Numerical Analyses on Geogrid-Reinforced Cushion in Pile-Supported Composite Foundation

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Abstract. A numerical analysis is conducted on the performance of geogrid-reinforced cushion in PCC pile-supported composite foundation for highway embankment applications. The finite element method is employed to simulate the behavior of cushion under loads. Soil arching effect and tensile membrane effect are two factors affecting cushion behavior. Two parameters, i.e. geogrid tensile strength and laying arrangement, are found effective in measuring soil arching and tensile membrane effects. Numerical analyses indicate that an increased geogrid tensile strength contributes to a reduced embankment settlement. The effect of geogrid laying arrangement on settlement is relatively small.

Keywords. Cushion, PCC pile, composite foundation, soil arching effect, tensile membrane effect.

1. Introduction

With the rapid development of highway constructions in the southeast of China, the geosynthetic-reinforced pile-supported (GRPS) embankment has been increasingly adopted on account of its advantages in suitability and economy. The total and different settlement of GRPS embankment can be controlled [1]. GRPS embankment consists of embankment fills, geosynthetic-reinforced cushion, piles and soil between piles. Piles and cushion play important roles in affecting embankment performance. GRPS embankment designs mainly focus on the designs of piles and cushion. Therefore, to understand performance of piles and cushion, in particular their interactions, is necessary.

Many cushion designs have been proposed, i.e. Catenary method [2], Carlsson method [3], BS8006 method [4] and SINTEF method [5]. These design methods are generally based on empirical data and lack numerical simulation verifications. Using numerical analyses, Han and Gabr [1, 6] considered embankment soil arching effect, geosynthetic tension membrane effect and stiffness difference between pile and soil, and analyzed the load transfer mechanism of GRPS embankment. Not many other efforts have been conducted on the cushion geogrid design. In this study, the GRPS cushion performance is simulated and analyzed by using finite element method (FEM). Influences of geogrid’s laying arrangements and tensile strength on pile-soil stress ratio, soil arching and tensile membrane effects are discussed to provide technical data for optimizing cushion design and improving GRPS performance.

2. Computation and Analyses

2.1. Software

ADINA, an FEM professional software kit, is used to implement numerical analyses. ADINA is able
to address various computations, e.g. non-linear and coupling problems in fields of civil engineering and traffic engineering. In addition, the software has programs for running models in geotechnical engineering, such as Mohr-Coulomb model, Drucker-Prager model, and Cambridge model.

2.2. Computation Model

The analyzed model is composed of a single cast-in-situ thin-wall concrete pipe pile (PCC), the soil around PCC pile and underlying layers, the geogrid reinforced cushion and the embankment, as illustrated in figure 1. Considering the symmetry of the model, a quarter of the model is used to replace the whole one. In mechanical simulations, Mohr-Coulomb model is used for stress-strain behaviors of embankment, soils and cushion. In the model, a frictional contact surface is adopted to simulate actual frictional resistance between contacts. The frictional coefficient is set a constant for a contact surface and varies for different contact surfaces. Elastic model is used for stress-strain behaviors of pile and cushion geogrids. The bottom and side boundary constraints are as well taken into account in the model.

2.3. Performance of GRPS Composite Foundation

Numerical analyses were first conducted to simulate performance of GRPS composite foundation, mainly in the aspects of its stress and deformation variation. Table 1 presents model parameters which are based upon general designs and measurements. In addition, dimensional parameters of components are selected as well. The embankment height is 4 m. The thickness of cushion is 0.5 m. The outer diameter of PCC pipe pile is 1.0 m. The pile length is 15 m. The thickness of underlying stratum is 10 m. The PCC piles are arranged in square shape, and the equivalent diameter of reinforced area is 1.13S, where S is the spacing between piles. If common pile spacing is 3 m, the diameter of a pile reinforced circular area is 3.4 m.

| Components          | Modulus (MPa) | Poisson’s ratio | Unit weight (kN/m³) | Shear strength c (kPa) | φ (°) |
|---------------------|---------------|-----------------|---------------------|------------------------|-------|
| Embankment          | 12            | 0.3             | 20                  | 10                     | 28    |
| Cushion             | 15            | 0.28            |                     | 0                      | 35    |
| PCC pile            | 12000         | 0.18            | 25                  | 10                     | 15    |
| Foundation soil     | 3             | 0.3             | 18                  | 10                     | 15    |
| Geogrid             | 75            | 0.45            |                     |                        |       |

Figure 1. Computation model.  
Figure 2. Deformation of computation model.
The deformed model is illustrated in figure 2. It is shown that the PCC pile penetrates into the cushion on top and the underlying stratum at bottom. It is interpreted that the pile modulus is much higher than that of cushion and soil, and a stress concentration exists on the top and at the bottom of pile. The pile penetrations enhance cushion, pile and soil to co-work together.

Figure 3 shows the relationship of pile-soil relative settlement along the depth. Figure 4 shows the relationship of pile axial stress along the depth. The pile-soil relative settlement follows a linear variation, starting from 0.02 m at pile cap to -0.055 m at 10 m deep. The axial stress starts from 650 MPa at pile cap, increases to 750 MPa at 3.5 m deep, then decreases to 460 MPa at 10 m deep. A neutral point, 3.5 m beneath the pile cap, is found, where the pile and soil settlements are the same, and the pile axial stress has a maximum value. It is inferred that the shaft friction resistance is negative for pile-soil contact surface of less than 3.5 m deep.

