Analysis of Action Mechanism for Rigid Flexible Pile Composite Foundation

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Abstract: In order to eliminate the collapsibility of loess collapsibility, reduce the deformation and improve the bearing capacity of foundation soil, and the thickness of collapsible loess about 4.0-9.0 m in Lanzhou Zhongchuan airport in which we made the static load test of composite foundation with rigid flexible piles, that revealed the rigid flexible pile composite foundation bearing deformation mechanism and load transfer characteristics. The results show that: Soil pile foundation compaction and replacement part of collapsible loess, the negative skin friction resistance around pile into positive friction, and improved the lateral resistance of foundation soil; rigid pile could be upper load transfer to the collapsible loess formation is hard; compared with the single pile bearing capacity and the deformation characteristics of rigid flexible pile could improve the bearing capacity, but also could reduce the foundation settlement of rigid pile. The proportional limit is 560Kpa, the corresponding settlement value was 2.424mm; pile foundation bearing capacity eigenvalue of 270Kpa in soil, 7.570mm sedimentation value; rigid flexible pile bearing capacity characteristic value was 570Kpa, settlement value of 2.904mm. In collapsible loess area, the treatment measures of reinforced concrete rigid pile are adopted, which could effectively improve the bearing condition of the foundation and provide design and construction reference for similar projects.

Key words: Just - flexible pile, Composite foundation, Static load test

1. INTRODUCTION

Theoretical research and engineering practice of composite foundation shows that bearing capacity increase range of single type pile processing composite foundation is limited(Zhu,2009), which can not meet bearing capacity requirement of the high-rise building foundation. Meanwhile, rigid-flexible piles composite foundation is chosen because it can eliminate the collapsibility, reduce the deformation and improve the bearing capacity of foundation soil on the collapsible loess foundation(Zhu,2006). In the research of bearing capacity of foundation, power transmission way of static load test is clear and it is also similar with the actual situation in size and boundary conditions, which can truly reflect load-bearing deformation of the foundation under the effect of upper load and can confirm bearing capacity of foundation in which close to the actual working conditions. It is the most intuitive and reliable experimental method to determine the bearing capacity of foundation for now.

There are related research results that rigid pile - sinking pipe compaction pile composite foundation treat soft soil foundation in our country. However, the application of this kind of binary composite foundation to collapsible loess foundation is relatively less. Jifu Liu and other people pointed out the important role of cushion layer in composite foundation according to a composite foundation project consisting of immersed tube pile, deep mixing pile and cushion. Hao Dai and other people considered that although the technology of rigid-flexible piles composite foundation is not mature enough, but it has a good prospect for soil layer diversity, especially for the further reinforcement treatment of existing foundations in house layer transformation. Xiaohong Bai considered that the application effect of composite pile in loess foundation is remarkable. Mingli Yan put forward the calculation method of bearing capacity and deformation of multi-pile composite foundation. Xinyue Xu considered that the concrete pile-cement mixing pile composite foundation is an effective foundation treatment method under a certain geological condition according to the engineering case. Zhaoyang Xu put forward the simple design method of composite pile foundation. Dequan Zhou considered that combined pile composite foundation should select cushion layer and pile materials, construction technology, size and layout rationally according to the foundation type, load weight, ground geological condition and environmental protection requirements, so that the foundation can meet the strength, deformation and stability requirements.

At present, the experimental study on composite foundation of rigid-flexible piles is only at the initial stage, systematic comparison of different parameters and conditions has not yet been carried out. Besides, study on load transfer behavior of rigid pile and flexible pile in rigid-flexible piles composite foundation is no person
involved. Based on the field test of bearing capacity of rigid - flexible piles composite foundation in Zhongchuan Airport Project of Lanzhou, this paper analyzes the deformation mechanism of foundation bearing.

2. PROJECT SUMMARY

Lanzhou Zhongchuan Airport New Terminal is located in the south of the original terminal. The length of terminal construction site is 493m from north to south and the width is 159 m from east to west. It is total construction area about 60,000 m², total height is 38 m and 2 to 3 layers. This new terminal plan to use reinforced concrete frame structure under 8 m with the pillars distance of 12m x 12m and 12m x 16m and over 8 m it plan to use bearing post and curved steel roof with the pillars distance of 12m x 24m and 24m x 32m.

