Study on the Effect of Cement Graded Gravel Pile on Treating Loess Foundation

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Abstract. In the context of existing transportation operations, cement-graded crushed stone compaction piles are used as a treatment method to address the damage caused by the infiltration of the lower layer of the loess foundation. By conducting numerical simulation analysis on this semi-rigid composite foundation and establishing models with different pile lengths and diameters, the variation pattern of the bearing capacity of the foundation is obtained. As the pile length increases, the settlement of the foundation decreases, the maximum stress of the pile body increases, and the stress at the pile end decreases; the increase in pile diameter increases the contact area between the pile and the foundation soil, increases the stress at the pile top, and similarly reduces the stress at the pile end; the cushion thickness has a significant impact on the bearing capacity of the composite foundation. The stress of the pile body changes significantly, and the smaller the thickness is, the greater the stress at the top of the pile is, while the stress at the pile body decreases. As the thickness of the cushion layer increases, the effect on the ratio of pile stress to soil stress is not significant, and to some extent, it also increases the cost. In practical engineering, its choice is not economical. Based on numerical simulation analysis of composite foundations, it provides a certain reference for the design selection and optimization of practical engineering in the future.

Keywords: Cement graded crushed stone compaction pile; Foundation settlement; Bearing capacity; Numerical simulation; Composite foundation; Pile-soil stress ratio; CFG pile; Cushion; Frictional resistance

1 Introduction

The treatment of collapsible loess foundations has always been a hot and difficult point in engineering construction in loess areas. For loess foundation, CFG piles, cement-soil compaction piles, and other methods are usually used to treat it to meet

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the design bearing capacity requirements [1]. These methods have to some extent reduced foundation settlement and improved foundation bearing capacity [2]. However, due to the use of a large amount of cement, it will greatly increase the engineering cost. Moreover, in the loess region, although CFG piles have significantly improved the bearing foundation bearing capacity, the inherent collapsibility of the loess foundation has not been eliminated. If cement-graded crushed stone compaction piles are used, not only can the bearing capacity of the roadbed be enhanced, but also the collapsibility of the loess roadbed can be more effectively eliminated [3]. For CFG piles and composite foundation treatment methods, their respective advantages can be fully utilized to achieve the expected treatment effect [4]. This article relies on practical engineering, and for loess foundation, a series of diseases caused by long-term immersion in groundwater have severely weakened the bearing capacity and do not meet engineering requirements. Therefore, based on this, a cement-graded crushed stone compaction pile is proposed, and its bearing capacity characteristics are obtained by changing its immersion conditions [5].

2 Finite Element Numerical Analysis Method

Finite element numerical analysis divides the model into many elements and nodes, which define contact between these elements and nodes, and then assign specific material parameters to each part of the elements, such as cohesion, internal friction angle, and Poisson's ratio. Finally, by designing different operating conditions, solution analysis is carried out. This article uses the Mohr-Coulomb model [6-8] in Midas GTS NX software for numerical simulation analysis. By establishing a model using this software, complex model visualization can be achieved.

Mohr-Coulomb yield condition is shown in Formula (1):

$$F = \frac{1}{2}\left(\sigma_1 - \sigma_3\right) + F_1\left[\frac{1}{2}(\sigma_1 + \sigma_3)\right] \tag{1}$$

If stress tensor I, stress deviator J, and Lord's angle are used θσ to represent, the form is shown in Formula (2):

$$F = \frac{1}{3} I_1 \sin\varphi + (\cos\theta_\sigma - \frac{1}{\sqrt{3}} \sin\theta_\sigma \sin\varphi)\sqrt{J_2} - c\cos\varphi \tag{2}$$

Among them, Formula (3) is shown as follows:

$$-\frac{\pi}{6} \le \theta_\sigma \le \frac{\pi}{6} \tag{3}$$

3 Mechanism of Cement-Graded Gravel Pile Composite Foundation

3.1 Replacement effect of piles

The strength and modulus of the CFG pile body are much greater than that of soil between piles, so under load, the stress at the pile top is greater than the surface stress of soil between piles. The pile can transfer the load it bears to deeper soil layers, thereby reducing the load borne by the soil between the piles. The effect of piles on improving the bearing capacity and reducing the deformation of composite foundations is called pile displacement or pile effect.

