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Behaviors of Piled Reinforced Embankments on Soft Soils

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Abstract: Piled reinforced embankments are increasing widely used in soft soils due to their rapid construction, low costs, small total and differential settlements and high stability. Soil arching developed within the embankment is the definitive factor influencing the behaviors of the embankments while the pile-soil relative displacement is regarded as the most important factor to affect the evolution of soil arching during soft soil consolidation. In this study, an axis-symmetric numerical model of piled reinforced embankment was set up to explore the characteristics of soil arching during the embankment filling as well as the subsequent consolidation. Based on the analyses, the equal settlement plane elevation was determined. Furthermore, the evolution of the pile axial force, the skin friction and the neutral plane depth was also studied. The results show that the pile-soil relative displacement significantly influences the soil arching. The pile axial force, the skin friction along the pile shaft and the neutral plane depth experience a complicated evolution.

Key words: Piled reinforced embankment, soil arching, equal settlement plane, stress concentration ratio, negative skin friction, neutral plane

INTRODUCTION

A piled reinforced embankment consisting of embankment fill, single or muti-layer of geosynthetic reinforcements, piles, caps and foundation soil, is a new type of embankment (Pham *et al*., 2004; Collin *et al*., 2005; Jones *et al*., 1990). The system has been increasing widely used to construct highways on soft soils in recent years worldwide due to its more rapid construction, higher stability and smaller total and differential settlements over traditional soft soils treatment methods (Hewlett and Randolph, 1988; Low *et al*., 1994; Han and Gabr, 2002). Within such a piled reinforced embankment arching occurs, most of the embankment load is borne by the piles and transfer to a lower firm stratum, so there is no need of staged construction of embankment filling. Compared with the conventional pile-raft foundations, the piles are not needed to be closely spaced and not continuous slab but individual cap is placed on each pile head which enable the piled reinforced embankment a cost-effective method.

The interactions among embankment fill, geosynthetic reinforcements, piles and foundation soil are complex. Since the compression stiffness of the pile is greater than that of the foundation soil, the embankment fill mass directly above the foundation soil has a tendency to move downwards. This movement is partially restrained by shear stress from the embankment fill mass directly above the pile-cap. The shear stress increases the pressure acting on the pile-cap but reduces the pressure on the foundation soil. This load transfer phenomena is termed as soil arching (Terzaghi, 1936). The soil arching has a significant influence on the behaviors of the piled reinforced embankments. If the degree of soil arching is not sufficient, too much embankment load will be born by the foundation soil and the pile-soil relative displacement will be reflected to the top of the embankment and unacceptable differential settlements may occur which would harm the normal function of the embankment and its durability. However, too big value of the stress concentration ratio implies that nearly all the embankment load will be born by the piles and high costs. Consequently, a thorough understanding of soil arching mechanism within the embankments is essential for engineering design.

In this study, a numerical analysis was conducted to evaluate the development of differential settlement between the pile and surrounding soil, the stress concentration ratio, the pile axial force, the skin friction along pile shaft and the neutral plane depth. The equal settlement plane elevation within the embankment was also investigated in detail.

NUMERICAL MODEL

The axis-symmetric numerical model of piled reinforced embankment which considers a single pile and

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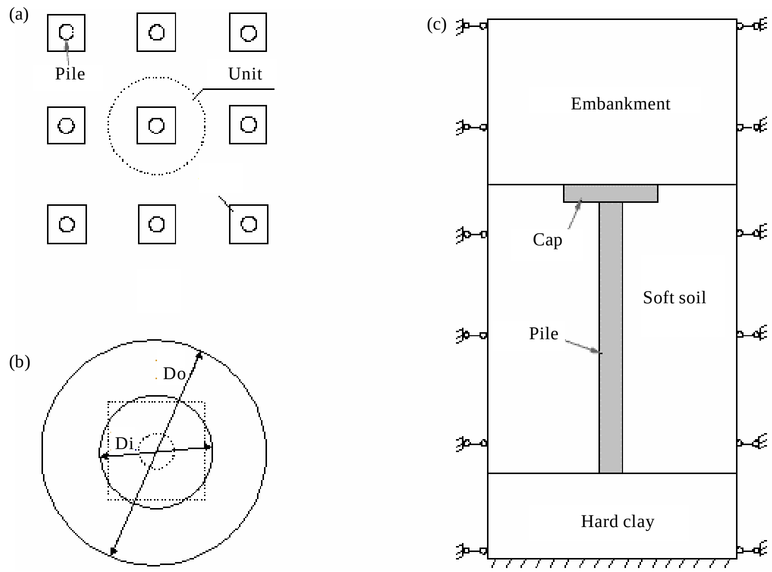

