Analysis of Interaction between Pile Foundation and Reinforced Earth Embankment under Surcharge Loading Considering Time-Effect Characteristics

Minghui Pan[1], Qiguang Wang[1], Shan Jiang[1], Liangdong Zuo[2,3,4,*]
[1]*Chongqing Engineering Corporation Limited of Power China, Chongqing, China*
[2]*Institute of Aeronautics and Astronautics, Shanghai Jiaotong University, Shanghai, China*
[3]*Chongqing Nearspace innovation R&D center, Shanghai Jiaotong University, Chongqing, China*
[4]*Chongqing College of Architecture and Technology, Chongqing, China*
**Corresponding Author.*

Abstract: For the bridge pile foundation built on the embankment filled with reinforced earth, the timely lateral deformation of the fill induced by the stacking load on the embankment can exert additional load on the pile side. The longer the stacking time, the greater the effect of the additional load, which leads to the additional deformation and internal force of the pile body, and further reduces the service performance of the pile foundation. Based on the pile foundation in the filling area of a section of Chengnan Expressway in Chongqing, a 1: 20 model test of pile-foundation was carried out indoors to monitor the distribution and variation of pile response, lateral earth pressure on pile side and horizontal displacement of embankment soil under different loading conditions. At the same time, based on the finite element calculation platform ABAQUS, a numerical model with the same parameters as the model test is established to simulate the change law of the above parameters under long-term surcharge, clarify the weakening mechanism of the soil arching effect between piles caused by the timely lateral deformation of reinforced soil embankment, and reveal the interaction mechanism of lateral reinforced soil and pile foundation. On this basis, the effects of stacking distance, stacking strength, relative soft soil thickness and pile-soil relative stiffness ratio on the response time of pile foundation are compared and analyzed.

Key words: Prescription Characteristics; Loading Action; Pile Foundation; Reinforced Earth Embankment; Interaction

1. Introduction

As the bridge pile foundation built on the embankment filled with reinforced earth, the timely lateral deformation of the fill induced by the stacking load on the embankment can exert additional load on the pile side. The longer the stacking time, the greater the effect of the additional load, which leads to the additional deformation and internal force of the pile body, and further reduces the service performance of the pile foundation [1].

In order to investigate the influence of time-dependent lateral displacement of soft soil on pile response under long-term surcharge, Karim et al. [2], Yang et al. [3] and Bian et al. [4] focused on the influence of soft soil consolidation effect on pile response by using numerical simulation method, and obtained the conclusion that long-term consolidation deformation makes pile deflection increase with the extension of surcharge time. Zuo Liangdong et al. used finite element analysis method to compare and analyze the influence of reinforcement arrangement [5], slope of fill area and physical and mechanical parameters of soil on soil arching effect and pile foundation stress. Li Zhiwei et al. [6] analyzed the lateral deflection of bridge deck and pier, displacement of fill slope, deformation of pile foundation and internal force by combining finite element method with field detection.

Most of the above studies only consider the influence of the main consolidation deformation of the filled soil on the response of the pile [7-9], while ignoring the influence of the secondary consolidation effect (creep effect). At the same time, the research on the mechanism of passive pile-soil interaction is still not deep enough, especially in the aspects of the time-sensitive change of the additional load on the pile side and the time-sensitive weakening mechanism of the soil arch between piles.

In this paper, based on the pile foundation in the filling area of a section of Cheng-Nan Expressway in Chongqing, a 1: 20 model test of pile-foundation was carried out indoors to monitor the distribution and variation of pile response, lateral earth pressure on pile side and horizontal displacement of embankment soil under different loading conditions.

At the same time, based on the finite element calculation platform ABAQUS, a numerical model with the same parameters as the model test is established to simulate the change law of the above parameters under long-term surcharge, clarify the weakening mechanism of the soil arching effect between piles caused by the timely lateral deformation of reinforced soil embankment, and reveal the interaction mechanism of the lateral reinforced soil and pile foundation.

On this basis, the effects of stacking distance, stacking strength, relative soft soil thickness and pile-soil relative stiffness ratio on the response time of pile foundation are compared and analyzed.

