Effect of supplementary pile reinforcement on the vertical bearing characteristics of pile foundation

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Abstract. To investigate the impact of supplementary pile reinforcement on the vertical bearing characteristics of the pile foundation, this study employs finite element simulation to analyze the settlement and stress before and after reinforcement. The results show that the settlement of the pile foundation decreases following reinforcement, leading to improved bearing capacity and rebound rate. Both the original and supplementary piles exhibit consistent force distribution, with a post-reinforcement rebound rate increases from 13.73% to 37.32%. The ultimate bearing capacity is approximately three times that of the unreinforced case. Simultaneously, due to predominant load-sharing by the post-added pile, the axial force of the pile foundation is minimal, resulting in a concentrated axial force curve at its base. Furthermore, in comparison to the unreinforced pile foundation, both the end bearing capacity and its proportion are significantly diminished in the reinforced pile foundation. The maximum end bearing capacity amounts to 7.45kN, accounting for merely 6.21%. However, owing to transmission of bending moment from the pile cap to the reinforced pile foundation, there exists a notable disparity in stress distribution across both sides of the reinforced pile foundation.

Keywords: supplementary pile reinforcement ; finite element simulation ; vertical bearing characteristics

1 Introduction

Pile foundation has high bearing capacity and stability, and is suitable for a variety of complex environments, which is widely used in the construction of foundation engineering[1]. However, under the continuous influence of environmental changes, construction activities and vehicle loads, the bearing capacity of the pile foundation gradually decreases, which affects the overall safety of the bridge[2].

At present, there are many kinds of reinforcement measures for bridge pile foundation. Lan[3] used grouting reinforcement method to reinforce the pile with quality defects, which shows that the grouting reinforcement method has remarkable effect and effectively improves the existing problems of pile foundation. Fang et al[4] proposed a reinforcement scheme for prestressed tubular pile. The end of the tubular pile was enlarged and the grouting material was poured to form a high-strength

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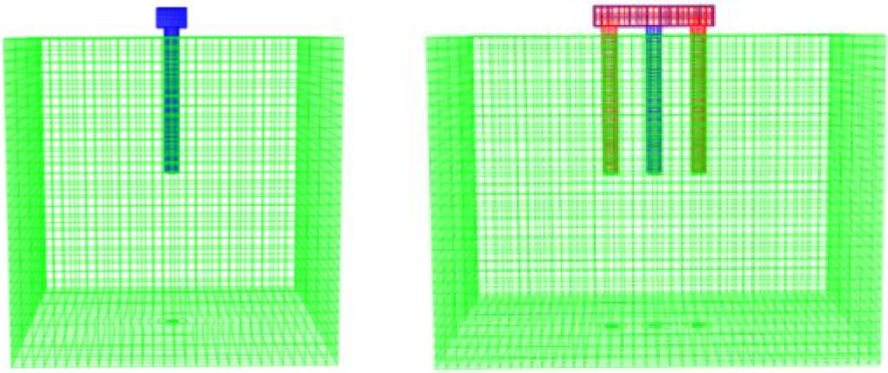
composite pile, which showed that the reinforcement method was convenient and reliable. Sun[5] et al used spiral pile to reinforce the pile foundation, which shows that the disturbance of pile sinking to soil can reach 9 times the pile diameter, and the ultimate bearing capacity of the reinforced composite foundation is about 6 times that of the original foundation. Chen[6] strengthened the pile foundation by increasing the cross section of reinforced concrete, which not only ensured the reinforcement effect, but also prolonged the service life of the structure. Zhou et al[7] studied the dynamic response law of pile foundation bearing characteristics in the process of pile bottom grouting through field tests, and revealed the enhancement mechanism of grouting on pile foundation resistance. Wei[8] based on the calculation method of structural damage degradation model, through the calculation of the structure after the reinforcement of the added pile foundation, it is helpful to ensure the reinforcement effect.

