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Research Article

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On equal settlement plane height in piled reinforced embankments

Zhao Min[1] and Cao Wei-Ping[*2]

[1]School of Civil Engineering, Xi'an Technological University, China
[2]School of Civil Engineering, Xi'an University of Architecture and Technology, China

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ABSTRACT

The determination of equal settlement plane height is of great importance when designing piled reinforced embankments. If the embankment height is greater than the equal settlement plane height, no apparent differential settlement occurs on the pavement, or unexpected differential settlement will appear and this will be harmful to the normal functions of the embankment. A numerical analysis by using a commercial FEM program was conducted to reveal the mechanism of equal settlement plane occurring within piled reinforced embankment. Especially, the influence of embankment height, pile-cap clear spacing, the cyclic traffic loading, cohesion and internal friction angle of the embankment fill and the geosynthetic reinforcement strength on the equal settlement plane height was mainly evaluated. Based on the analysis, an equation was fitted to estimate the equal settlement plane height.

Key words: Piled reinforced embankment, equal settlement plane height, cohesion, internal friction angle, cyclic traffic loads

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INTRODUCTION

A piled reinforced embankment, consisting of piles installed through soft soils and transferring its self-weight to lower hard stratums, is widely used in the construction of highway embankments over soft soils due to its rapid construction, low costs, small total and differential settlements and high stability. The load transfer mechanism in piled reinforced embankments is considerably complex, and not yet fully understood [1-5]. Since the compression stiffness of the pile is greater than that of surrounding foundation soil, differential settlement developed between the pile and surrounding soil generates shear stress that extend upwards into the embankment fill. The shear stress will reduce the differential settlement between the fill just above the pile-cap and the fill above the foundation soil. When the embankment is sufficiently high there will exist a plane in the fill on which no differential settlements occur; this plane is termed the equal settlement plane and the distance from the top of pile-cap to the equal settlement plane is defined as the equal settlement plane height. Obviously, when the embankment fill height is higher than the equal settlement plane height, no differential settlement will occur on the surface of the embankment, or unacceptable differential settlement will be induced. The determination of the equal settlement plane height is so important that numerous studies have been existed regarding the issue. Terzaghi [6] assumed that the equal settlement plane was at a height of 2.5 times the width of the trapdoor. BS 8006 [7] and Nordic handbook [8] specify that the equal settlement plane height is 1.4 and 1.2 times the pile-cap clear spacing, respectively. Carlsson [9] adopted the equal settlement plane was at a height of 1.87 times the pile-cap clear spacing. Hewlett & Randolph [10] proposed that the equal settlement plane height can be taken 1.4 times the pile-cap clear spacing. Chen et al. [11] have shown the existence of the equal settlement plane by using 2-D model tests and suggested 1.6 times the pile-cap clear spacing for the height. Apparently, big difference existed on magnitude of the equal settlement plane height and all the mentioned studies only considered the influence of the pile-cap clear spacing on the critical height. However, whether the equal settlement plane height is influenced by other governing factors, such as the strength parameters of embankment fill and tensile strength of the geosynthetic reinforcement still remains poorly understood by far. This paper presents a numerical analysis to explore how some factors, i.e., the cohesion and internal friction angle of the embankment fill, the geosynthetic reinforcement tensile strength and the cyclic traffic loads influence the equal settlement plane height. Moreover, a formulation based on the analysis was proposed to estimate the equal settlement plane height for practical engineering.

1. NUMERICAL MODEL

The 3D numerical model of the piled reinforced embankment is presented in Figure.1. The embankment fill is supported by piles and soft soils underlain by hard clay on which the piles rest. When conducting numerical analysis in this paper, the pile was considered as Linear-Elastic material with a length of 25 m and a diameter of 0.4m. Both the 6m high embankment fill and the 25m thick soft soils as well as 3m thick hard clay were considered as Mohr-Coulomb materials, while the geosynthetic reinforcement was regarded as membrane. The square cap placed on each individual pile top was also Linear-Elastic material with a thickness of 0.35m. All of the material parameters are listed in Table 1.

