ANALYSIS OF AN EARTH EMBANKMENT CONSTRUCTED ON A SOFT CLAY FORMATION STABILIZED BY PREFABRICATED VERTICAL DRAINS

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Keywords: Embankment, soft clay, prefabricated vertical drains, case study, numerical analysis.

Abstract. Design and construction of earth embankments on soft formations encounters the problem of excessive total and differential settlements, large lateral displacement and inadequate bearing capacity of such formations. Preloading fills coupled with prefabricated vertical drains (PVD) is one of the soil improvement techniques exhibiting successful use in stabilizing soft clay formations. This study investigates, numerically, the performance of a monitored earth embankment that was constructed on a very soft to soft clay formation improved by PVD. Numerical analysis was carried out using the two-dimensional finite element program PLAXIS, considering the smear effect. A good comparison was revealed between the monitored and the predicted responses. In addition, a sensitivity study was carried out to highlight the influence of some modeling parameters and design considerations that may be of a major concern on designing such embankments. The considered parameters were the PVD length, the PVD spacing, the smear zone permeability and the soft clay characteristics.

Introduction

Growth of population and associated developments lead to construction activities on soils which were considered unsuitable in the past decades. The soft soil deposits have a low bearing capacity and exhibit large settlements when subjected to loading. It is therefore inevitable to treat soft soil deposits prior to construction activities in order to reduce the total and differential settlements and subsequently potential damages to structures. Stabilization of soft clay formations is one of the important construction techniques in geotechnical practice. Different stabilization techniques are being used to overcome the problems associated with the foundations and embankments work on soft formations.

In Sweden in the mid to late 1930's, Kjellman began experiments and obtained patents on the first prototype of a prefabricated drain made entirely of cardboard, as a core. It was soon discovered that the prefabricated drains were subject to undesirable rapid deterioration. Even with these disadvantages, Kjellman wick drains have been used occasionally in both Europe and Japan during the past 50 years. However, until the early 1970, the vast majority of vertical drains installed in the world were sand drains. In 1971, Wager improved the Kjellman wick drain by using a grooved plastic (polyethylene) core in place of the cardboard one. Later models were provided with non-woven textile filters [1]. Currently PVD are adopted for soft soil stabilization, especially for roads, railways, ports, airports and various other infrastructure projects, to reduce the total and differential settlements, reduce the lateral displacement and increase the ground bearing capacity [2].

Different approaches have been adopted to analyze the behavior of earth embankments constructed on soft clay formations stabilized by PVD. These methods can be grouped into three categories; analytical, observational and numerical techniques. Barron [3] first presented the analytical solution to the problem of soil consolidation due to horizontal flow towards vertical drains. Hansbo [4] recommended some modifications to Barron's solution, to take into account the physical dimensions, characteristics of prefabricated drains and the effect of drain installation. The observational methods uses the settlement monitoring records to back-calculate the degree of consolidation and the coefficient of consolidation, such as the Asaoka method [5].

Numerical analysis of earth embankments constructed on soft ground improved by PVD, should be analyzed adopting three dimensional (3-D) models because the consolidation around vertical drains is not truly axisymmetric or plain strain. Three dimensional idealization is very infrequent for routine analysis due to its complexity [6]. To employ a realistic two dimensional (2-D) finite element analysis for vertical drains, the equivalence or matching between the three dimensional condition versus the plane strain or axisymmetric conditions needs to be established ([7], [8], [9], [10] and [11]). Hird [7] pointed out that the matching of axisymmetric and plane strain conditions can be done in three ways: (a) geometric matching approach where the spacing of the drains is matched while keeping the permeability the same, (b) permeability matching approach where the permeability coefficient is matched while keeping the drains spacing to be the same, and (c) combination of permeability and geometric matching approaches where a plane strain permeability is calculated for a convenient drain spacing. Bergado and Long [8] proposed another matching approach for 2-D modelling of PVD effects. The PVD are transformed to continuous walls with the same spacing and with the assumption that the coefficient of permeability is independent of the state of seepage flow.