To sum up, different reinforcement methods have obvious reinforcement effect on pile foundation. Among them, the reinforcement of supplementary pile foundation is to expand the pile cap and increase the pile foundation on the original pile foundation to achieve the dispersion of pier pressure. Its construction has little influence on the original foundation. The construction method is simple and the construction speed is fast. It has played an effective reinforcement for the bridge pile foundation with insufficient bearing capacity[9-10]. In this paper, the influence of pile foundation reinforcement method on the vertical bearing characteristics of pile foundation is explored by finite element simulation. The load-settlement and stress of pile foundation before and after pile foundation reinforcement are analyzed. It shows that the reinforcement of pile foundation not only improves the bearing capacity of pile foundation, but also improves its stress characteristics, so that the stress distribution of pile body is more uniform, which can provide reference and basis for the reinforcement of pile foundation of bridge pile foundation.

2 Establish the finite element model

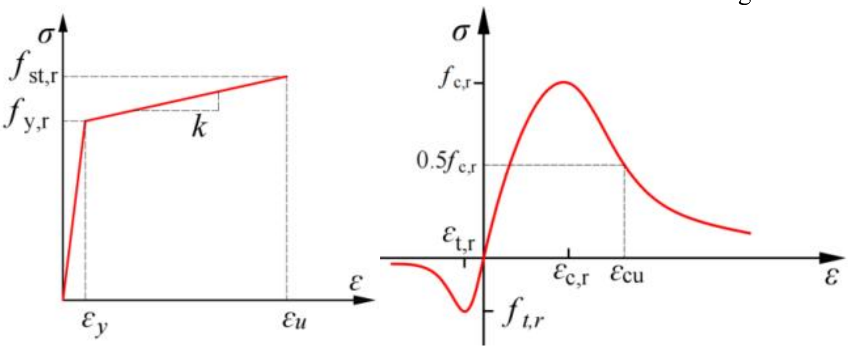
The finite element model uses a scale model, mainly including soil, pile and its reinforcement. The unreinforced model is a single pile , in which the pile length is 1.5m, the pile diameter is 0.15m, and the pile cap geometry is 0.3m×0.3m×0.2m. Four steel bars with a diameter of 5mm are configured inside the pile, and the reinforcement ratio is 0.44%. The soil geometry is modeled in the transverse direction according to the 20 times of the pile diameter (3m), and the longitudinal direction is modeled according to the 2 times of the pile length (3m), as shown in Figure 1 (a). The reinforcement method is to symmetrically arrange two piles with the same length and diameter on both sides of the original pile. The reinforcement ratio and form of the pile are consistent with the original pile , and the pile cap is expanded. The center spacing of the pile foundation is 3 times the pile diameter (0.45m), the size of the pile cap is 1.05m×0.3m×0.2m, and the geometric size of the soil is 4.05m×3m×3m, as shown in Figure 1 (b).



(a)Unreinforced (b) Reinforced

Fig. 1. Finite element model

The Mohr-Coulomb model is used for the material properties of the soil, and the mechanical parameters are shown in Table 1. The bilinear constitutive model is used for the steel bar, and the pile is C30 concrete. In order to ensure that the new pile can bear the force together with the original pile , the material of the pile cap is set to C40 concrete, and the material properties of the concrete are the corresponding CDP model[11]. The constitutive model of steel bar and concrete is shown in Figure 2.



(a)steel bar (b) concrete

Fig. 2. Constitutive model of steel and concrete

Table 1. Soil mechanical parameters

Elastic modulus/MPa	Poisson's ratio	Friction angle/°	Cohesion/kPa
16.8	0.3	19.5	15.6

The soil and pile are simulated by solid elements, the steel bar is simulated by truss elements. The contact mode between the steel bar and the pile is embedded contact. The soil and the pile adopt hard contact in the normal direction and friction contact in the tangential direction. The friction coefficient is defined as $\mu = \tan\varphi$, where φ is the friction angle of the soil, and the boundary condition of the soil is to limit the displacement of the side and the bottom.