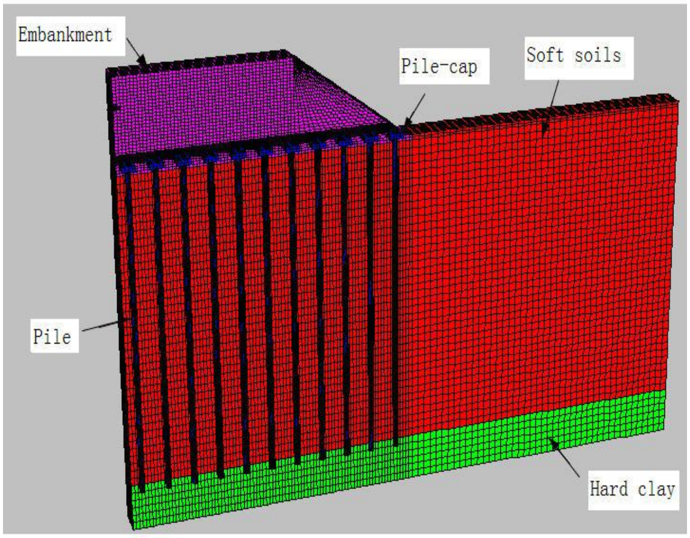

Figure1. Numerical Model

The displacements of the bottom boundary in three directions x, y and z are all zero. The displacement of left and right boundary in the x direction is zero, while in the y and z direction is free. The displacements of the back and front boundaries in the y direction is zero, while in the x and z direction is free. The top boundary can deform freely. The underwater level is just at the surface of the soft soils. Except for the side boundary within the pile length and the bottom boundary, other boundaries are permeable.

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)	υ	c (kPa)	φ (°)
Embankment	6	20	-	-	30	0.25	0	30
Soft soils	20	12.5	17.5	0.00124	3	0.35	1.5	9
Hard soils	3	12.5	17.5	0.00124	25	0.25	18	22
Pile	25	25	-	-	30000	0.167	-	-
Pile-cap	0.35	25	-	-	30000	0.167	-	-

In order to simulate the practical step by step filling of the embankment, the construction of the embankment fill was simulated as a series of instant fillings; each filling of 0.2 m high embankment was followed by a 2-day of consolidation. After the filling is completed, the excess pore pressures in the soft soils were allowed to dissipate to no more than 1kPa.

The cyclic traffic load is a kind of periodically dynamic load applied on the pavement repeatly. Hyodo et al. [11] Measured the vertical soil pressure below pavement in a field test and found that the soil pressure in a certain depth below the pavement could be described as sinusoidal function. When conducting numerical analysis in this paper, the cyclic traffic load was simulated as two parallel rotating wheel loads which were further simplified as a series of discrete semi-sinusoidal function with amplitude of 100 kN and a frequency of 2 Hz. The cyclic traffic load was assumed to apply on the pavement for 6000 times. In the subsequent analysis, unless stated otherwise, 1.0m, 10 kPa, 30° and 6.0 m are assumed for the pile-cap clear spacing, the cohesion and the internal friction angle of the fill and the embankment height, respectively.

RESULTS AND ANALYSES

The settlements on different elevations within the embankment under traffic loads are shown in Figure 2. Overall, the differential settlements at the lower part of the embankment are quite bigger while become smaller and smaller upwards. It can be seen that on a plane with a height of 0.65 m, the minimum settlement is 52.88 mm while the maximum settlement is 61.28 mm, the corresponding differential settlement is 8.4 mm. It can also be noticed that the maximum differential settlement reduced to 1.04 mm on a plane with a height of 1.6 m and the maximum differential settlement can be negligible on the plane with a height of 2.4 m. Therefore, the equal settlement plane height can be taken 2.4 m. For the situation discussed in this section, the pile-cap clear spacing is 1.0m so the corresponding ratio of the equal settlement plane height to the pile-cap clear spacing, He/S, is 2.4.

The influence of the embankment height on the equal settlement plane height is depicted in Figure 3. With the embankment height increasing from 4.0 m to 8.0 m, the equal settlement plane height increases from 2.2 m to 2.6m, and the corresponding value of He/S increases from 2.2 to 2.6. This implies that the bigger the value of the embankment height, the bigger the ratio of the equal settlement plane height to the pile-cap clear spacing.