The behavior of a 6m high embankment constructed on marine clays strata at Singapore was analyzed by Arulrajah et al. [12]. Two designs of the embankment were considered; an embankment without vertical drains was modeled as control, while the other one was the actual embankment with vertical drains. The numerical analysis was carried out using the two-dimensional (2-D) finite element program PLAXIS [13]. The PVD were modeled adopting an axisymmetric unit cell model and full scale plane strain model. The equivalent horizontal permeability of the surrounding soils were estimated using the approach of Lin [10]. The predicted embankment performance was compared via the field measurement and Asoaka's method [5]. Good agreement was noticed between the finite element results and the field settlements for both embankments. The axisymmetric unit cell analysis was found to provide a slightly smaller settlement values than that of the full scale analysis. The predicted settlement rate using Asoaka's method was found to be much more than the actual field settlement.

Hien [14] analyzed the behavior of the monitored Muar bypass road embankment, Malaysia. The embankment was 2.6m high and was constructed on a soft clay formation stabilized with PVD and a geotextile layer along the embankment base. The numerical simulation was carried out using the 2-D finite element program PLAXIS [13]. The Mohr Coulomb constitutive model was adopted to represent the behavior of the soft clay and embankment fill. The numerical results exhibited acceptable comparison with the field measurements.

This study presents the results of a detailed numerical study to investigate the response of a monitored earth embankment constructed on a soft clay formation improved with PVD. A comparison between the numerically predicted response and the monitored response is presented to assess the adequacy of the adopted numerical modeling approach. A sensitivity study is, also, presented to investigate the influence of some parameters that may be of a major concern on designing such embankments such as the PVD length and spacing. These two parameters are of major economical impact for such projects. In addition, the sensitivity study investigates the influence of the smear zone permeability on the embankment deformational response.

Embankment Configuration, Material Properties and Numerical Modeling

The full scale earth embankment *TS1* that was constructed and monitored at the proposed Second Bangkok International Airport at Nong Ngu Hao, East Bangkok, Thailand [15] was considered in the current study. The soil profile at the test site is consisting of 2m thick weathered clay crust overlying a very soft to soft clay layer, approximately 10 m thick. Underlying the soft clay is a medium stiff clay layer, about 4 m thick, that is followed by a stiff clay layer extending down to 24 m below the ground surface where a dense sand layer was ecountered. The groundwater was encountered at a depth of 0.5

to 1.0 m below the ground surface. The embankment was 4.2 m in height with side slopes of 3H: 1V. Figure 1 presents the embankment configuration. The prefabricated vertical drains were installed in a square pattern at spacing of 1.5m and were of depth 12 m. The embankment was constructed by first excavating 0.3 m below the ground surface, constructing the sand blanket to a level of 1.2 m above the ground surface. Clayey sand was subsequently used to raise the embankment to its final height.

Numerical analysis, in the current study, was carried out using the two dimensional finite element program PLAXIS software [13]. The elasto-plastic Mohr-Coulomb model was used to simulate the behavior of the embankment materials, both the sand blanket and the clayey sand layer. All site natural layers were modeled using the hardening soil model. This model is an advanced model for simulating the behavior of different soils, both soft and stiff soils. In brief, the hardening soil model consists of a fixed ultimate surface and a moving cap surface to model the continuous hardening of the material [13]. Table 1 presents a summary of the parameters that were adopted in the numerical analysis of the current study. The vertical and horizontal permeability coefficients of the different layers were converted in the current study to their equivalent plain strain permeabilities using the approach proposed by Hird [7]. In this approach, the spacing between the drains was kept as it is in the numerical model while an equivalent permeability was considered (permeability matching approach). A ratio of ten was considered between the horizontal permeability of the natural clay to the horizontal permeability of the smear zone. The diameter of the smear zone was considered to be twice the mandrel diameter [16].

Embankment construction was carried out in six stages of variable fill thickness (1.0m, 1.5m, 0.5m ,0.65m , 0.35m and 0.20 m consecutively). During stage (3) of the embankment construction, a 5m width and 1.5m high berm was added. The berm width was increased to 7m during stage (4) of construction [15]. The same sequence was considered during numerical modeling of the embankment.

