Soil Arch Analysis of Piled Embankment by a Modified 3D Model and Field Experiments

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ABSTRACT: Piled embankments have been widely used in road engineering. A unique mechanical behavior which is called soil arching effect in piled embankments is a key factor in load distribution. In this study, a modified 3D finite element model is presented to analyze the soil arching effect in piled embankments. The interaction among the pile, subsoil and embankment fill is simulated by springs with various stiffness values. A field test is conducted to get the actual engineering data. Based on the results comparison, several contrast numerical analyses are performed by changing the pile spacing. The critical maximum and minimum heights of the soil arch can be clearly obtained via the numerical model and the critical height of soil arching of the numerical model is consistent with that of Hewlett’s theory. The numerical model is not only easily implemented but time-saving, which is a new method for researchers to analyze soil arching effect in piled embankments.

INTRODUCTION

Piled embankments (Han J et al., 2002; Abusharar SW et al, 2009) is an effective method to be used for ground treatment and is extensively applied. Soil arching effect (Terzaghi K, 1936) in piled embankments is a key factor in load distribution, which has been researched by many scholars.

Assumptions regarding the shape of soil arching were proposed to help identify the load transfer mechanism in embankments (Hewlett W J et al., 1988; Low B K et al., 1993). For calculation methods for stress and stress ratio were proposed by scholars or standards (Zheng J J et al., 2007; British Standard BS 8006 1995). A number of field and laboratory tests were conducted to investigate soil arching effect (Chen R P et al., 2010; Van et al., 2012). For the complexity of the field test, many numerical analyses were also presented, such as the finite element analysis (Han J et.al 2007; Zhuang Y et al., 2012) and discrete element analysis (Han J et al., 2012; Lai H J et al., 2014).

A modified 3D finite element model is presented in this paper to study the mechanical behavior of the soil arching effect. The interaction among the pile, subsoil and embankment fill is simulated by springs with various stiffness values. The proposed 3D model is easily implemented without the creation of the pile and subsoil, which is time-saving. A field test is conducted to get the actual engineering data. Based on the results comparison, several contrast numerical analyses are performed. Essentially, the soil arching effect is a stress transfer process. The conclusions could be used to get a better understanding of the mechanical behavior of the soil arching effect.
FIELD TEST

The location of the field test is shown in Fig.1. The embankment fill height is 4 m. The pile diameter and spacing value are 0.5 m and 1 m, respectively. The embankment fill is constructed layer-by-layer, and the roller (10 t) will compact the embankment fill after construction. The burying conditions of the transducers are shown in Figs.2, 3, and 4. The field test results are presented in Table 3.

![Figure 1. Construction of the embankment fill.](image1)

![Figure 2. Buried earth pressure cell.](image2)
Figure 3. Buried geogrid and flexible displacement meter.

Figure 4. Burying conditions of the transducers in the test section.

NUMERICAL MODEL

The numerical model is simulated layer by layer, which is the same as the actual engineering process. The embankment fill is divided into 8 layers and the height of each layer is 0.5 m. A 100 kPa pressure will be added on the top surface of the embankment fill. The Mohr Coulomb constitutive model is used as the constitutive model for the soil and the parameter of the model are obtained from the indoor test. Table 1 shows the parameter values of the soil parameter.

The degrees of freedom in x and y direction of the lateral boundaries are limited. The ground water is not considered in the embankment fill. The study object is the soil arching effect, so the embankment slope is disregarded. The mesh condition of the model is shown in Fig.5. For obtaining complete stress distribution and depressing the deficiency of the traditional man-made boundary condition, 8 piles are created in the numerical model. The interaction among the pile, subsoil and embankment fill is simulated by springs with various stiffness values. The stiffness values of the springs
shown in Table 2 are selected based on the actual modulus of the subsoil and pile. The distribution and number of the springs are properly selected based on the model. The local setting conditions of the springs are shown in Fig. 6.

For symmetry of the mesh and results, the square pile is treated as equivalent to the round pile based on the same area principle. The diameter of the round pile is 0.5 m in actual engineering, so the side length of the square pile is 0.44 m under the same area principle.