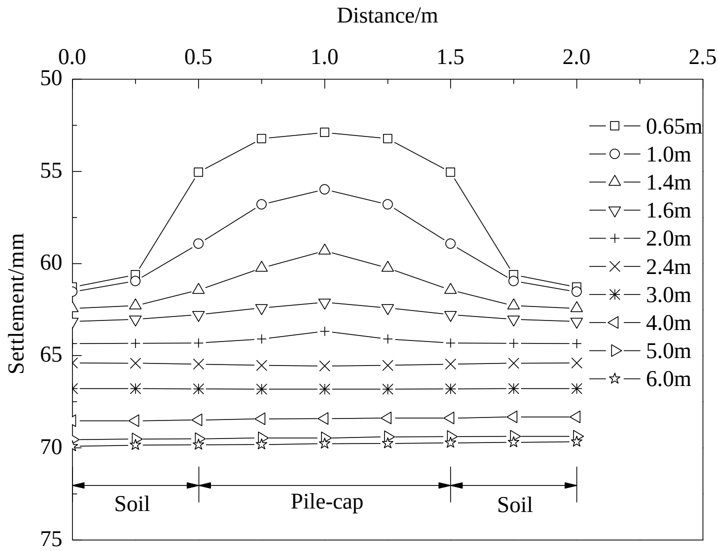

Figure 2. Settlements of the Embankment

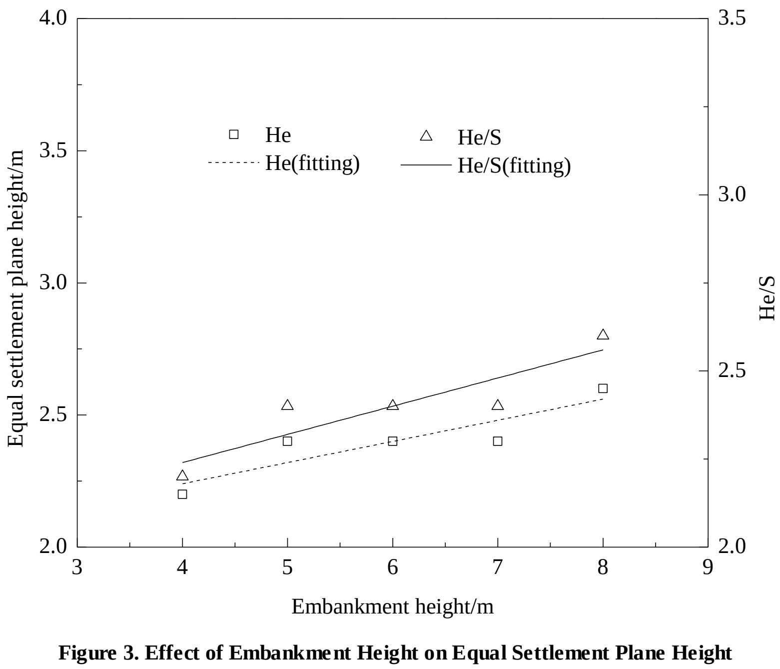

Figure 3. Effect of Embankment Height on Equal Settlement Plane Height

Figure 4 shows the relation of the equal settlement plane height and the pile-cap clear spacing. It should be noticed that the equal settlement plane height increases with the increasing of the pile-cap clear spacing, e.g., when the pile-cap clear spacing increases from 0.4 m to 1.4 m, the equal settlement plane height increases from 1.0 m to 3.0 m, while the ratio of He/S decreases from 2.5 to 2.14. The increasing in the pile-cap clear spacing denotes the increasing in the equal settlement plane height, but the decreasing in the ratio, He/S.

Both Figure 3 and Figure 4 demonstrate that whether the embankment height or the pile-cap clear spacing has effect on the ratio of the equal settlement plane height to the pile-cap clear spacing, but the influence is considerably limit.