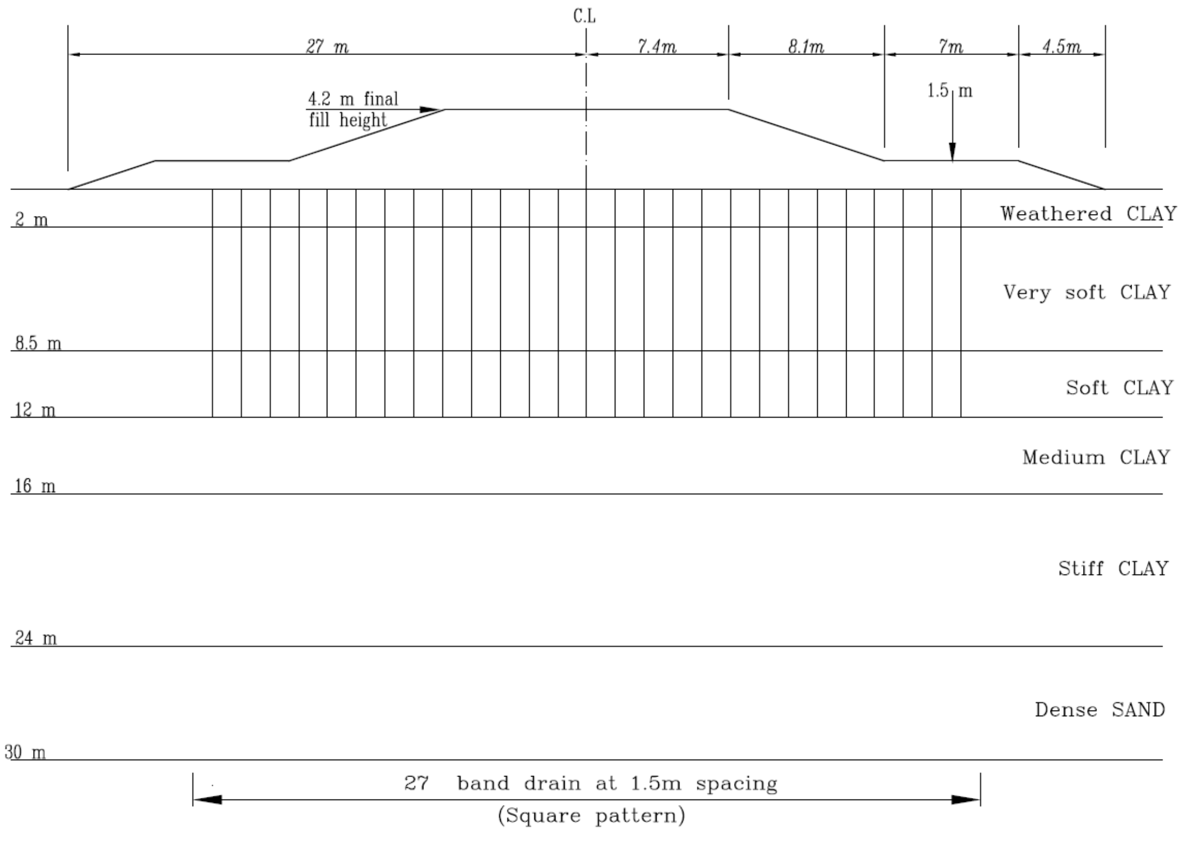


Fig. 1**:** embankment TS1 configuration

Table 1: Materials parameters adopted in numerical analysis

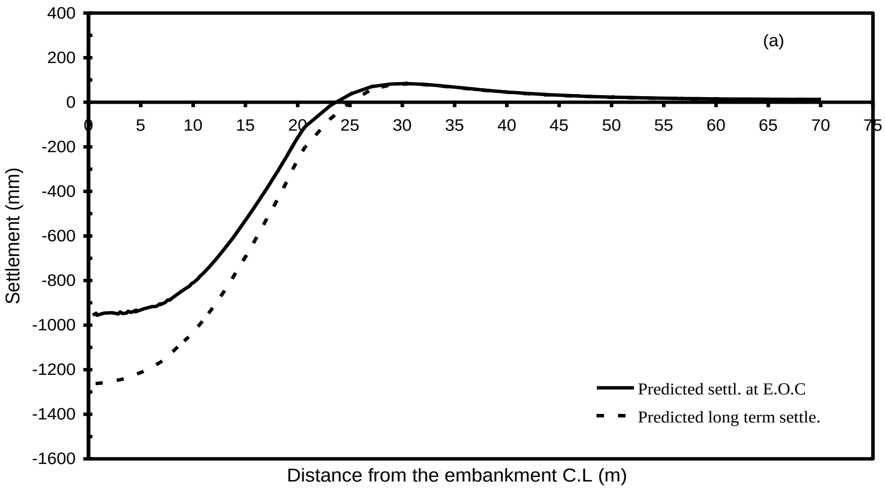
Parameter/Layer	Clayey sand	Sand blanket	Crust	Very soft clay	soft clay	Medium stiff	stiff clay	Dense sand
Model	Mohr-Coulomb		Hardening soil model					
Cohesion (Kpa)	1	1	2	2	2	2	2	1
Friction angel (°)	33	36	30	20	22	28	30	37
Dilatency angel (°)	5	3	-	-	-	-	-	5
Young's modulus *	40	60	-	-	-	-	-	50
Primary loading stiffness modulus *	-	-	10	0.45	0.65	5	12	60
Unloading/reloading stiffness modulus*	-	-	30	1.5	2.1	15	36	180
Poisson's ratio	0.3	0.3	-	-	-	-	-	-
Unloading/reloading Poisson's ratio	-	-	0.2	0.2	0.2	0.2	0.2	0.2
Hz. Permeability (m/day)	8	20	1.14 E -04	4.40 E -05	2.30 E -05	2.10 E -04	5.0 E -05	1
Permeability ratio**	1	1	1	1.7	2	2.1	1.67	1

* (MPa); ** Permeability ratio=horizontal permeability/ vertical permeability

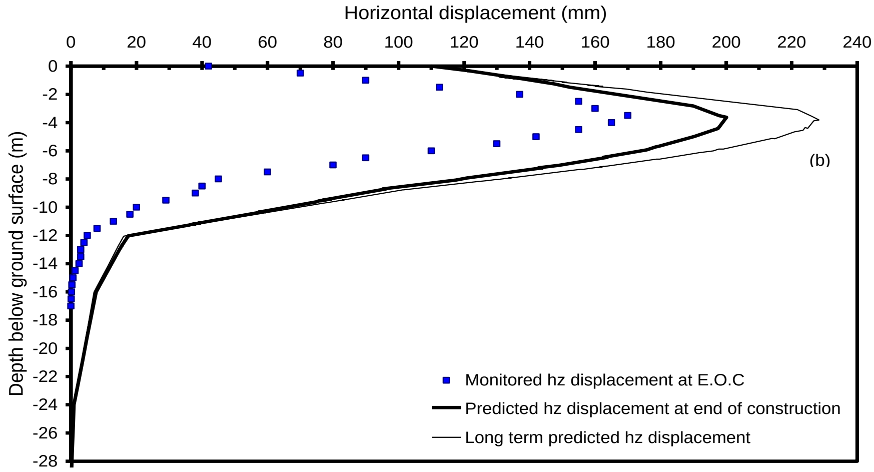
Numerical Modelling Results

The settlement profile along the embankment base just after construction and the long term settlement is shown in Fig. 2-a. For the long term conditions, the figure shows that the settlement underneath the embankment was increased while the heave outside the embankment toe was slightly decreased. The settlement increase was due to the consolidation of the different clay formations that lie in between and underneath the PVD. The predicted and monitored horizontal displacement trend just after construction and the predicted long term horizontal displacement along the vertical line passes through the crest edge are shown in Fig. 2-b. The figure exhibits that the maximum lateral displacement occurred below the ground surface, within the soft / very soft clay layer. In addition, Fig. 2-b exhibits that the monitored and predicted trends of the horizontal displacement are identical. However, Fig.2-b shows that the numerical analysis slightly overestimated the horizontal displacement.