A large number of engineering practices have shown that the difference in the replacement effect of composite foundations is caused by the pile material, which is the reason for the different stress situations of gravel piles and CFG piles. Because the material of the gravel pile body is loose and the pile body has no cohesive strength, it is constrained by the surrounding soil to bear the upper load. A small range below the pile top creates a pressure expansion zone, and the pile body below the pressure expansion zone has little ability to transmit vertical loads. When the pile grows beyond the depth of the pressure expansion zone, it is difficult to increase the pile length to improve the bearing capacity of a single pile. Semi-rigid piles, due to their material having a certain bonding strength, will not experience compression deformation after the upper load is applied. The load is transmitted to the deep foundation through the frictional resistance around the pile and the pile end resistance, thereby improving the bearing capacity of the foundation [9].

3.2 The stress adjustment effect of the cushion layer

When a composite foundation is equipped with a cushion layer, the pile body gradually penetrates the cushion layer under the action of the upper load, causing the cushion material to flow towards the surrounding area. This phenomenon can partially avoid stress concentration at the top and bottom of the pile, and also maintain contact between the soil between the piles and the bottom of the foundation, fully exerting the bearing capacity of the soil between the piles. Under load, the cushion layer generates compression and complementary effects in both vertical and horizontal directions, which promotes close contact between the soil between piles and the foundation during the loading process, thereby homogenizing the contact pressure and vertical stress distribution of the foundation, and greatly improving the bearing capacity of the composite foundation [10-13].

3.3 Drainage effect

Gravel piles and sand piles have good drainage channels, while CFG piles do not. Whether a pile can form a drainage channel mainly depends on the pile material and the forming process of the pile. Research has shown that the permeability of CFG pile material is related to the amount of fly ash and cement used in the mixture, as well as the properties of fly ash [14]. The indoor test results show that the permeability coefficient of the CFG pile body is generally within the range of 10.3-10.1, while the permeability coefficient of the natural soil layer within the range of pile placement is generally between 10.6-10.4. CFG piles also have significant permeability before the initial setting of the pile, allowing the excess pore water pressure generated by vibration to quickly dissipate through the pile. From this perspective, the pile body constitutes a consolidation drainage channel relative to the soil, and the pile placement accelerates the consolidation process of the soil around the pile, thus the pile body has a drainage effect.

3.4 Improvement of soil properties between piles

The use of compaction and vibration pile forming techniques for loose fill, loose fine sand, silt, and cohesive soil with low plasticity index can reduce the pore ratio, increase compactness, and frictional resistance of the soil between piles, and improve the strength and modulus of the soil between piles. The test results indicate that the physical and mechanical properties of the soil between piles have been greatly improved after foundation reinforcement. In the case of high water content, after treatment, the water content decreases by 14%-19%, the natural bulk density increases by more than 1%, the pore ratio decreases by more than 3%, and the compression coefficient decreases by 11%-52%. Especially for silty clay and silt with good engineering performance and structure, the improvement of the properties of the soil between piles is more significant [15].

4 Numerical Simulation Analysis of Cement-Graded Crushed Stone Compaction Pile

4.1 Modeling

This article conducts numerical simulation analysis to analyze the factors affecting the bearing capacity of the composite foundations by establishing different pile lengths, pile diameters, and cushion layer thicknesses [16]. As shown in Figure 1, it is the contour cloud map of the composite foundation settlement. Figure 2 shows the vertical deformation profile of the model.

For composite foundations, the pile length, diameter, and thickness of the cushion layer have a significant impact on the bearing capacity on the one hand. On the other hand, they also have a significant impact on the cost. If the designed pile length is too short or the pile diameter is too small, the bearing capacity cannot meet the requirements. If it is too long or the pile diameter is too large, the engineering cost is relatively high and uneconomical. This article selects three lengths of 8 m, 10 m, and 12 m to simulate and analyze the impact of pile length on the bearing characteristics of the roadbed; it also selects three different pile diameters of 0.2 m, 0.4 m, and 0.6 m, and cushion thicknesses of 0 m, 0.3 m, and 0.6 m to analyze the impact of cushion thickness on the bearing capacity of the foundation.