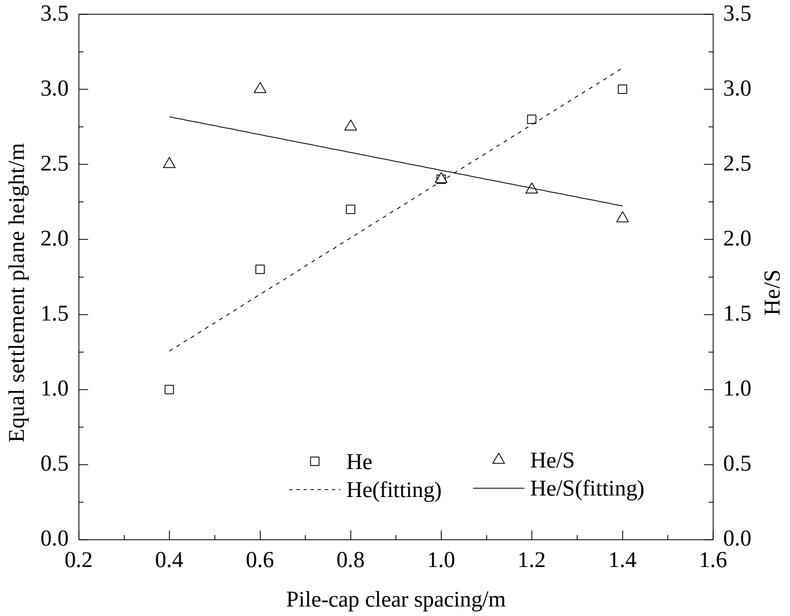

Figure 4. Effect of Pile-cap Clear Spacing on Equal Settlement Plane Height

Figure 5 presents the influence of embankment fill internal friction angle on the equal settlement plane height. With the increasing of the internal friction angle from 20° to 40°, the equal settlement plane height decreases from 2.6 m to 2.2 m, and the ratio of the equal settlement plane height to the pile-cap clear spacing decreases from 2.6 to 2.2. This implies that a higher value of the fill internal friction angle will result in a lower value of the ratio.

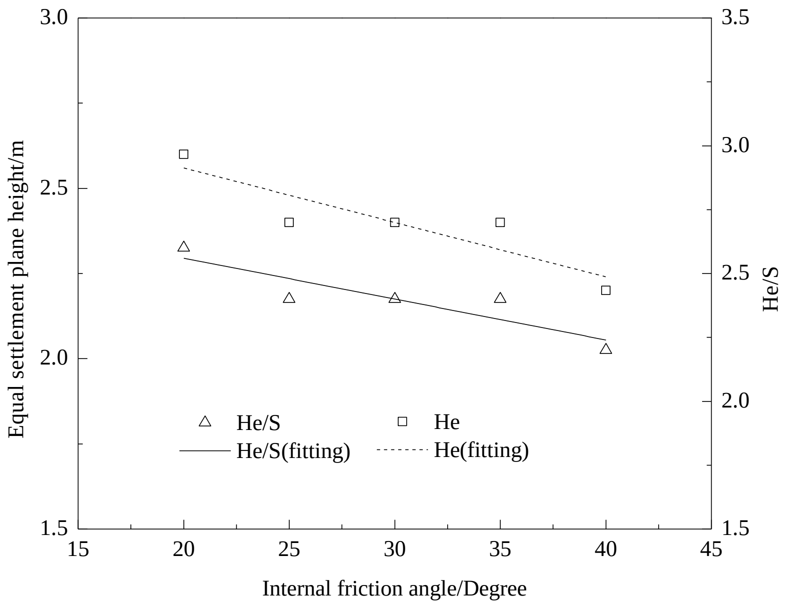

Figure 5. Effect of Internal Friction Angle of the Fill on Equal Settlement Plane Height

Figure 6 shows the effect of embankment fill cohesion on the equal settlement plane height. Apparently, the equal settlement plane height remains a constant of 2.4 m despite of the increasing of cohesion from 0 kPa to 20 kPa. This suggests that the cohesion of the embankment fill has no effect on the equal settlement plane height.

Geosynthetic reinforcements are often included to strengthen the soil arching within piled reinforced embankment but different arguments exist regarding the effect of the geosynthetic reinforcements on the equal settlement plane height. Figure 7 suggests the tensile strength of geosynthetic reinforcement has no effect on the equal settlement plane height; this maybe attributes to the assumption of zero flexural stiffness for the geosynthetic reinforcement.