The time-settlement profiles at a point located at the intersection of the embankment centerline and the ground surface are shown in Fig. 3. The figure presents the settlements estimated using numerical analysis, Asaoka method in addition to the monitored settlements. The predicted settlement using both the numerical model and Asaoka method is slightly greater than the monitored values specially during the construction period of the embankment. However, the numerically predicted settlement exhibits a good comparison with the monitored settlement until the end of the monitoring program, around 400 days. Figure 3 shows, also, that the numerically predicted long term settlement is less than the value estimated by Asoka method, a difference of around 25%.



a. Vertical displacement profile at ground surface.



b. Horizontal displacement profile at the embankment crest

Fig. 2. Embankment deformational response

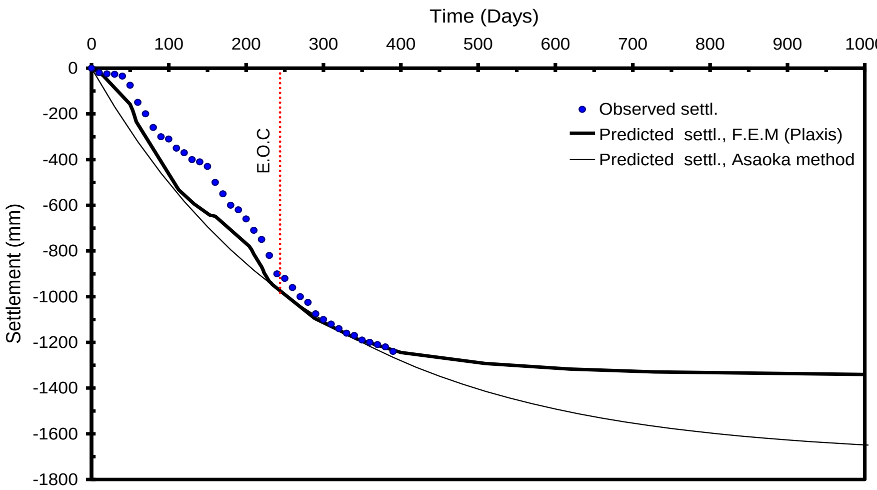
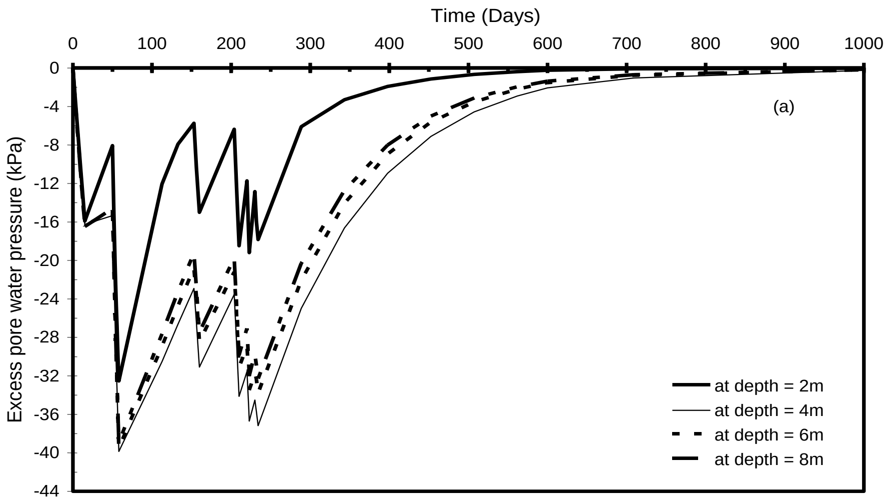
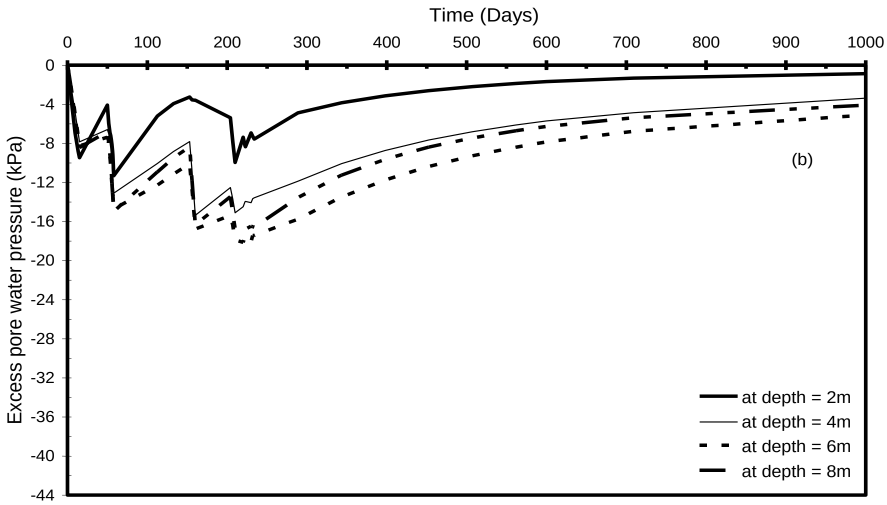