Fig. 1(a-c): Numerical model, (a) Piles arrangement pattern, (b) Equivalent unit and (c) A single pile and its tributary section

Table 1: Physical and mechanical parameters of the materials

Materials	h (m)	γ_d (kN/m^3)	γ_{sat} (kN/m^3)	k (m/d)	E_S (Mpa)	u	c (kPa)	φ (°)
Embankment	4.50	20.0	-	-	30	0.250	0	30
Soft soils	25.00	12.5	17.5	0.00124	3	0.350	1.5	9
Hard clay	5.00	15.5	18.7	0.008	22	0.250	10	25
Pile	15.00	25.0	-	-	30000	0.167	-	-
Pile-cap	0.35	25.0	-	-	30000	0.167	-	-

its tributary embankment and foundation soil is presented in Fig. 1. The embankment fill is supported by piles and soft soils underlain by hard clay on which the piles rest. The pile spaced 2.0 m in square pattern is considered as no-porous elastic material with a length of 25 m and a diameter of 0.4 m. The hard clay is 5 m thick and its bottom was taken as the bottom boundary without any displacements. The side boundary can freely slide only along the vertical direction and the top boundary is free in displacements. Except for the side boundaries within the pile length and the bottom boundary, other boundaries are permeable. The underwater level is just at the surface of the soft soils.

When conducting numerical analysis in this study, the 4.5 m high embankment fill, the 25 m thick soft soils and the 5 m thick hard clay were all considered as Mohr-Coulomb materials while the pile and pile-cap were considered as Linear-Elastic materials. All of the material parameters are listed in Table 1. In order to simulate the practical step by step filling of the embankment, the construction of the embankment was simulated as a series of instant fillings, each filling of 0.5 m high embankment was followed by a 3 day of consolidation. The excess pore pressures in the soft soils were allowed to dissipate to no more than 1 kPa after the filling.

RESULTS AND ANALYSES

Figure 2a shows the variation of the total settlements of pile and surrounding soil during embankment filling and subsequent consolidation process. It is apparent that the development of the settlements can be divided into two stages. During the first stage, i.e., the embankment filling, the settlements of the soil are greater than that of the pile. During the second stage, i.e., from the completion of the filling to the end of consolidation, both pile and soil settled a little further. Obviously, whether the pile or the subsoil, most of their settlements developed during the embankment filling and the pile settled much less than that of surrounding soil. The development of the pressures on the pile and surrounding soil is shown in Fig. 2b. It is obvious that the variation of soil pressure can be divided into three stages. In the first stage, i.e., from 0 to 24 day, the soil pressures increase gradually with the embankment filling; the pressures on the pile head are