3 Pile foundation settlement analysis

3.1 Q-S curve

The model loading method is to apply the concentrated load to the center of the pile top of the original pile step by step, and the unloading is carried out twice as much as the loading level. The Q-S curve before and after reinforcement is shown in Figure 3. The Q-S curve of unreinforced pile is a steep drop type. When the pile top load reaches 40 kN, the displacement of the pile top was significantly increased. The displacement corresponding to the maximum load of 56 kN is 17.92 mm. The rebound value of the pile after unloading is 2.46 mm, and the rebound rate is 13.73 %. When the pile foundation is reinforced, the Q-S curve is a slow-down type. The displacement of the pile under the maximum load of 120 kN is only 9.82 mm, and the rebound value after unloading is 3.37 mm. The rebound rate is 34.32 %. Therefore, after the pile foundation is reinforced, the displacement of the pile is significantly reduced, and the rebound rate is significantly increased. The difference curve of the pile top displacement of the supplemental pile foundation is drawn as shown in figure 4. The displacement variation trend of the supplementary pile foundation is basically the same as that of the original pile foundation, which can basically ensure the common force of the supplemental pile and the original pile.

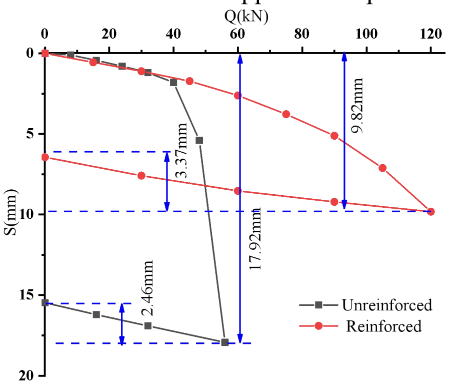


Fig. 3. Q-S curve

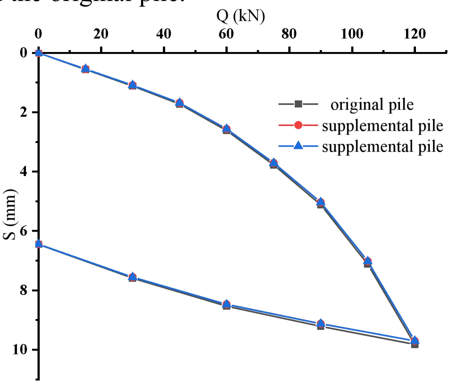


Fig. 4. Settlement difference curve

3.2 S-lgQ curve

The S-lgQ curve is calculated from the Q-S curve as shown in Figure 5.The calculated ultimate bearing capacity of the unreinforced pile is 31.62kN, and the ultimate bearing capacity of the reinforced pile is 89.12kN, which is about three times of the unreinforced pile foundation. Therefore, the bearing capacity of pile foundation is greatly improved after reinforcement of pile foundation.

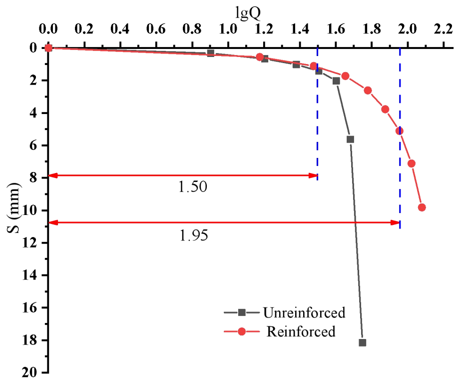
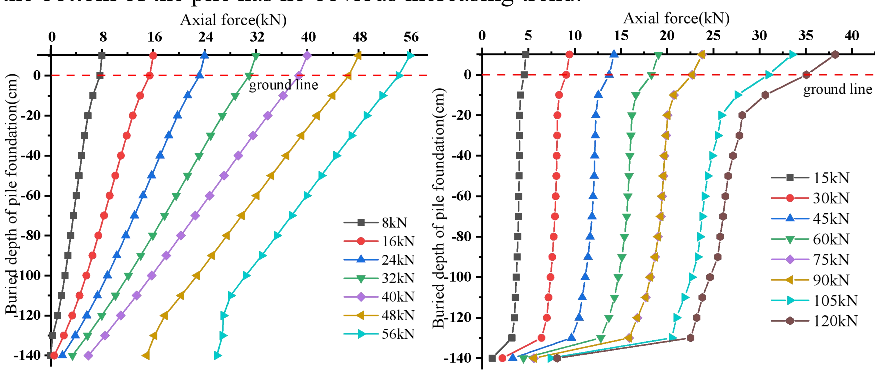