Fig. 3. Settlement accumulation at point located on embankment centerline and at ground Surface

The dissipation of the excess pore water pressure with time near the embankment centerline and the toe at different depths is shown in Fig. 4. Figure 4-a compares the dissipation of the excess pore water pressure near the embankment centerline and exhibits that the maximum excess pore water pressure occurred at a depth of around 4m below the ground surface. At the toe, the maximum excess pore water pressure, Fig. 4-b, occurred at a depth of around 6m below the ground surface. After the end of construction, Fig. 4 shows that the rate of dissipation of the excess pore pressure near the embankment centerline is greater than that at the toe. This is referred to the point that near and outside the embankment toe there are no PVD whileas the zone at the embankment centerline is surrounded by PVD that conventionally speeds the dissipation of the excess pore water pressure due to shortening the drainage path.



a. Excess pore water pressure distribution with time at 0.75 m away from the embankment centerline and at various depths



b. Excess pore water pressure distribution with time at the embankment toe and at various depths

Fig. 4. Profiles of excess pore water pressure distribution with time

Sensitivity Study Results

A sensitivity analysis was carried out for the considered embankment to investigate the effect of some parameters that may have an influence on the embankment deformational response. The numerically investigated parameters were the PVD length, PVD spacing, smear zone permeability and friction angel of the soft clay.

Effect of the PVD length. To explore the effect of the PVD length on the embankment deformational response, the embankment under consideration was reanalyzed considering that the PVD were of length up to the centerline of the medium stiff clay layer, i.e. 14m in length, and the PVD were constructed to the end of this stratum, i.e. PVD length of 16m. The settlement accumulation with time at a point located at the intersection of the embankment centerline and the ground surface is shown in Fig. 5. Figure 6 exhibits the settlement trend along the embankment base and the horizontal displacement trend a long a line through the edge of the embankment crest. These figures show that extendening the PVD to 14 and 16m below ground surface to reach the underlying stiff clay layer did not significantly affect the deformational response of the embankment under consideration.

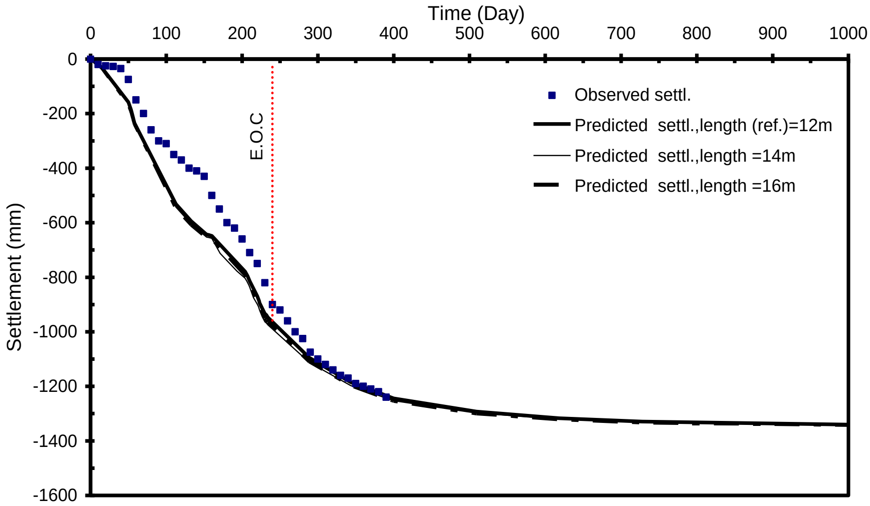
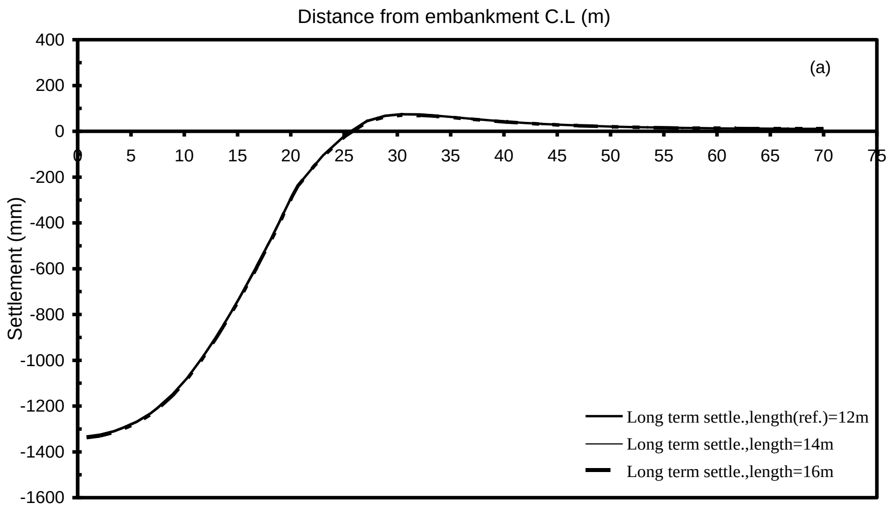


