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Numerical Study of Bearing Deformation Characteristics of Geo-encasement Stone Column under Embankment Load

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Abstract: This paper uses FLAC3D software to establish a numerical model of unit cells below the embankment, studying the characteristics of pile-soil settlement and settlement difference under different parameters. The results show that the cohesion of the road embankment has a higher impact on the pile-soil settlement difference compared to the road embankment load and the friction angle of the embankment. When the cohesiveness of the road embankment is less than 10kPa, increasing the cohesiveness can reduce the pile-soil settlement difference; but when the cohesion of the road embankment is greater than 10 kPa, continuing to increase the cohesiveness has a negligible effect on reducing the pile-soil settlement. When the friction angle of the embankment is below 30°, increasing the friction angle of the embankment can significantly reduce the pile-soil settlement difference. However, when the friction angle is above 30°, continuing to raise the embankment friction angle results in minimal changes in the pile-soil settlement value and the pile-soil settlement difference.

1. Introduction

Under the rapid development of China's economy, the transportation industry is also making continuous progress. As a vital infrastructure of the country, the railway has evolved into a major artery of the national economy, a pillar of the transportation industry, and is closely related to the production and daily life of the people. When constructing railway embankments on soft soil foundations, the engineering characteristics of soft soils, such as low permeability and high compressibility, result in a lower bearing capacity of the foundation and excessive settlement. This can lead to various types of embankment slope instabilities, including local, surface, general, and deep-seated slope failures, which may have serious consequences.

Although gravel pile reinforcement technology in pile foundation treatment can improve the bearing capacity of soft soil foundations, reduce settlement, enhance foundation stability, and improve drainage [1-6], under the conditions of soft soil foundations, due to the poor radial confinement of soft soil, sufficient passive resistance cannot be provided, thereby reducing the bearing capacity of the piles. To address this issue, gravel piles can be wrapped with geosynthetic materials that have very high axial stiffness to form geo-encasement stone column. These geosynthetic materials have considerable axial stiffness, which can generate significant circumferential stress to withstand radial deformation [7-8]. Due to the presence of geosynthetic materials, the filler material within the pile is confined, and they also act as a barrier between the filler and the surrounding soil, thereby effectively enhancing the bearing capacity of the piles.

Ayadat and Hanna[9] studied the performance of geo-encasement stone column under different water levels through laboratory testing. The results indicated that increasing the strength of geosynthetics or the length of the piles could improve the bearing capacity and reduce settlement. It was also demonstrated that under identical conditions, an increase in the degree of water submersion would lead to increased settlement and significantly reduce the bearing capacity of the piles. Zhang Yiping et al. [9] through the application of full volume strain elements and considering both radial and vertical seepage within the pile and soil body, deduced the theoretical solution for the calculation of consolidation degree of composite foundation geo-encasement stone column under non-instantaneous loading. Lo et al. [10-11] based on numerical simulation and using embankment load and an idealized unit cell model, found that the stiffness generated by compacted aggregate had no significant impact on predicted performance; it depends on the locking stress induced during the installation of the geosynthetic casing. At the same time, they confirmed that the performance of piles carrying loads is related to time. Nasiri and Hajiazizi[12] discovered through experiments and the three-dimensional finite difference method that, compared to ordinary gravel piles, geo-encasement stone column increased the bearing capacity of slopes by 1.66 times and improved slope stability by 65.63%, also enhancing the safety factor. At the same time, it was found that while geo-encasement stone column increased the capacity to withstand bending failure, they did not significantly change the capacity to withstand shear failure.

Research has revealed that there is a lack of studies on the pile-soil settlement and differential settlement of the unit cell model beneath embankments, and most studies simulate the stability of embankments over geo-encasement stone column using two-dimensional models, with fewer studies using three-dimensional models. Therefore, this paper will establish a Unit Cell Numerical Model for Geo-encasement stone column to investigate the characteristics of pile-soil settlement, as well as the stress and deformation of pile-soil under different parameters.

2. Settlement Study of the Unit Cell Model under Embankment Load

2.1 Introduction to the Unit Cell Model Under Embankment Load

2.1.1 Model Dimensions and Boundary Conditions

The numerical model of the unit cell under the embankment established in this chapter is shown in Figure 1. The pile diameter is 0.3375 m, the radius of the soil is 0.955 m, the pile-soil replacement rate is 0.125, and the length of the pile and the depth of the soil are both 1.25 m. The model is constructed using the MADIS software, and employs a mapped mesh refinement strategy.