2. Model Test of Influence of Surcharge

2.1 Experiment Design

The main purpose of model test is to focus on the formation mechanism and scope of soil arching effect of pile foundation in reinforced embankment area. For this reason, this paper monitors the distribution of internal stress, pile strain and pile top displacement of soil between piles under different reinforced soil fillers and different slopes by applying vertical surcharge in stages. The basic arrangement of the test device is shown in Figure 1.

The plane size of the experimental model pool is 6000mm×3000mm, and the depth is 1500mm. The wall of the pond is supported by clay brick mortar masonry with a thickness of 240mm, and the bottom of the pond is leveled by plain concrete with a thickness of 120 mm.

The test model pile is a reinforced concrete circular section pile with a diameter of 125mm and a length of 1900 mm. In order to test the curvature change of the pile body in the filling section under horizontal load, two rows of strain gauges are symmetrically arranged along the length direction of the pile, with a distance of 150mm, and the number of strain gauges is 11 pairs, including 7 pairs in the filling section, 3 pairs in the rock-socketed section and 1 pair at the boundary.

According to the change of fill slope gradient, different numbers of strain gauges will play a role in the test, and the surface will be waterproof with AB glue after the strain gauges are attached.

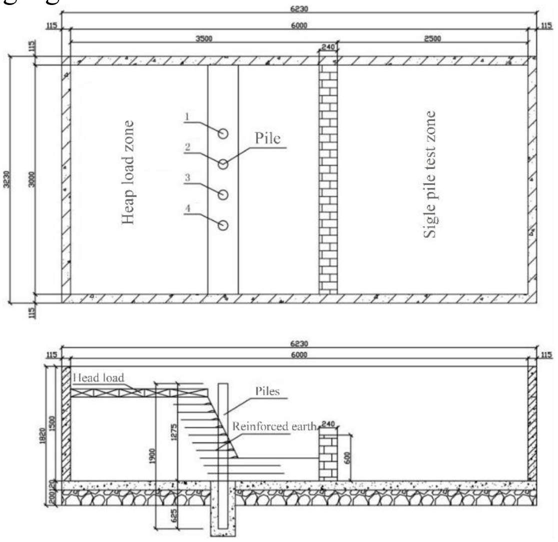


Figure 1. Model Test Scheme Design Drawing

The model fillers used are: 1)cohesive soil, taken from alluvial soil on the terrace of Chongqing section of the Three Gorges reservoir area of the Yangtze River; 2)Stone powder: sand rock powder with particle size of 0.5 ~ 3.0 mm is selected; 3)Gravel: limestone gravel aggregate with particle size of 14 ~ 18 mm is selected.

2.2 Stacking and Data Monitoring

In order to simulate the stacking load at the top of the slope, the test adopts the method of filling sand and gravel in woven bags and stacking them in layers after tying the mouth.

The stacking volume of each bag is about $0.12m^3$, the bulk density of filler is about $1.5t/m^3$, the weight of each bag is about 70Kg, the stacking area is 2800mm×1600mm, the stacking quantity of each layer is 21 bags, and the uniform load applied by a single layer is 3.1KPa. As shown in figure 2.

According to the test plan, there are two aspects of data to be monitored. One is the distribution of earth pressure in the reinforced high slope soil under the action of surcharge; the second is the stress distribution of pile body in reinforced high fill slope area. The vibrating wire earth pressure gauge with a diameter of 108mm is adopted to monitor the earth pressure; the stress of pile body is obtained by surface attached strain gauge.

Figure 2. Model Experiment Stowage Scheme

2.3 Analysis of Test Results

(1) Bending moment and displacement of pile

In this paper, the pile body near the side of stacking load is called "before pile", and vice versa.

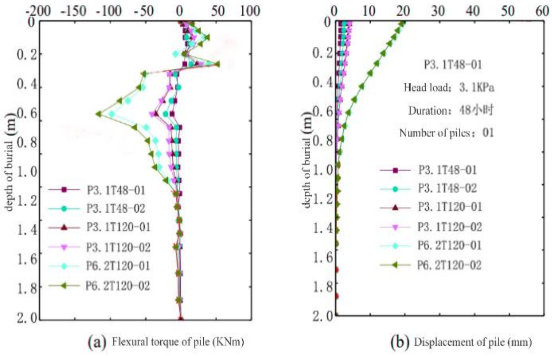


Figure 3. Response Data of Model Piles

As Figure 3 show, the curves of bending moment and displacement of the pile under different loading conditions, in which the positive bending moment indicates the compression in front of the pile, and the positive displacement indicates that the pile moves away from the loading side, and vice versa.