There is no continuous and stable pile - bearing stratum within the depth of 50 m in the proposed project site. Over embedded depth 20m, the foundation soil is mainly composed of loess silt, silty sand, silt and breccia. Loesssilt is widely distributed in the upper part of the site with thickness of 4.0 ~ 9.2 m, which has poor engineering properties and low carrying capacity and it belongs to medium compressive soil. Besides, it also has moderate to strong collapsibility and belongs to class Ⅰ non-self-weight ~ Ⅱ self-weight collapsible loess foundation. It can not be used as natural foundation shallow base bearing stratum of the proposed terminal if not untreated. When the foundation design of the proposed terminal is to adopt the shallow base form, it is necessary to carry out effective ground treatment for the foundation soil within the depth of the main bearing layer.

3. COMPOSITE BEARING CAPACITY EXPERIMENT OF RIGID - FLEXIBLE PILES

3.1. Experimental Summary

The rigid-flexible piles composite foundation is affected by many factors, such as rigid piles, flexible piles, soil between piles, cushion layer and replacement rate. All of them will make the bearing deformation characteristics different. In order to comprehensively and systematically understand the influence of these technical parameters on the characteristics of rigid-flexible piles composite foundation and reveal the cooperative working mechanism of rigid piles, flexible piles and soils in rigid-flexible piles composite foundation, field tests are carried out on rigid piles-plain soil immersed tube compaction pile composite foundation. In order to study the deformation mechanism of rigid - flexible piles composite foundation under different conditions, there are a large number of sensors embedded in different positions under the bearing plate before static load test to finish synchronous testing.

3.2. Experimental Method

Compaction process of flexible piles to foundation soil must be carried out before use rigid piles on rigid - flexible piles composite foundation. After once treatment of foundation, the lateral and vertical characteristics of the soil have changed. And then rigid piles are applied on the composite foundation that already finished the flexible piles compaction process to form the binary composite foundation of rigid-flexible piles.

The static load test device and experimental method of rigid - flexible pile composite foundation include the following aspects:

- Bearing plate: It uses steel structure to meet the resistance stiffness of bending, cutting and deformation.
- Counterforce device: Load platform counterforce device often be adopted in test according to site conditions.
- Load and settlement: The load is finished through the jack and settlement measurement uses displacement sensor.
- Pile head treatment: The elevation of plain concrete piles and plain soil piles are strictly controlled according to the design elevation to prevent the change of bearing characteristics caused by different elevation.
- Cushion layer: The material and thickness of cushion layer should be consistent with the design.
- Foundation soil: The site experiment of rigid - flexible piles composite foundation should select the soil layer that elevation same to design base. Meanwhile, static load test should carry out in the short time after excavation of the foundation trench to prevent the influence of moisture loss and dry hardening on the experimental results.
- Pile-soil displacement experiment: The pile-soil displacement experiment is a supplement to the in-depth analysis of the experimental results of composite foundation bearing capacity.
- Soil pressure experiment: Rigid - flexible pile composite foundation soil pressure experiment is generally used pressure box and sand cushion layer to be buried. As shown in figure 1.
Experiment on axial force and side friction resistance of plain concrete pile: The axial force and friction resistance of the pile were measured by using the steel bar stress meter embedded in the pile.

4. ANALYSIS OF STATIC LOAD EXPERIMENTAL RESULTS

4.1. Analysis of Characteristics of Settlement

(1) Bearing Settlement Characteristics of Rigid Single Pile

The Q-S curve of single pile was obtained by vertical static load test. S-lgt curves are shown in Figure 2 respectively. Figure 2 shows that the Q-S curve of plain concrete rigid pile shows three-fold line features, which can be divided into three stages.

First stage is elastic phase. When the curve between 0 ~ 560kN, Q-S curve can be described as linear because of its linear correlation, quite gentle curve and small slope.

The second stage is elastoplastic stage. When the curve between 560~800kN, Q-S curve shows a non-linear characteristic. Figure 2 shows the curve appears inflection point and the slope significantly becomes larger. The plain concrete rigid pile proportion limit can be determined as 560kPa and the corresponding settlement value is 2.424mm at this time.

The third stage is plastic damage stage. When the curve between 800~880kN, Q-S curve appears steep drop section and the settlement increases sharply, indicating that the rigid pile into the plastic damage stage. The total settlement value of rigid pile is 10.248mm and the settlement value of this grade is 4.781mm. The increasing value of settlement at the corresponding level load is 3.5 times of level 1 load. The residual settlement is 8.791mm and the rebound rate is 14.2% after unloaded, indicating that the residual stress inside the pile is large. This problem is also verified by the fact that the frequency of the pile stress meter is not reduced for a long time.