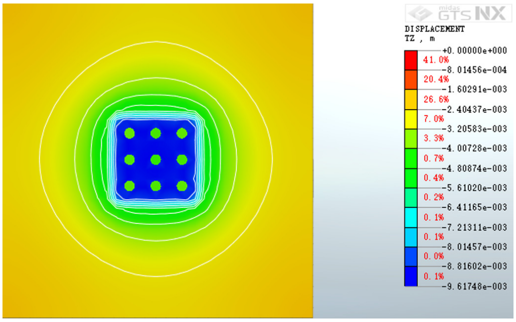

Fig. 1. Contour map of composite foundation settlement

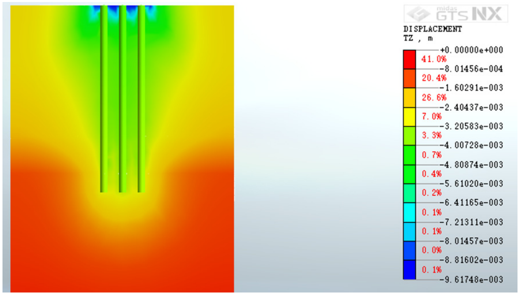

Fig. 2. Vertical deformation profile of the model

4.2 The results of numerical simulation

As shown in Figure 3, p-s curves for different pile lengths, pile diameters, and cushion thickness are presented. From the graph, it can be seen that the p-s curve shows a downward trend. For different pile lengths, an increase in pile length results in a decrease in settlement; as the load increases, the difference in settlement becomes increasingly apparent. For different pile diameters, the increase in pile diameter reduces the area replacement rate of the loess foundation, and the contact between pile and soil increases, resulting in a decrease in settlement. For the thickness of the cushion layer, there is no significant difference in settlement between 0 m, 0.3 m, and 0.6 m. When the load is small, there is basically no difference. When the load is large, it is more obvious compared to others.

As shown in Figure 4, the stress distribution of the middle pile body with different pile lengths is presented. Different pile lengths have an impact on the stress of the pile body at different depths. When the load remains constant, as the depth increases, the stress first increases, peaks appear, and then decreases. When the depth remains constant, the greater the load is, the greater the stress at different positions of the pile body is. However, as the depth increases, the degree of difference shows a trend of first increasing and then decreasing. At a depth of about 4 m, the difference reaches its maximum.

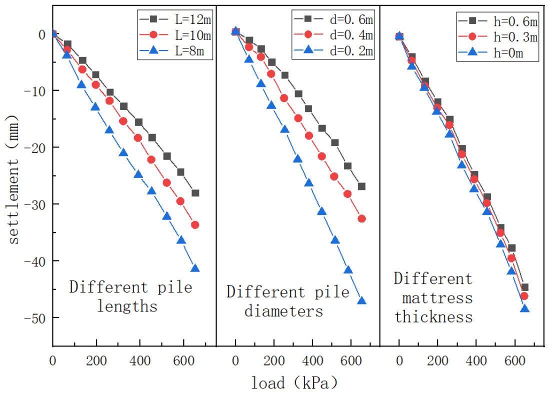

Fig. 3. Load settlement curves for different pile lengths, pile diameters, and cushion thickness

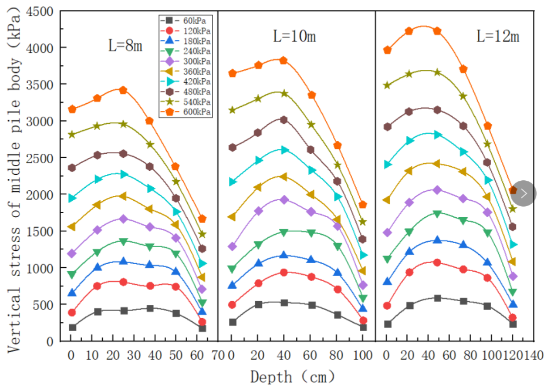

Fig. 4. Stress of piles in different pile lengths

The stress of piles in different pile lengths is shown in Figure 5. From it, it can be seen that the trend of change is basically consistent with the trend of different pile lengths. The maximum stress of the pile body increases with the increase of the pile diameter, but the stress at the pile end shows a slightly decreasing trend with the increase of the pile diameter.

The stress distribution of cement-graded crushed stone piles with and without cushion separately at p=300 kPa is shown in Figure 6. From it, it can be seen that when h=0, the stress at the top of the pile is relatively high. After setting the cushion layer, the stress at the pile top is significantly reduced. When no cushion layer is set up, there is no negative frictional resistance between the pile top and the foundation soil. The peak stress of the entire pile body is located at the pile top. After the cushion layer is set up, negative frictional resistance is generated between the pile body and the cushion layer. The cushion layer plays a compensating role, causing load transfer and to some extent improving the bearing capacity of the foundation.