From the curve in Figure 3, it can be seen that the bending moment and displacement of the model pile show similar changes along the depth under different surcharge loads. The turning point of positive and negative bending moments is located at the buried depth of 0.3 meters, and the maximum bending moment appears at the buried depth of 0.6 meters. This point is the lowest section of the reinforced area, and the change of soil physical characteristics leads to greater thrust. From the displacement curve of pile body, it can be seen that the maximum displacement of all pile foundations occurs at the top of the pile, and its displacement decreases gradually with the increase of buried depth.

It can be concluded that under the same loading time, the bending moment and horizontal displacement of pile body increase with the increase of loading strength.

(2) Timeliness of stacking

Select the data of No.01 pile foundation at 6.2Kpa for 7 days and 10 days after unloading, and draw it as shown in Figure 4.

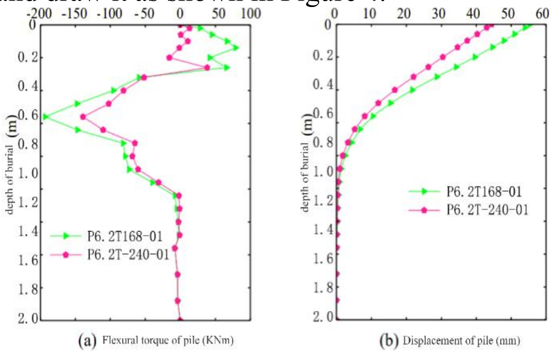


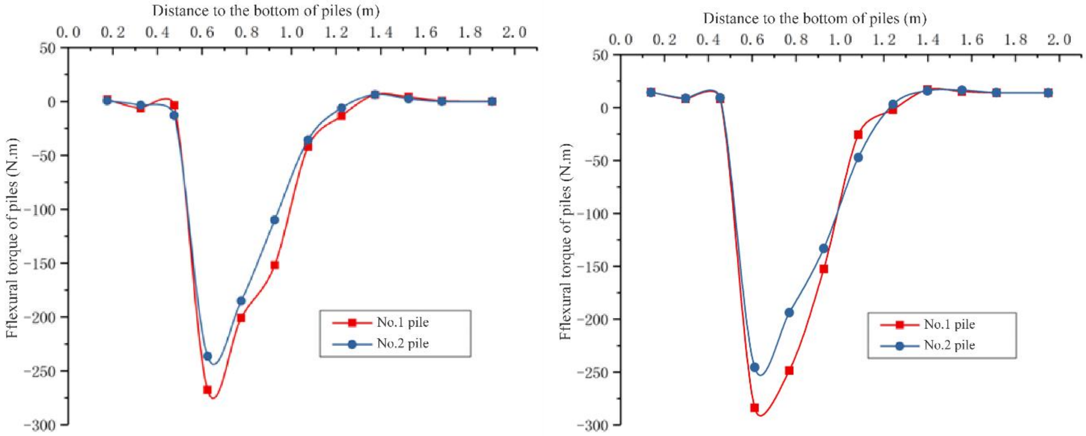
Figure 4. Response Data of Model Piles

It can be seen from Figure 4 that the maximum bending moment of the model pile is 581.65KN·m at the buried depth of 0.6 m and the maximum displacement at the top of the pile is 56.31mm after the stacking load lasts for 7 days. By contrast, when the data were measured on the 10th day after unloading, the maximum bending moment of the pile was reduced to 413.66 KN·m, a decrease of 28.89%, and the displacement of the pile top was 43.99 99mm, a decrease of 22.98%.

It can be seen that the deformation of pile foundation did not fully recover with unloading, and the rebound amount was only 22.98%. There are two main reasons for this phenomenon: 1) the reinforced soil will undergo plastic deformation under surcharge, which will not recover with unloading, so it will continue to exert lateral thrust on the model pile; 2) due to the existence of soil arching effect between piles, the arch structure is formed, and the arch structure will continue to exist under the action of rebound reaction of pile foundation.

(3) Timeliness analysis

In order to reveal the time-sensitive change of pile foundation response under different loading conditions, the bending moment of model piles No.1 and No.2 under different loading duration is taken as the index of response analysis, and a curve is drawn, as shown in Figure 5.