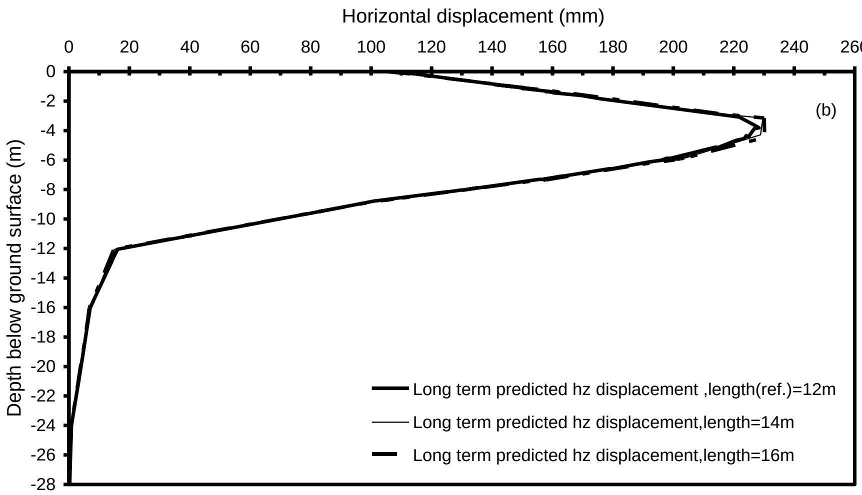
Fig. 5. Effect of the PVD length on settlement accumulation at intersection of embankment center line and ground surface

Effect of the PVD spacing. To evaluate the effect of the PVD spacing, the embankment under consideration was reanalyzed considering the PVD spacing to be 1m and 2m. Figure 7 shows settlement accumulation with time at a point located at the intersection of the embankment centerline and the ground surface. The figure exhibits that the final settlement is independent of the PVD spacing. However, the degree of consolidation at any time is increased with decrease of the PVD spacing.

Effect of Smear Zone Permeability. The installation of vertical drains by means of mandrel causes some disturbance of the subsoil surrounding the mandrel. The disturbed zone is known as the smear zone. This disturbance leads to a reduction of the permeability coefficient of this zone. To investigate the effect of the permeability variation on the embankment behavior, the variation of the ratio (R_s) of the coefficient of permeability of the original soil (k_h) to the coefficient of permeability inside the smear zone (k'_h) was considered. Figure 8 shows the settlement accumulation with time at a point located at the intersection of the embankment centerline and the ground surface. The figure points out that when PVD was considered as perfect drains (no smear, i.e. R_s = 1), the predicted settlement was overestimated and the inclusion of smear effect significantly improved the prediction. A better match between the predicted and monitored data was noted when R_s was taken equal ten. In addition, Fig. 8 shows that the final settlement of the system was not affected by the value of the permeability ratio, in spite of the figure shows a greater degree of consolidation for the perfect drains.



a. Vertical displacement profile at ground surface.



b. Horizontal displacement profile at the embankment crest

Fig. 6. Effect of the PVD length on the long term deformational response of the embankment.