The pile radius is divided into 12 grids, the soil radius into 20 grids, and the height into 25 grids. Except for the top surface, the remaining four surfaces are fixed in the normal direction and free in the other directions, with no boundary constraints set on the top.

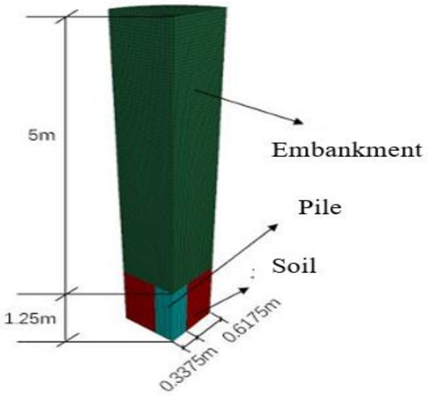

Figure 1: Unit Cell Model Under an Embankment

2.1.2 Material Properties and Constitutive Relations

In the model, both the piles and the soil are modeled using solid elements. The piles are assigned the Mohr-Coulomb constitutive relationship, whereas the soil is modeled using an elastic model. Geosynthetic materials are represented using the Geogrid structural element in FLAC3D, with an elastic modulus of 110 kPa, a coupling cohesion of 1 kPa, and a coupling friction angle of 38°, behaving as an isotropic linear elastic material. The thickness of the geosynthetic material shell is maintained at 2 millimeters, consistent with the thickness of woven geogrids used in most laboratory tests. The embankment parameters are taken from the embankment parameters in the article by Zhang et al.[13]. The embankment is modeled with solid elements and the Mohr-Coulomb model, with a total height of 5 meters, constructed in five stages. The material parameters used for the study are as in Table 1.

Table 1. Characteristics of Pile-Soil Materials[13-14].

Material	E（kPa）	ν	φ（°）	c（kPa）	Severity（kN/m^3）
Pile	3.3e5	0.4	38	1	28
Soil	110	0.4	24	9	18
Embankment	46200	0.3	39.8	0	24

2.2 Analysis of the Relationship between Embankment Fill and Pile-Soil Settlement

2.2.1 The influence of embankment load

To study the impact of pile-soil settlement and the differences in settlements under different embankments, this section selects six types of embankment fill materials with different material characteristics. The embankment loads are converted into uniformly distributed loads of 100 kPa, 110 kPa, 120 kPa, 130 kPa, 140 kPa, and 150 kPa, respectively, with all other parameters held constant. The settlement values at the top of the pile are all taken from the embankment centerline position (0 m, 0 m, 1.25 m), and the settlement values at the top of the soil body are selected from the position (0.6 m, 0.6 m, 1.25 m) for analysis. The embankment parameters are shown in Table 2.

Table 2. Characteristics of Embankment Materials.

Material	E（kPa）	ν	Severity（kN/m^3）	c（kPa）	φ（°）
Embankment 1	35400	0.3	20	0	34.6
Embankment 2	40800	0.3	22	0	37.2
Embankment 3	46200	0.3	24	0	39.8
Embankment 4	51600	0.3	26	0	42.4
Embankment 5	57000	0.3	28	0	45
Embankment 6	62400	0.3	30	0	47.6

From Figures 2 and 3, it can be seen that with an increase in embankment load, the settlement values of the soil top in the numerical model of the unit are in good agreement with the top settlement solution values of the analytical model. Therefore, the magnitude of the embankment load does not affect the agreement between the numerical solution and the analytical solution, and the settlement results obtained analytically can be used to simulate the settlement at the soil top beneath the embankment. It is also observed that with the increase in embankment load, the pile-soil settlement increases; the settlement of the numerical solution soil body increases from 158 mm to 228 mm, with an increase of 70 mm, and the DOI value is 36%. The settlement at the pile top increases from 77.5 mm to 119.5 mm, with an increase of 42 mm, and the DOI value is 43%. The difference in pile-soil settlement increased from 80.5 mm to 108.2 mm, an increase of 27.7 mm, with a DOI value of 29%. Therefore, under the numerical solution, the embankment load has a "medium" degree of influence on the settlements of both the soil body and the pile body, and a "low" degree of influence on the pile-soil differential settlement.