(a) 24h after head load **(b) 168h after head load**

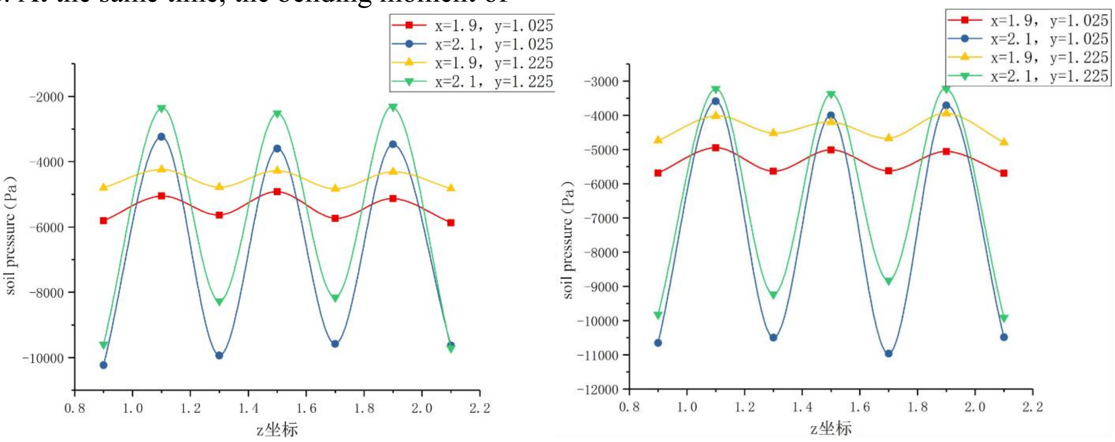
Figure 5. Bending Moment Curve of Model Piles

It can be seen from Figure 5 that with the increase of the stacking time, the variation law of the bending moment of model piles No.1 and No.2 along the length of the pile body is basically the same, but the magnitude of the bending moment has obviously increased, increasing by about 11.5% and 18.6% respectively.

It can be seen that the response of pile foundation is in direct proportion to the growth of pile foundation under two working conditions with different stacking time, and the bending moment of pile foundation shows an increasing trend with the increase of stacking time. At the same time, the bending moment of the pile body presents an "S" shape, which does not change with the increase of stacking time, and the maximum bending moment is about 0.73m below the pile top.

(4) Geotechnical effect analysis

Under the interaction between reinforced embankment and pile foundation, the influence of reinforced layers on soil arching effect between piles is one of the research directions in the experiment. Plot the earth pressure values at different positions behind the pile under the conditions of 4-layer reinforcement and 8-layer reinforcement, as shown in Figure 6.



(a) 4 layers reinforced condition **(b) 8 layers reinforced condition**

Figure 6. Bending Moment Curve of Model Piles

Observing the horizontal release and vertical distribution of soil arching effect under the condition of 4-story and 8-story reinforcement, it can be seen that the distribution law of soil pressure behind the pile under the two working conditions is basically the same.

Specifically, taking the data of four layers of reinforced soil as an example, it is found that the closer to the pile, the more obvious the soil arching effect, the greater the earth pressure value behind the pile, and the farther away from the pile, the more 3.75cm(x=2.1) and 23.75cm(x=1.9) behind the pile in the horizontal plane with y=1.025m (the plane with 400mm filling height). The plane with y=1.225m (the height of filled soil is 600mm) has a similar law, and the horizontal distribution of soil arching effect shows the characteristics of gradual weakening with the increase of the distance from the pile. Compared with the vertical plane with x=1.9 and x=2.1, it is found that the soil arching effect behind the pile decreases gradually with the increase of height, and the degree of soil arching effect is not obvious.

In order to analyze the soil arching effect between piles, the model soil was demolished after a stacking load was completed, and the loose soil before the pile was excavated, and the soil flush with the pile foundation row surface had obvious "wedging" phenomenon, which indicated that the stress transfer began from the pile foundation row surface. As shown in Figure 7.