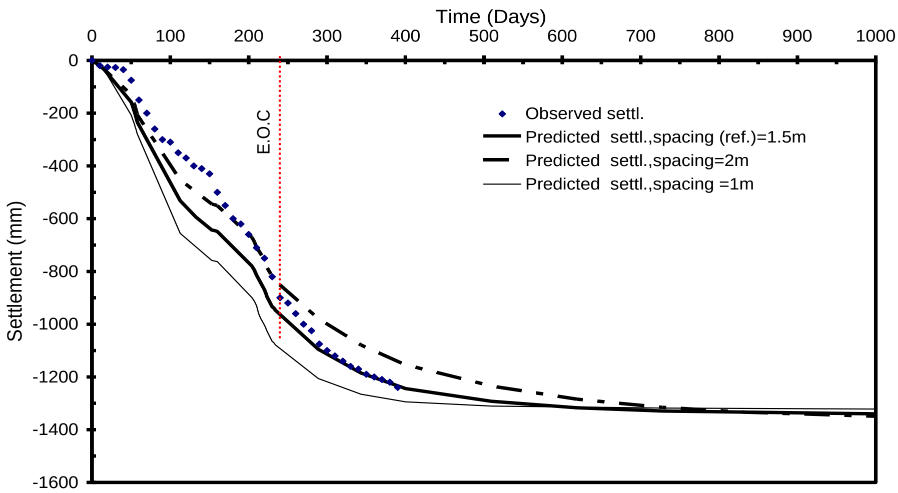


Fig. 7. Effect of the PVD spacing on settlement accumulation at intersection of embankment center line and ground surface

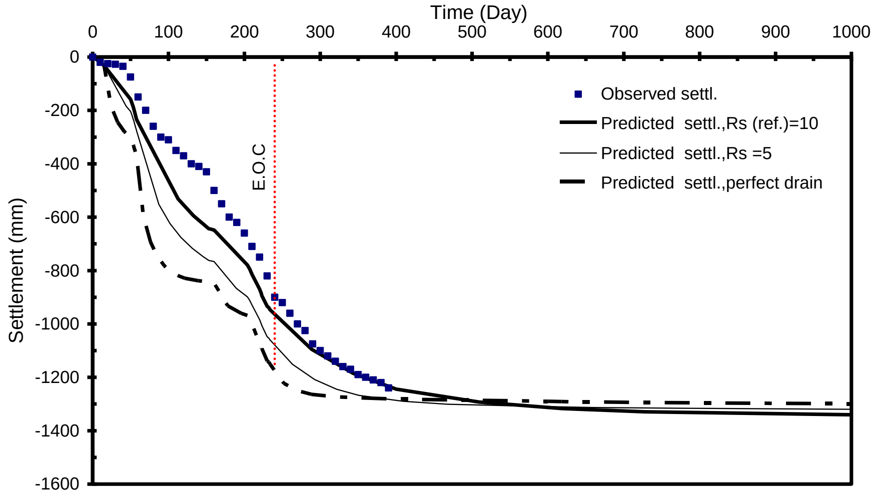


Fig. 8. Effect of the smear zone permeability on settlement accumulation at intersection of embankment center line and ground surface

Summary and Conclusions

Two-dimensional plain strain numerical modeling can be adopted adequately to analyze earth embankments constructed on soft clay formations improved by PVD. Good agreement was noticed between the finite element results and the field measurement for the considered embankment. Maximum settlement was,also, found to occur at the embankment centerline while maximum lateral displacement was found to occur below the ground surface, within the soft / very soft clay layer. In addition, the rate of dissipation of the excess pore pressure near the embankment centerline is greater than that at the toe. A sensitivity study was carried out to highlight the influence of some parameters that may be significant impact on the performance, numerical analysis, and cost of such embankments. This study led to the following conclusions:

- Two-dimensional numerical analysis can be adequately used to model the behavior of earth embankments constructed on soft clay formations stabilized by PVD.
- It is not necessary to fully extend the prefabricated vertical drains through the entire thickness of clay formations.
- Decrease of the PVDs spacing, increased the degree of consolidation. However, the final settlement was independent of the PVD spacing.
- Neglecting the smear effect (perfect drain) resulted in overestimating the predicted degree of consolidation while inclusion of the smear effect significantly improved the prediction.

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