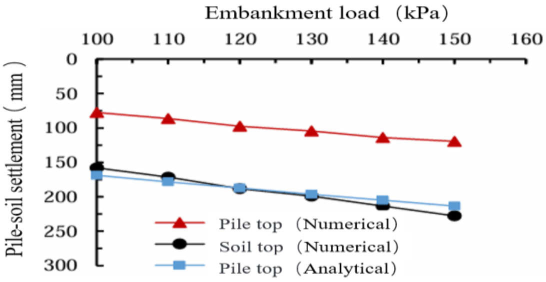

Figure 2: Pile-soil settlement under different embankments

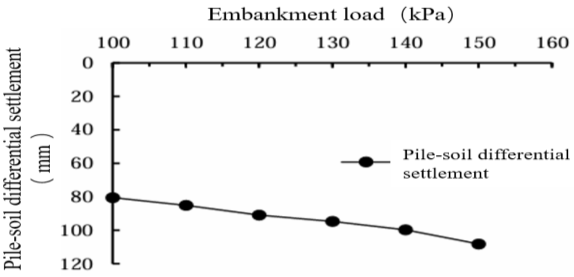

Figure 3: Differential settlement of pile-soil under different embankments

2.2.2 The influence of embankment cohesion

When In order to study the impact of pile-soil settlement and settlement differences under different embankment cohesions, 8 types of embankment cohesions were selected as 0 kPa, 2 kPa, 4 kPa, 6 kPa, 8 kPa, 10 kPa, 12 kPa, and 15 kPa, with all other parameters held constant. As shown in Figure 4, as the cohesion of the embankment increases from 0 to 10 kPa, the settlement value of the soil gradually decreases, from 188.3 mm to 135.2 mm, a reduction of 53.1 mm, with a DOI value of 33%, while the pile settlement increases from 97.4 mm to 121 mm, an increase of 23.6 mm, with a DOI value of 22%. When the embankment cohesion is greater than 10 kPa, the pile-soil settlement remains almost unchanged. From Figure 5, it can be seen that increasing the cohesion of the embankment can effectively reduce the differential settlement between the pile and the soil, from 90.9 mm to 14.2 mm, a reduction of 76.7 mm, with a DOI value of 146%. When the cohesion of embankment fill material increases to 6 kPa, the rate of reduction in pile-soil differential settlement increases; however, when the cohesion is greater than 10 kPa, the differential settlement becomes almost unchanged. Therefore, it can be concluded that the cohesion of the embankment has a "medium" degree of influence on the settlement value of the soil, a "low" degree of influence on the settlement of the pile, and a "high" degree of influence on the differential settlement between the pile and soil. Increasing the cohesion of the embankment can rapidly reduce the differential settlement, but when the embankment cohesion is greater than 10 kPa, it has almost no effect on the pile-soil settlement and differential settlement.

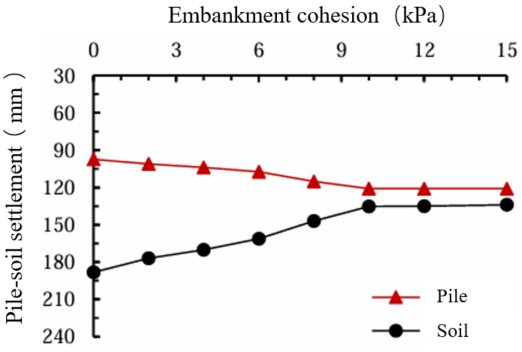

Figure 4: Pile-soil settlement under different embankment cohesion

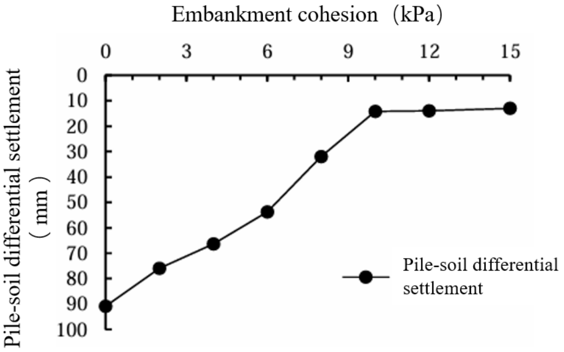

Figure 5: Differential settlement of pile-soil under different embankment cohesion