Table 1. Parameter values of the soil.

<table>
<thead>
<tr>
<th>Unit weight (kN/m³)</th>
<th>Young’s modulus (MPa)</th>
<th>Possion’s ratio</th>
<th>Cohesion yield stress kPa</th>
<th>Friction angle (°)</th>
<th>Dilation angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.5</td>
<td>20</td>
<td>0.3</td>
<td>16.8</td>
<td>24.6</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 5. Mesh conditions of the model.

Table 2. Stiffness values of the springs.

<table>
<thead>
<tr>
<th>Stiffness value (MPa)</th>
<th>Springs for the subsoil</th>
<th>Springs for the pile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6</td>
<td>5000</td>
</tr>
</tbody>
</table>

Figure 6. Springs setting conditions of the bottom surface.
(Red square represents the pile, while the other part represents the subsoil)

NUMERICAL ANALYSIS

Table 3 shows the comparison results between numerical analysis and field test. The
comparative results prove the reasonability of the numerical model. Based on a pile spacing of 1 m, the pile spacing values of 1.5 and 2 are selected for contrast tests. Different numerical analyses are performed to investigate the soil arching effect.

Table 3. Comparison of results.

<table>
<thead>
<tr>
<th></th>
<th>Earth pressure of the pile top $\sigma_C$ (MPa)</th>
<th>Earth pressure between the two piles $\sigma_B$ (MPa)</th>
<th>Earth pressure among the four piles $\sigma_A$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field test results</td>
<td>0.450</td>
<td>0.165</td>
<td>0.084</td>
</tr>
<tr>
<td>Numerical analysis results</td>
<td>0.443</td>
<td>0.191</td>
<td>0.037</td>
</tr>
</tbody>
</table>

The vertical stress distribution of the pile top and subsoil along the depth of the embankment fill is investigated. The changing curves are shown in Fig.7.
The vertical stress distributions of different regions along the depth of the embankment fill are shown in Fig.7. With the increasing depth of the embankment fill, the stress values of the three regions all initially increase, and the values are the same. Thus, no soil arching effect is noted in the soil of the depth. With the depth of embankment fill increasing to a certain value, an inflection appears in the curves. After the inflection, the vertical stress value of the pile top increases rapidly but the value of the subsoil decreases promptly. The depth of the inflection can be considered as the maximum critical height of soil arching. Fig.7 also shows that the maximum critical height in numerical model is consistent with that of Hewlett’s theory, when the pile spacing value is changed. Notably, a second inflection appears in the blue curve (stress of the subsoil between two piles) with the increase in the embankment fill depth. After the second inflection, the stress value of the subsoil between two piles increases rapidly and is larger than that of the subsoil among four piles. The reason for this phenomenon is that the soil arching effect of the position is too weak to transfer stress to the piles, therefore, the vertical stress increases. The depth of the second inflection can be considered as the minimum critical height of soil arching. Thus, soil between the maximum and minimum critical height is influenced by the soil arching effect, and different load distributions exist between the pile top and subsoil. For the vertical stress being transferred to the piles because of the soil arching effect, the subsoil between the two piles is also strengthened, which leads to more load being transferred to the subsoil between two piles. Hence, the final vertical stress value between two piles is larger than that among four piles.

CONCLUSIONS

A modified 3D finite element model is presented in this study to analyze soil arching effect in piled embankments. A field test is conducted to get the actual engineering data. After comparison, the numerical results are consistent with those of the field test. Under this premise, several contrast analyses are performed by changing the pile spacing. The
vertical stress distributions along the depth of the embankment fill are investigated. It is found that the critical maximum and minimum heights of the soil arch can be clearly obtained via the numerical model and the critical height of soil arching of the numerical model is consistent with that of Hewlett’s theory. Thus, the reasonability of the numerical model is verified. The numerical model is not only easily implemented but time-saving, which is a new method for researchers to analyze soil arching effect in piled embankments.

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