Figure 7. Bending Moment Curve of Model Piles

Obviously, a small soil arch is formed between the model piles, and the arch foot is located on the side of the pile foundation, supported by the friction between the soil and the pile foundation surface. However, due to the limited friction, this part of the soil can still be relatively loose. When the small soil arch is pulled out, it can be seen that the soil above the hollowed-out place is "supported" by the geogrid, so that the soil above is not unstable and collapsed. This is because the soil behind the pile and the soil between the piles form a "film-pulling effect" here, and the trend of soil collapse between the piles is transferred to the stable soil without settlement after the pile by the soil arch geogrid.

The large soil arch behind the small soil arch is very stable for two reasons:

First, this part of the soil between piles has been able to stably transfer the landslide thrust to the back of the pile through its own shear strength, forming a large soil arch based on the arch foot behind the pile. The large soil arch is based on the direct support of the pile foundation, so its strength is much greater than that of the small soil arch.

Secondly, due to the existence of geogrids, based on the quasi-cohesion theory, the cohesion of the soil-geogrid mixed structure in this part of the large soil arch is increased, which is not available in the soil without reinforcement, and is the additional cohesion of the reinforced soil, which makes the formed soil arch stronger. In the vertical direction, the vertical load above the slope is transferred to the soil, and the geogrid can unload a part of the vertical stress in the soil, which is transferred to the front of the pile through the grille, so the geogrid in the X direction bears this part of the tension, and the closer it is to the pile, the greater the tension. With the decrease of vertical stress, the thrust load transferred by the soil arching effect behind the pile is also reduced accordingly, and the purpose of optimizing the stress of the pile foundation is realized.

3. Influencing Factors of Timeliness

3.1 Influence of Stacking Strength

From the experimental results, it can be seen that the magnitude of the heap load and the distance from the pile foundation will have a significant impact on the response of the model pile foundation.

The displacement and maximum bending moment of model pile will increase with the decrease of stacking distance or the increase of stacking strength, and will increase with the increase of stacking time.

With the increasing of the heap load and the shortening of the distance, the consolidation speed of the soil behind the pile is accelerating and it is easier to reach a stable state. Based on the criterion that the displacement growth rate of the pile top is not more than 0.05‰/ day, the time required for the response of the pile foundation to reach a stable state is 116d, 85d, 52d and 29d when the pile load changes from the first floor to the fourth floor during the experiment.

3.2 Influence of Reinforcement Effect

During the experiment, the response data of pile foundation were collected under three working conditions: no reinforcement, 4-layer reinforcement and 8-layer reinforcement.

Comparing the response data of pile foundation under three different working conditions, it can be seen that the maximum bending moment point of pile foundation is on the upper side under the condition of non-reinforcement, which is because the point of horizontal displacement of soil behind pile caused by surcharge occurs in the shallow layer, and the horizontal force exerted on pile foundation is also on the upper side.

Compared with the unreinforced soil, the response of reinforced pile foundation is basically the same, but the maximum bending moment point moves downward, which is because the mechanical properties of reinforced soil are improved and the deformation under surcharge is reduced, but the maximum acting point tends to develop deeper.

Comparing the response data of pile foundation with 4-layer reinforcement and 8-layer reinforcement, it can be seen that the bending moment of pile body in 8-layer reinforced soil tends to decrease, which is because reinforcement improves the performance of soil, which leads to the formation of soil arch after pile in soil, the horizontal displacement of soil decreases, and the response to pile foundation decreases.

3.3 Stiffness Ratio of Pile and Soil

The stiffness ratio of pile to soil is the main index to characterize the deformation coordination characteristics of pile-soil interaction. In this experiment, the stiffness of pile foundation itself does not change, but the stiffness of soil changes due to the change of reinforcement conditions.

From the experimental results, with the decrease of pile-soil rigidity ratio, the maximum displacement and bending moment of pile body gradually decrease, and the distribution shape of pile body response along the depth gradually changes.

The conclusion of this paper is different from that of some existing achievements [10,11], mainly because most scholars use the method of reducing the stiffness of pile to adjust the stiffness ratio of pile to soil for comparative study.

In this experiment, with the appearance of reinforcement effect, the reinforced soil is regarded as a composite material, and its overall stiffness increases, which leads to the relative decrease of the stiffness of the pile, thus making the pile foundation show some characteristics of "flexible pile" and the displacement of the pile body presents a fluctuating distribution along the depth. The experiment also proves that the distribution shape of pile response will not be affected by the pile-soil stiffness ratio with the passage of surcharge time, and will remain basically unchanged.