Fig. 5. S-lgQ curve

4 Pile foundation stress analysis

4.1 Axial force of pile foundation

The axial force curve of the pile foundation reflects the load transfer of the pile in the soil. The axial force curve of the unreinforced pile is shown in Figure 6(a). When the load is 0-40kN, the curve is concentrated at the bottom of the pile. After 40kN, there is a clear increasing trend. The reason is that the load is mainly borne by the side friction resistance in the early stage of loading. As the load continues to increase, it gradually changes from the side friction resistance to the end bearing force. The curve of the pile after reinforcement is shown in Figure 6(b). The curve under all levels of load has agglomeration phenomenon at the bottom of the pile, and the axial force is about 1/3 of the applied load. The reason is that the post-added piles share most of the load, so that each pile bears less load, and it is mainly borne by the side friction resistance, so that the end bearing force is not fully exerted. Therefore, the axial force at the bottom of the pile has no obvious increasing trend.

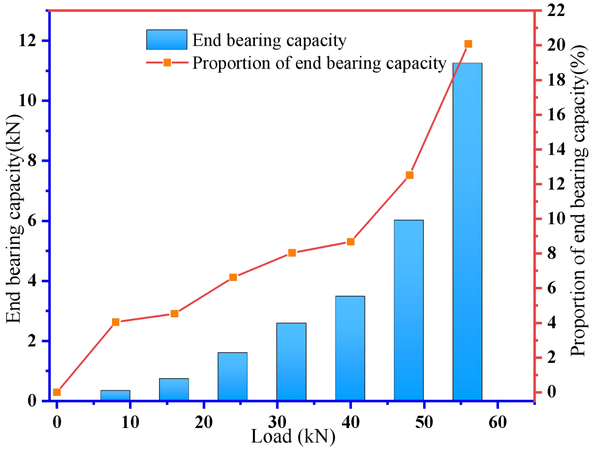


(a)Unreinforced (b)Reinforced

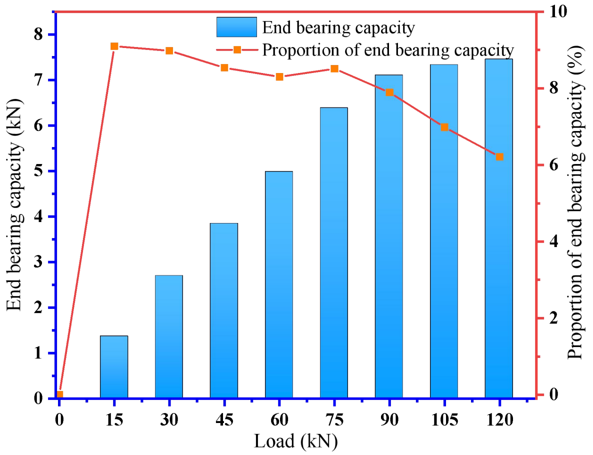
Fig.6. Axial force curve of pile foundation

4.2 End bearing capacity and its proportion

The curve of the end bearing capacity and its proportion of the pile is shown in figure 7. For the unreinforced pile, the change trend of the two is similar, and both increase with the increase of load. The maximum end bearing capacity is 11.25kN, and the corresponding proportion is 20.09%. The end bearing capacity of the reinforced pile increases first and then stabilizes with the increase of the load, and the ccorresponding proportion shows a trend of steady first and then decline, and all change when the load is about 90kN. The maximum end bearing capacity is 7.45kN, and the corresponding proportion is 6.21%. Therefore, the end bearing capacity and its proportion of the pile after reinforcement are significantly reduced.