(2) Load-Settlement Characteristics of Single Pile Composite Foundation with Soil Compaction Pile

Fig. 3 is p-s curve of single pile composite foundation with soil compaction pile, a total of three groups of experiment. From the p ~ s curve, it can be seen that the vertical deformation of single pile composite foundation with soil compaction pile is small and the proportion limit is not obvious after loaded. The eigenvalues of the bearing capacity of the composite foundation are determined by the relative deformation.
According to "Building Code for collapsible loess area" (GB50025-2004), the eigenvalues of bearing capacity of single pile composite foundation with soil compaction pile can be the pressure corresponding to $s/d = 0.01$, but not more than half of the maximum load. Therefore, the eigenvalues of bearing capacity of single pile composite foundation with soil compaction pile can be the pressure value corresponding to $s/d = 0.01$ in this experiment. The experimental results are shown in Table 1.

<table>
<thead>
<tr>
<th>Test number</th>
<th>area displacement ratio</th>
<th>$s/d=0.001$ pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1#</td>
<td>0.16</td>
<td>282</td>
</tr>
<tr>
<td>2#</td>
<td>0.16</td>
<td>262</td>
</tr>
<tr>
<td>3#</td>
<td>0.16</td>
<td>268</td>
</tr>
</tbody>
</table>

According to "Technical Code for Building Foundation Treatment" (JGJ79-2012), the number of test points should not be less than 3. When the range is not more than 30% of the mean value, the average value is bearing capacity eigenvalues of composite foundation. The average value of bearing capacity eigenvalues $f_{spk}$ of single pile composite foundation of flexible pile is 270 kPa in the test area of rigid-flexible piles composite foundation.

(3) Load-Settlement Characteristics of Rigid-Flexible Piles Composite Foundation

It can be seen from Fig. 4 that the binary composite $p ~ s$ curve of rigid-flexible piles composite foundation is a slow type. With the load increase in the late deformation has accelerated. However, it is difficult to determine the ultimate bearing capacity from the figure. With the help of $s$-lg$p$ curve in Fig. 5 and comprehensive settlement, it can be determined that the ultimate bearing capacity is 1140kPa, the corresponding settlement value is 6.084mm, the eigenvalues of bearing capacity is 570kPa and the corresponding settlement value is 3.287mm. Therefore, it can be comprehensive determined that the eigenvalues of bearing capacity is 570 kPa in the test area of rigid-flexible piles composite foundation.

![Figure 3. P ~ S curve (1#) of single pile composite foundation with soil compaction pile](image)

![Figure 4. P ~ s curve of rigid flexible pile composite foundation load test](image)
4.2. Force-Loading Investigation of Rigid-Flexible Piles Composite Foundation Pile

(1) Distribution of Soil Reaction Force under the Load Bearing Plate

Fig. 6 is the distribution of soil reaction force under the load bearing plate. When the load is small, the soil reaction force curve is close to horizontal line, that is to say, the soil reaction force distribution is relatively uniform. With the increase of load, the central and corner soil reaction force differences become larger. In general, the central big and the edge is small, which is a inverted disk. There are two main reasons for this phenomenon as below: On the one hand, the existence of rigid pile and flexible pile changes the stress state of composite foundation. The deformation of rigid pile, flexible pile and different parts of soil under the flow regulating effect of the cushion layer is different after the cushion layer is set on the rigid-flexible piles composite foundation. Rigid pile will pierce into the cushion layer, and then appear negative friction resistance of the pile side. The pile has a negative friction resistance to the soil, so that the soil reaction force near the pile body is less than the soil reaction force far away from the pile body. On the other hand, the deformation of the middle soil is bigger than the side soil, and the soil reaction force is positively related to the deformation. Therefore, the soil reaction force occurs the above situation.

(2) Stress Condition of Pile Soil

Fig. 7 shows the stress condition of rigid pile, soil compaction pile and soil between piles during the static load test of the rigid pile-soil compaction pile composite foundation. The experimental result shows that the stress of the rigid pile, soil compaction pile and soil between piles are increasing steadily with the increase of the load, and the pile soil interaction is good. The top stress of the rigid pile increases rapidly with the increase of the load and the stress growth of the flexible pile is slightly larger than that between the pile. Both these two growth rate are slow.
Figure 7. Relationship between stress and load

Figure 8 is variation of stress ratio between rigid pile and pile soil, and soil compaction pile and pile soil with the load increase during rigid pile-soil compaction pile composite foundation static load test. The experimental result shows that the stress ratio of the rigid pile increases with the load increasing, and the pile soil stress ratio is maintained between 15 and 32. The stress ratio of pile is low under small load. This shows that under the flow regulating effect of the cushion layer, the rigidity of the rigid pile in the early stage of the load is not sufficient, with the load increases the rigid pile bearing role was obvious. The stress ratio between plain soil compacted pile and pile soil is maintained at a low level, fluctuating between 1 and 1.4, which because the two stiffness is close and affect by stress concentration of rigid pile.