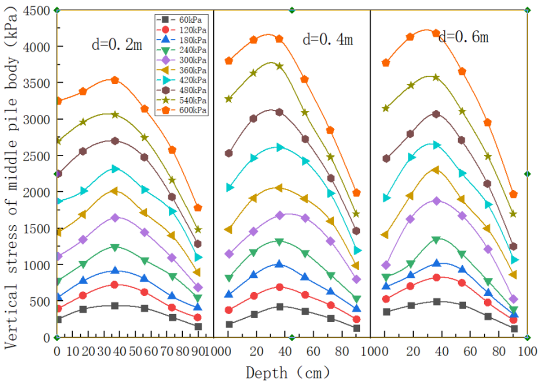

Fig. 5. Stress changes of cement-graded crushed stone piles under different diameters

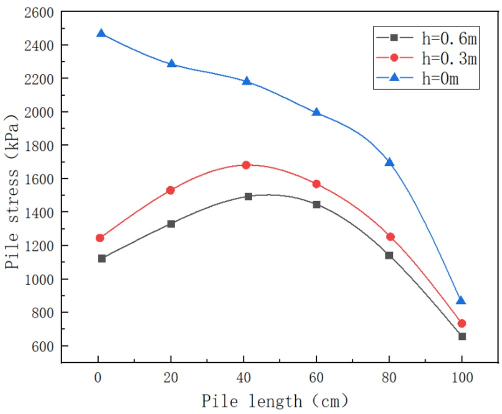

Fig. 6. Pile stress with different cushion layer thicknesses

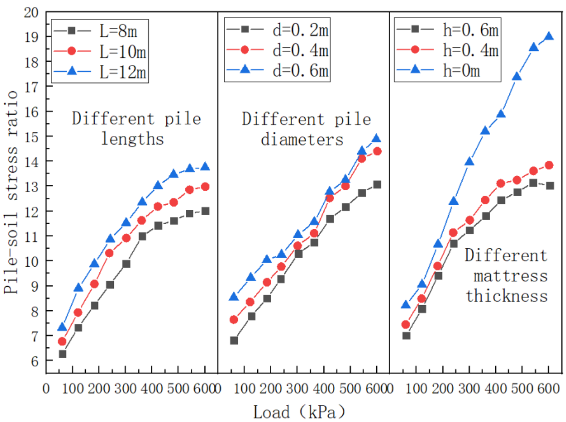

Fig. 7. The ratio of the stress of cement-graded crushed stone pile to that of foundation soil

Figure 7 shows the ratio between pile stress and soil stress for different pile lengths, pile diameters, and cushion thickness. From it, it can be seen that the trend of pile soil stress ratio is similar for different pile lengths and diameters, and eventually tends to stabilize. When the cushion layer is not set, the pile-soil stress ratio shows a linear change, showing an upward trend and not reaching a stable state. In this case, the load borne by the pile body gradually increases, while the load borne by the foundation soil gradually decreases [17]. After setting the cushion layer, it shows an upward trend with the increase of load and finally tends to stabilize. However, compared to the thickness of the 0.3 m and 0.6 m cushion layers, the difference in pile-soil stress ratio is not significant in both cases. Therefore, considering the engineering cost, the thicker the cushion layer is, the better it is.

5 Conclusions

This article analyzes the influence of the length and diameter of cement piles and the establishment of a numerical simulation analysis model for the influence of cushion setting and thickness on the bearing capacity of the loess foundation. The following conclusions are drawn:

Under different pile lengths, the larger the length of the pile is, the smaller the settlement of the foundation is. The stress of the entire pile increases and the stress at the bottom of the pile decreases. As the load increases, the difference in settlement becomes increasingly apparent.

As the diameter of the pile increases, the contact between the cement-graded gravel pile and the foundation soil increases, and the area replacement rate of the composite foundation changes, resulting in a decrease in settlement. As the diameter increases, the stress in the upper part of the pile gradually increases, while the stress in the bottom gradually decreases.

When the thickness of the cushion layer is 0, the stress at the pile top is greater, and the pile-soil stress ratio increases linearly. After setting up the cushion layer, negative frictional resistance is generated between the pile and the cushion layer, resulting in a significant decrease in the stress at the pile top, and the stress ratio between the pile and soil first shows an increasing trend, and then gradually stabilizes.

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