 10 shows that, the faster rate of construction induces lesser settlement as it results in slower dissipation of excess PWP.

4 Conclusions

The study aimed at the response of the embankment on PVD improved soft soil to the different rates of construction. An embankment on soft soil improved by the installation of PVDs has been simulated for three different construction rates. Following are the conclusions obtained from the analyses:

(a) Installation of PVDs results in higher stability values as compared to the stability values of an embankment on a soft ground without PVDs.
(b) It is observed that the stability of the embankment having a slower rate of construction is high.
(c) The rise of excess PWP below the embankment is very high for rapid rates as compared to the slower rates.
(d) The excess PWP is maximum below the embankment, and it reduces toward the toe.
(e) The rate of construction does not have significant effect on the lateral displacement near the toe region.

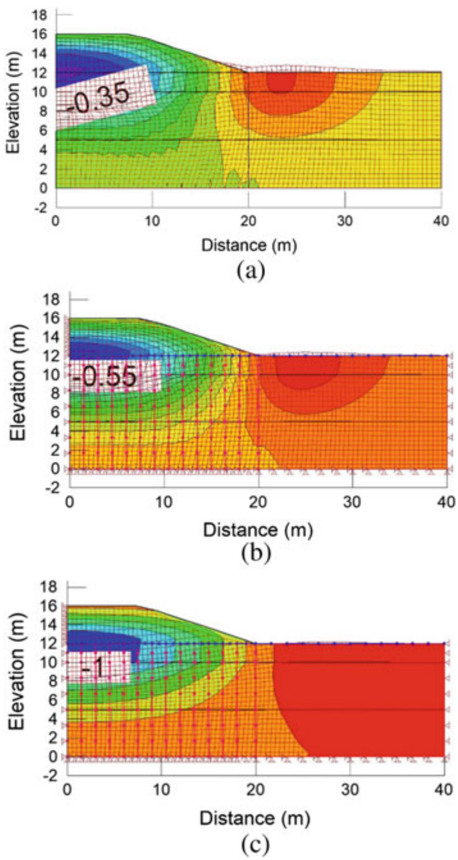

Fig. 10 Observed deformed mesh along with vertical displacement contours for different rates of construction **a** rate 0.5 m/day **b** 0.05 m/day **c** 0.005 m/day

(f) The ground surface settlement at the end of construction is less for rapid rates as it corresponds to the undrained behavior of the foundation soil with slow dissipation of excess PWP.

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