The soil arching effect in embankment, geogrid tensile membrane effect in cushion and the pile-soil modulus difference are three main aspects determining load transfers of GRPS embankment. The soil arching effect can be quantified by using soil arching ratio \( \rho_a \), which was defined by McNulty [7] as shown in Equation (1).

\[
\rho_a = \frac{p_b}{\gamma H + q_0}
\]

where, \( \gamma \) is the unit weight of embankment landfill, \( H \) is embankment height, \( q_0 \) is the surcharge on the embankment, and \( p_b \) is the stress loaded on the top of cushion. It is inferred that the smaller \( \rho_a \), the better soil arching works, and that \( \rho_a \) being zero represents a complete soil arching existence. According to numerical simulations of the discussed model, the soil arching ratio \( \rho_a \) is equal to 0.753.

Parameter \( \rho_{u,m} \) is introduced to measure both soil arching and tensile membrane effects. Parameter \( \rho_m \) is used to measure the tensile membrane effect. The definitions are presented in equations 2 and 3.

\[
\rho_{u,m} = \frac{p_s}{\gamma H + q_0}
\]

\[
\rho_m = \rho_a - \rho_{u,m}
\]
where, $p_s$ is the average stress loaded on the top of soils between piles. Numerical simulations indicate that $\rho_{m, e}$ is equal to 0.586 and $\rho_{m, a}$ is equal to 0.167, respectively.

Road embankment is generally regarded as flexible loads. The different settlement of embankment is more concerned than the absolute settlement in practices. With the increase of embankment height, the different settlement becomes smaller. There exists a plane where even settlements are observed. The plane is called plane of equal settlement. In practices, the embankment surface should be higher than the plane of equal settlement. For the modeling analyses above, the height of the plane is about 1.75 m, which is much lower than the designed embankment height. Accordingly, a favorable embankment settlement is offered.

2.4. Behaviors of Geogrid-Reinforced Cushion

2.4.1. Effect of Geogrid Tensile Strength. Cushion geogrid’s tensile strength plays an important role in affecting cushion behavior and thus performance of GRSP embankment. To observe the effect of geogrid’s tensile strength, a series of geogrid’s moduli were taken in the model analyses, i.e. 7.5 MPa, 75 MPa, 750 MPa, 3 GPa, 7.5 GPa, 15 GPa and 45 GPa. In the computation, all other parameters are kept the same to make a noticeable observation on the effect of geogrid’s tensile strength.

Figure 5 presents the effect of geogrid tensile strength on the pile-soil stress ratio. With the increase of modulus from 7.5 MPa to 100 GPa, the pile-soil stress starts from 20, appropriately keeps constant till modulus being 1 GPa. Then, the ratio increases linearly up to 50. It is inferred that no significant pile-soil stress ratio is found when the geogrid modulus is less than 1 GPa. The pile and soil always share the loads at a constant ratio. However, when the pile-stress ratio exceeds 1 GPa, the stress share ratio between pile and soil is changed, with increasingly more loads borne by the pile.

![Figure 5. Effect of geogrid tensile strength on pile-soil stress ratio.](image-url)

The effect of geogrid tensile strength on soil arching effect and tensile membrane effect is demonstrated in figure 6 by numerical simulations. It is indicated that with the increase of geogrid’s tensile strength or modulus, the different settlement of embankment will become smaller. The soil arching effect becomes weakened and the soil arching ratio $\rho_u$ is increased. However, the tensile membrane effect works better resulted from the increased tensile strength. Therefore, with the coupling of the two effects, more and more loads are carried by piles.
2.4.2. Effect of Geogrid Laying Arrangement. Layer numbers and embedding locations regarding cushion geogrid are varied to analyze resulted effects on the performance of GRPS embankment using the numerical model simulations. Layer numbers have two options: one layer and multiple (2-3) layers of geogrid. The embedding locations of geogrid are indicated by the (average) geogrid distance beneath the cushion top.

Figure 7 shows the effects of embedding one and multiple layers of geogrid on pile-soil stress ratio. For one layer geogrid, geogrid embedding depth is almost linear related with pile-soil stress. It is inferred that a deeper embedded geogrid favors more loading transfer to piles. For multiple layers of geogrid, the increased average layer depth largely results in an increased pile-stress ratio. Comparing these two situations, increasing the geogrid layer number demonstrates a greater effect on pile-soil stress ratio than changing the geogrid place. Hence, in designs, it is better to design relatively more geogrid layers to increase the bearing capacity of GRPS embankment.

Figure 8 demonstrates the effects of embedding one and multiple layers geogrid on the soil arching effect and tensile membrane. For one layer geogrid, an increased geogrid embedding depth results in a slight increase of tensile membrane effect and decrease of coupled effect. And more loads are carried by piles in this manner. For multilayer geogrid, similar observations are found. For both situations, however, changing geogrid’s embedding depth and adding geogrid layers do not have clear effect on soil arching.
3. Concluding Remarks

Numerical analyses are implemented to observe performance GRSP embankment, particularly the cushion geogrid’s influences on pile-soil stress ratio, soil arching and tensile membrane effects. According to the load transfer mechanisms of soil arching and tensile membrane effect, two parameters are discussed about their influences, i.e. the geogrid’s tensile strength and laying arrangement. Following remarks are summarized.

(1) Most loads are carried by the piles in the GRSP embankment systems due to the soil arching effect in embankment and the tensile membrane effect of geogrid in cushion.

(2) With the increase of geogrid’s tensile strength or modulus, cushion’s resistance to deformation is increased, which results in a weakened soil arching effect and a strengthened tensile membrane effect. As a result, the pile-soil stress ratio is increased.

(3) For the monolayer cushion geogrid, to embed the geogrid close to cushion bottom helps increase the pile-soil stress ratio and geogrid’s tensile membrane effect. With the increase of geogrid layer number in cushion, both the pile-soil stress ratio and the tensile membrane effect have a slight increase. The effects of geogrid’s depth and layer number on soil arching are largely slight as well.

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