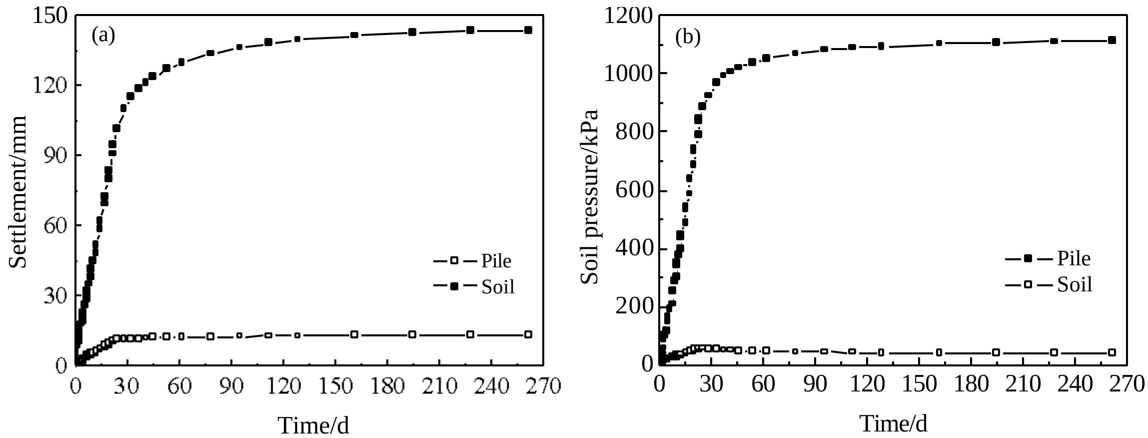

Fig. 2(a-b): Development of (a) Settlement and (b) Soil pressure

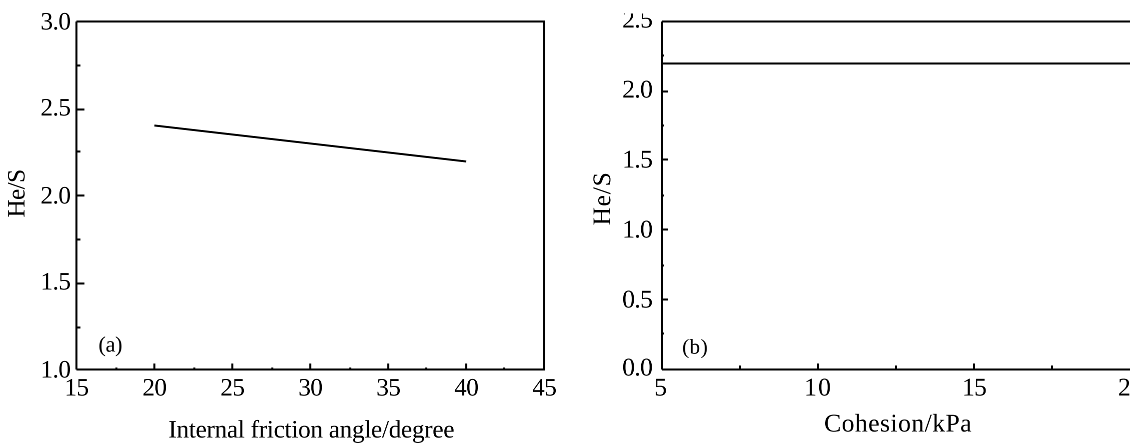

Fig. 3(a-b): Influence of (a) Internal friction angle and (b) Cohesion on the ratio of the equal settlement plane height to pile-cap clear spacing

greater than that on the soil. In the second stage, i.e., from 24 to 60 day, the pressures on the soil decrease slightly while the pressures on the pile head increase dramatically. From 60 day on, the pressures vary slightly and maintain nearly unchanged at the end of the consolidation.

When the embankment is high enough compared to the pile-cap clear spacing, there will exist a certain plane within the embankment, on which all settlements are equal and the plane is called equal settlement plane. Cao *et al.* (2007) demonstrated that the elevation of the equal settlement plane is very important to the engineering practice.

It is advised by Terzaghi (1936) that the equal settlement plane is at a height of two times the width of trapdoor above pile-cap. NGG (2002) and BS8006 (1995) specify that the equal settlement plane is at the 1.2 and 1.4 times the pile-cap clear spacing above pile head, respectively. These specifications indicate that the elevation of the equal settlement plane is indeed influenced by the pile-cap spacing, however, if the equal settlement plane is influenced by other factors, such as the strength parameters of embankment fill still remains poorly understood till now.

Figure 3a plots the relation of the internal friction angle of embankment fill and the ratio of the equal settlement plane height (He) to the pile-cap clear spacing (S). It can be noted that the ratio decreases slightly from 2.4 to 2.2 while the internal friction angle increases from 20° to 40°. Fig. 3b suggests the ratio remains a value of 2.2 unchanged while the cohesion increases from 5 to 20 kPa. Therefore, the equal settlement plane height can be taken as 2.3 times the pile-cap clear spacing for 3-D soil arching situation.