4. Conclusion

(1) The model test results show that the lateral displacement of reinforced soil caused by surcharge is significantly smaller than that of plain fill under the same conditions. Under different loading conditions, the maximum bending moment and maximum horizontal displacement of pile body increase with the increase of loading strength and the decrease of loading distance, but their depth remains basically unchanged. With the extension of surcharge time, the response of pile body shows an obvious law of increasing timeliness, but its distribution law along the depth remains basically unchanged; under different loading conditions, the distribution law of foundation lateral deformation along the depth is basically the same, showing an "inverted triangle".

(2) For the pile foundation in reinforced earth embankment, it presents the characteristics of some flexible piles, that is, the stress mode of pile segments at different depths is different, and it is composed of active pile segments, passive pile segments and embedded segments. The passive load on the pile side caused by soil lateral displacement is mainly distributed in the depth range of soil layer, which basically does not change with the extension of stacking time, but the maximum lateral additional pressure continues to increase with the extension of stacking time.

(3) Under the same conditions of pile foundation and reinforcement, the shorter the stacking distance or the greater the stacking strength, the longer the time for the pile response to reach the stable growth stage, and the more significant the influence of the deformation of reinforced earth embankment on the timeliness of the pile response. Different layers of reinforcement have different distribution ranges of additional loads on the pile, which leads to different effects of stacking conditions and holding time on the

response distribution of the pile.

Acknowledgments

This paper is supported by:

(1) The Science and Technology Research Program of Chongqing Municipal Education Commission (Grant No. KJZD-K202305201)

(2) Chongqing Transportation Science and Technology Project (NO: CQJT-ZCXM2023-12)

(3) Science and Technology Project of East China Survey and Design Institute of China Power Engineering Corporation (NO: HDEC-KJ-2022-CQ01).

References

[1] YANG Xun, DUAN Li-qiang. Analysis and discussion on the influence of ground surcharge on pile foundation of bridge substructure. China Water Transport, 2024, 24(04): 121-122+125. (in Chinese)

[2] Karim M R, Lo S C R, Gnanendran C T. Behavior of piles subjected to passive loading due to embank- ment construction. Canadian Geotechnical Journal, 2014, 51(3):303-310.

[3] Yang M, Shangguan S, Li W, et al. Numerical study of consolidation effect on the response of passive piles adjacent to surcharge load. International Journal of Geomechanics, 2017, 17(11):04017093.

[4] Bian X, Liang Y, Zhao C, et al. Centrifuge testing and numerical modeling of single pile and long-pile groups adjacent to surcharge loads in silt soil. Transportation Geotechnics, 2020, 25:100399.

[5] ZUO Liang-dong, ZHOU Shi-liang, QUAN Jin. Influential factors of pile foundation stress of wharf in reinforced high fill area. Port & Waterway Engineering, 2022(5): 170-177. (in Chinese)

[6] LI Zhi-wei, YANG Yue-feng, ZHAO Jian-hao. Influence of High-Fill Surcharge on Load Bearing Behavoir of Pile Foundation of Adjacent Bridge and Treatments. Bridge Construction, 2023, 53(03): 143-150. (in Chinese)

[7] Koppejan A W. A formula combining the Terzaghi load compression relationship and the Buisman secular time effect//Proc. 2nd ICSMFE, Rotterdam, the Netherlands, 1948, 272:32-37.

[8] Sivakumar V, Moorhead M C, Donohue S, et al. The initial, primary and secondary consolidation response of soft clay reinforced with a granular column under isolated loading. Géotechnique, 2021, 71(6):467-479.

[9] QI Ge-ping, ZHOU Hang. Consolidation Character-istics of XCC Pile Composite Foundation. China Civil Engineering Journal, 2023, 56(S1): 43-54. (in Chinese)

[10]Karim M R. Behavior of piles subjected to passive subsoil movement due to embankment construction -a simplified 3D analysis. Computers & Geotechnics, 2013, 53(9):1-8.

[11]Miao L F, Goh A T C, Wong K S, et al. Three-dimensional finite element analyses of passive pile behaviour. International Journal for Numerical and Analytical Methods in Geomechanics, 2006, 30:599-613.