2.2.3 The Influence of the Friction Angle of the Road Embankment

This article analyzes the effects of different embankment friction angles on pile-soil settlement and differences in settlement. We selected 5 different embankment friction angles of 25°, 30°, 35°, 40°, and 45° respectively. From Figures 6 and 7, as the embankment friction angle increases, the settlement value of the soil gradually decreases from 218.2 mm to 184.7 mm, reducing by 33.5 mm, with a DOI value of 17%. However, the settlement value of the pile gradually increases, from 86.4 mm to 98.1 mm, an increase of 11.7 mm, with a DOI value of 13%. When the embankment friction angle increases from 25° to 30°, the rate of change in the pile-soil settlement value is relatively rapid, while the difference in the pile-soil settlement also rapidly decreases from 131.8 mm to 100 mm, a reduction of 31.8 mm, with a DOI value of 27%. When the embankment friction angle increases from 30° to 45°, the trend of change in the pile-soil settlement value remains unchanged, but the rate of change slows down. The rate at which the difference in the pile-soil settlement decreases also gradually slows, dropping from 100 mm to 86.6 mm gradually. Therefore, overall, the embankment friction angle has a "low" influence on the settlement values of the pile and soil, as well as the difference in pile-soil settlement. However, when the embankment friction angle is less than 30°, different embankment friction angles affect the pile-soil settlement value as well as the difference in pile-soil settlement more significantly. When the embankment friction angle is higher than 30°, the change in pile-soil settlement value and the difference in pile-soil settlement are not significant.

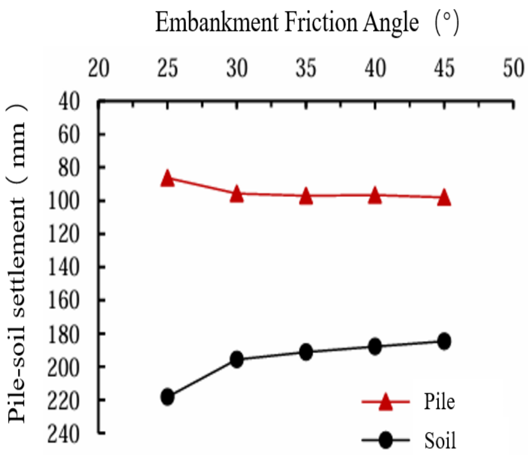

Figure 6: Pile-soil settlement under different embankment friction angles

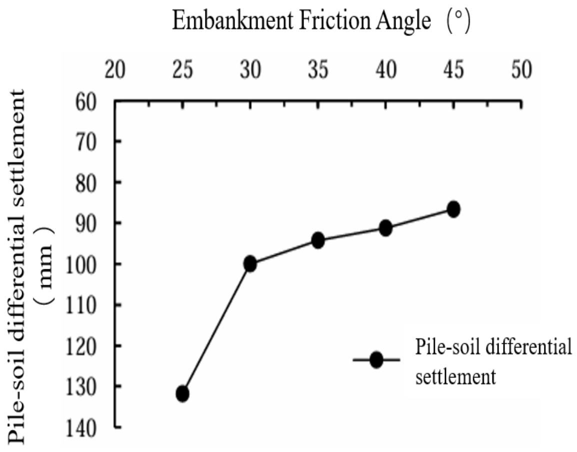

Figure 7: Differential settlement of pile-soil under different embankment friction angles

3. Conclusions

This paper analyzes the pile-soil settlement and its difference under different conditions by establishing a numerical model of single cells under the embankment, and the conclusions are as follows:

(1)When the cohesion of the embankment is less than 6 kPa, increasing the cohesion can reduce the difference in pile-soil settlement; when the cohesion of the embankment is more than 6 kPa but less than 10 kPa, the rate of reduction in the pile-soil settlement difference increases significantly; when the cohesion of the embankment is more than 10 kPa, the impact on pile-soil settlement and the difference in settlement can be ignored.

(2)When the friction angle of the embankment is below 30°, increasing the friction angle will rapidly reduce the pile-soil settlement difference, but when it is above 30°, the changes in both the pile-soil settlement and the pile-soil settlement difference are not significant.

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If any, should be placed before the references section without numbering.

Data Availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

Conflict of Interest

The author states that this article has no conflict of interest.

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