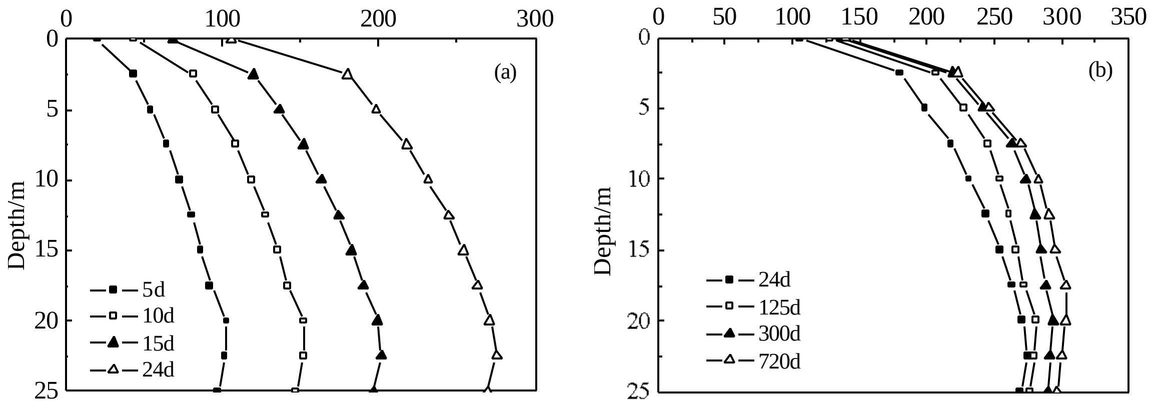

Fig. 4(a-b): Development of pile axial force during (a) Embankment filling and (b) Consolidation

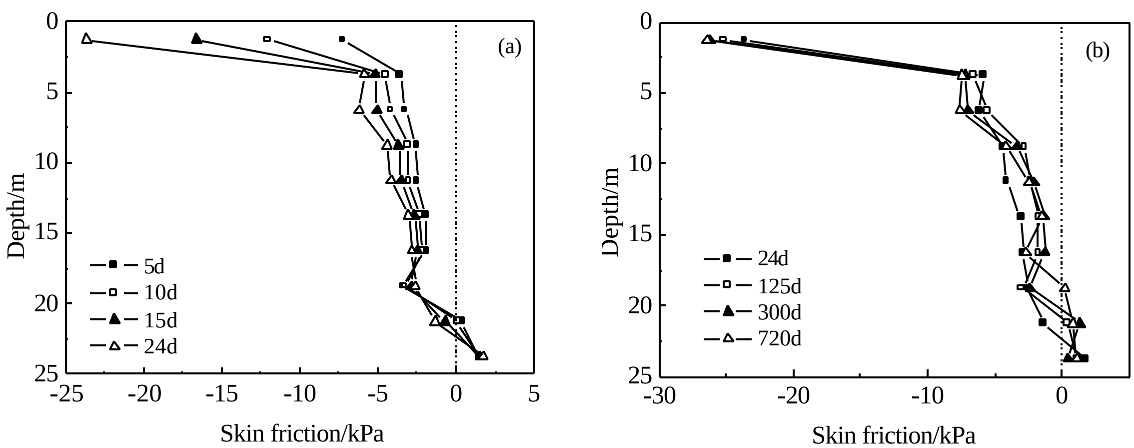

Fig. 5(a-b): Development of skin friction during (a) Embankment filling and (b) Consolidation

Figure 4 shows the development of the pile axial forces during the embankment filling as well as the subsequent consolidation process. It is clear that the pile axial force increases rapidly during embankment filling. This is rather reasonable for the pressure on the pile head increases rapidly with the continuous embankment filling (Fig. 2b). While during the subsequent consolidation, although the total embankment weight remains unchanged, partial load originally born by the soft soils is transferred to the pile, so the pile axial force would continue to increase a little further.

It should also be noted from Fig. 4 that whether during the embankment filling or the subsequent consolidation process, the maximum pile axial force developed not at the pile head, but a depth near the pile tip, this implies Negative Skin Friction (NSF) mobilized on most segment of the pile shaft.

The development of skin friction along pile shaft during the embankment filling and subsequent consolidation process is shown in Fig. 5. It is obvious that whether during the embankment filling or during the subsequent consolidation process, the NSF decreases downwards the pile shaft. It can also be noted that NSF is mobilized along most part of the pile shaft while Positive Skin Friction (PSF) developed near the pile tip. Apparently, the skin friction increases more quickly during the embankment filling than during the subsequent consolidation and the location of the NP exhibits a complex variation of descending at first and then ascending and maintaining unchanged at the last.

CONCLUSION

The performance of piled reinforced embankment was analyzed and the 3-D soil arching developed within the embankment was mainly investigated and the following conclusions can be drawn.

Soil arching will be mobilized within the embankment as soon as the beginning of the filling. The equal settlement plane occurs when the embankment height is relative high compared to the pile-cap clear spacing The numerical analysis results indicate that the height of the equal settlement plane is about 2.3 times the pile-cap clear spacing in 3-D situation.

Negative skin friction will be mobilized along most upper part of pile shaft and positive skin friction near the pile tip during embankment filling as well as the subsequent consolidation. The neutral plane descends at the start of the filling and then ascends a little until the completion of the filling. During the subsequent consolidation, the neutral plane shows a tendency to ascend to a maximum depth and finally remains unchanged.

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