The effect of the cyclic traffic loads on the equal settlement plane height is presented in Figure 8. It can be seen that with the increasing of the single axial load from 50 kN to 150 kN, the equal settlement plane height increases from 2.2 m to 2.6 m, while the corresponding ratio, He/S, increases from 1.25 to 2.6. This suggests that the application of the cyclic traffic loading will make the equal settlement plane move upwards and the bigger the single axial load, the higher the equal settlement plane.

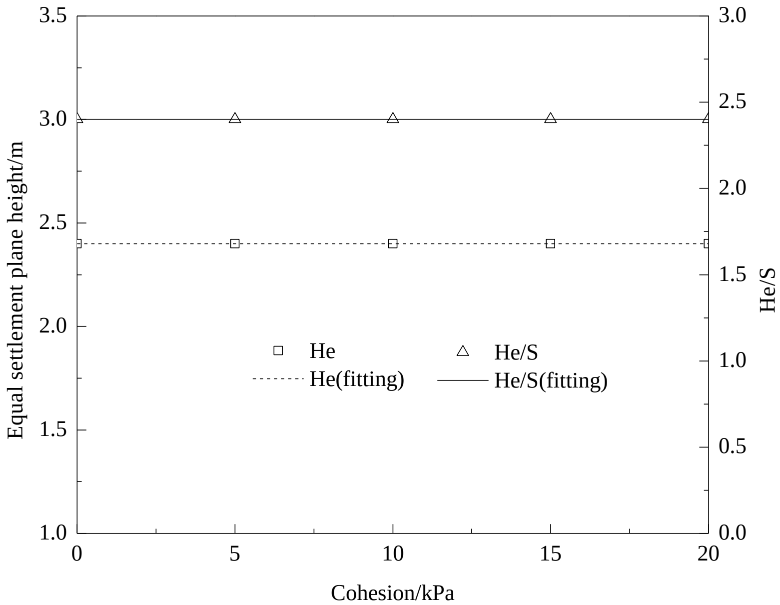

Figure 6. Effect of Cohesion of the Fill on Equal Settlement Plane Height

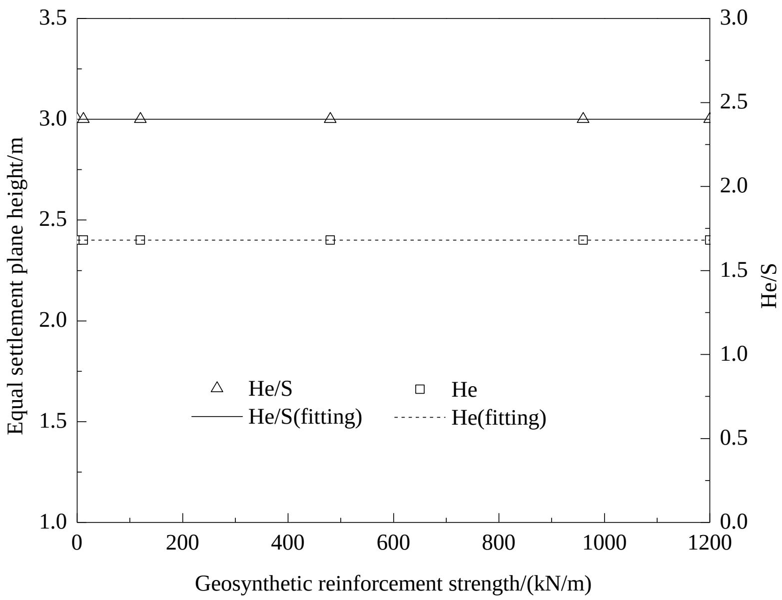

Figure 7. Effect of Geosynthetic Reinforcement Strength on Equal Settlement Plane Height