(a)Unreinforced

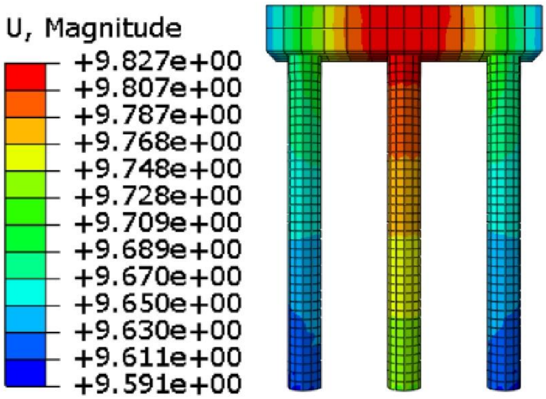


(b)Reinforced

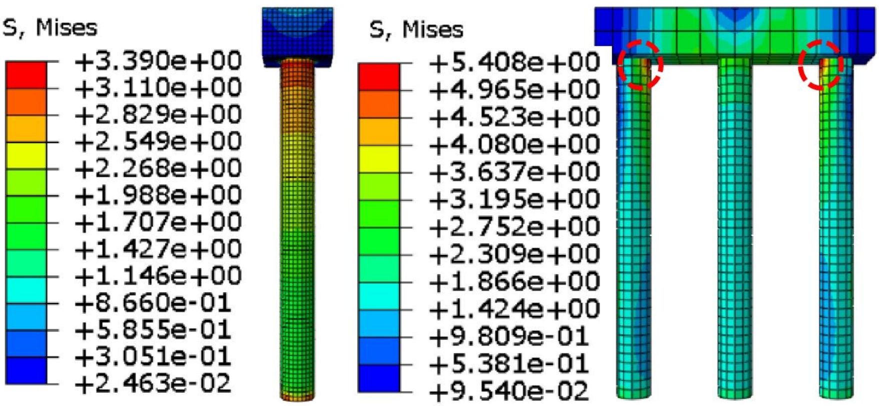
Fig.7. End bearing capacity and its proportion

4.3 Stress cloud

The equivalent displacement and stress nephogram of the pile after reinforcement are shown in figure 8. The equivalent displacement of the supplementary pile is basically the same as that of the original pile, and the error is about 0.1 mm. The maximum stress of the pile before reinforcement is concentrated at the top of the pile, and the stress difference is large. After reinforcement, the stress distribution is more uniform, but there is a high stress area near the surface of the soil. This is because the load is preferentially applied to the original pile, and then transmitted to the supplementary pile through the cap. In this state, the cap is slightly deformed due to the large bending moment. At the same time, the cap and the pile are completely fixed, so that part of the bending moment of the cap is transmitted to the supplementary pile , resulting in the supplementary pile to bear the bending moment. On the stress cloud diagram, there are obvious differences in the stress on both sides of the supplementary pile.



(a)Equivalent displacement



(b)Equivalent stress

Fig. 8. Equivalent displacement and stress cloud of pile foundation

5 Conclusion

In order to find out the change of vertical bearing characteristics of pile foundation after reinforcement of supplementary pile, the settlement and stress change of pile foundation before and after reinforcement are analyzed by finite element model, and the following conclusions are obtained :

(1) After reinforcing the pile foundation, the displacement is significantly reduced while the rebound rate experiences a significant increase. And the pile can basically maintain the common force. Simultaneously, there is a noticeable enhancement in the bearing capacity of the reinforced pile foundation, which is approximately three times greater than that of the unreinforced counterpart.

(2) The axial force curve of the unreinforced pile foundation exhibits an agglomeration phenomenon at the bottom of the pile under loads ranging from 0-40kN. Beyond this range, there is a significant increase. However, the post-added pile foundation shares most of the load, making the axial force of each pile foundation smaller.

(3) The end bearing capacity and its proportion curve of unreinforced pile foundation increase with the applied load. The end bearing capacity is 11.25kN, accounting for 20.09% of the total load. In contrast, the end bearing capacity of reinforced pile foundations initially increases and then stabilizes with the increasing top load. The corresponding end bearing capacity is 7.45kN, representing only 6.21% of the total load applied to the piles. Moreover, it should be noted that the end bearing capacity and its proportion of reinforced pile foundation are significantly reduced.

(4) The equivalent displacement of the supplementary pile foundation is essentially identical to that of the original pile foundation. However, the supplementary pile foundation exhibits a pronounced high-stress region near the soil surface. This can be attributed to the transmission of the bending moment from the cap to the supplementary pile foundation, resulting in its bearing of such moment. Notably, discernible disparities in the stress distribution are observed on either side of the pile foundation.

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