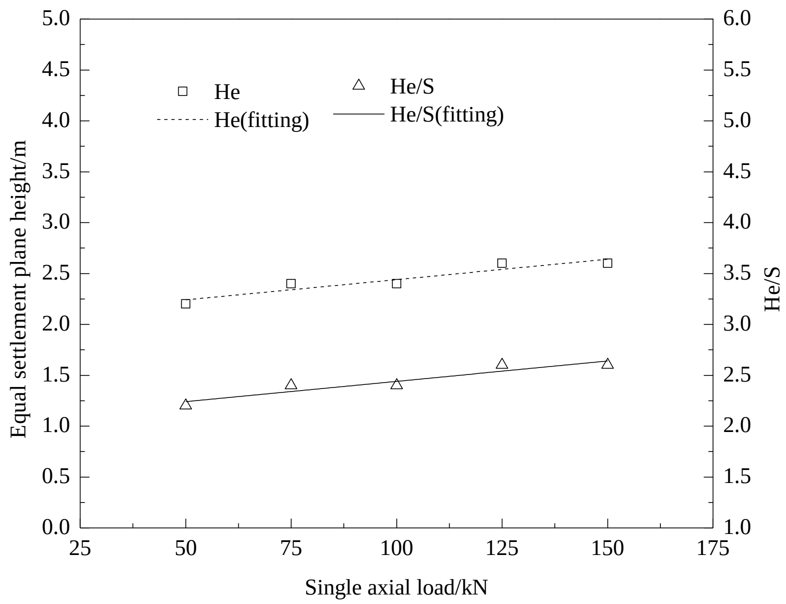

Figure 8. Effect of Single Axial Load on Equal Settlement Plane Height

Based on the above analyses, it should be concluded that the pile-cap clear spacing has notable effect on the equal settlement plane height, the single axial pressure, the embankment height and the fill internal friction angle have some little effect, while the fill cohesive and the tensile strength of the geosynthetic reinforcement has no effect at all. Therefore, an empirical equation was proposed to calculate the equal settlement plane height, i.e.,

$$\frac{H_e}{S} = 2.4 + 0.91 \cdot \tan(30^\circ - \varphi) + 0.16 \cdot \frac{H\text{ - }6}{S} + 0.08 \cdot \frac{P\text{ -}100}{100} \qquad (1)$$

Where He = the equal settlement plane height, m; S = the pile-cap clear spacing, m; H = the embankment height, m; φ = the internal friction angle of the embankment fill and P = the single axial load, kN.

Cao et al. [13] investigated the mechanism of soil arching in piled reinforced embankment by field test and presented the equal settlement plane height according to the development of the soil pressures on pile-cap as well as that on foundation soils. The comparison of the calculated equal settlement plane height using equation (1) and that measured by Cao et al. [13] is given in Table 2. It should be pointed out that the measured equal settlement plane heights in Table 2 were not really measured but inferred according to the variation of soil pressures applied on the pile-cap and that on surrounding soils. The maximum and the minimum relative error between the measured and the present calculated equal settlement plane height are 35.29% and 6.25%, respectively. Considering the fact that the measured equal settlement plane heights in Table 2 were not really measured and the calculated equal settlement plane height is always greater than the measured one, the Equation presented above for estimating the equal settlement plane height is considerably trusted.

Table 2 Comparison of Measured and Calculated Equal Settlement Plane Height

Position	Embankment height(m)	Pile spacing (m)	Cap width (m)	Pile-cap clear spacing (m)	Equal settlement plane height(m)		Relative error
					Measured	Calculated	
K10+825	5.0	3.0	1.5	1.5	3.2	3.4	6.25%
K10+850	5.0	3.0	1.75	1.25	2.4	2.8	16.67%
K16+820	5.0	2.0	1.0	1.0	1.7	2.3	35.29%
K19+930	5.0	2.5	1.0	1.5	2.8	3.4	21.43%

CONCLUSION

The equal settlement plane has been used in some existing design methods and shown to exist in the numerical analysis. The effect of the pile-cap clear spacing, the cyclic traffic loading, mechanical properties of the embankment fill as well as some other factors on the equal settlement plane height was analyzed. The results indicate that the equal settlement plane height is significantly affected by the pile-cap clear spacing, the fill cohesion and geosythetic reinforcement tensile strength have no effect on the height, while the internal friction angle of embankment fill and single axial load have some little influence on the height. An expression considering the effect of the pile-cap clear spacing, the internal friction angle of the fill, the embankment height and the single axial load, was proposed for estimating the equal settlement plane height.

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