Figure 8. curve of soil stress ratio with load

Figure 9 is the curve of soil load sharing ratio with load. The load sharing ratio of the rigid pile is not large at the initial stage of loading, but the rigid pile will play the leading role in load sharing with the load increased. The load sharing ratio of rigid pile is nearly 60% under ultimate load, which indicates that rigid pile not only has the function of controlling settlement, but also has a great contribution in improving bearing capacity. The load sharing ratio of the soil compaction pile is always kept at a relatively low value, which is relatively large at initial stage, then gradually decay, generally maintained at about 10%. The soil between the piles also plays a role that can not be neglected in the process of bearing the load, fluctuating basically in the vicinity of 30%.

Figure 9. the curve of soil load sharing ratio
4.3. Load Transfer Rule of Rigid Pile

(1) Distribution of Axial Force

The axial force distribution of rigid pile in rigid-flexible piles composite foundation is shown as Fig. 10. Fig. 10 shows that the maximum value axial force of the rigid pile occurs at the top of the pile when the load is small after the rigid-flexible piles composite foundation is loaded. With the increase of load, the maximum value of axial force of rigid pile gradually decreases and finally stabilizes at 1m-2m below the pile top, which shows that negative friction resistance appears at 1 m to 2 m. The axial force of the pile tip increases with the load increasing, which indicating that the rigid pile has a good effect of the pile and the load is transferred to a harder fine sand layer at the end of pile.

![Figure 10. axial force distribution of rigid pile](image)

(2) Distribution of Frictional Resistance

Fig. 11 shows that the frictional resistance of 1m-2m below the top of the pile is large, frictional resistance is big above and small below under 2m. With the increase of load, friction distribution gradually uniform. The distribution of measured friction resistance and its variation with load indicates that when the load is small, the displacement of the lower pile is relatively small, and the pile friction resistance has not been exerted. With the increase of load, friction gradually exert from top to bottom. Due to the uniformity of the vertical in the treatment range of the compaction pile, the friction resistance distribution of pile side is more even when the test pressure is close to the ultimate load.

![Figure 11. the distribution of frictional resistance of rigid pile](image)

(3) Curve of Stress Time History

Fig. 12 is stress time history curve of rigid pile 8m below the top of the rigid pile when rigid-flexible piles composite foundation is loaded at 1045 kPa. Fig.8 shows that the stress of rigid pile has an adjustment process with time, which indicates that rigid-flexible piles composite foundation under the action of the upper load, rigid pile, soil compaction pile and soil between piles has self-adjustment ability for bearing capacity under the adjustment of the cushion.
4.4. Load Transfer Rule of Flexible Pile

The axial force distribution of soil compaction pile in the rigid-flexible piles composite foundation is shown as Fig. 13. It can be seen that the axial force of soil compaction pile is different from that of the rigid pile in composite foundation. The maximum value of soil compaction pile appears at the top of pile, indicating that there is no negative friction resistance. The modulus of soil compaction pile is close to the modulus of pile soil, which is much lower than stiffness of rigid pile, so that pile effect is very weak and stress at the top of pile is not high. When the rigid-flexible piles composite foundation is subjected to force, soil compaction pile can not penetrate upwardly into the cushion layer. The stress transmission length of soil compaction pile is very small due to the limit of pile strength. The stress of pile foundation at the position below 4m is about 20%, and the larger axial force occurs in the 0 ~ 2m zone.

5. INVESTIGATION ON MECHANISM OF RIGID-FLEXIBLE PILES COMPOSITE FOUNDATION

Rigid-flexible piles composite foundation can form a new type composite foundation of two kinds of vertical reinforcement by putting plain concrete rigid pile on strengthened soil compaction pile to collapsible loess foundation, so as to eliminate collapsibility of collapsible loess foundation, improve bearing capacity of foundation and reduce settlement and inhomogeneous settlement. The compaction of the collapsible loess foundation was carried out by replacing part of collapsible loess with soil compaction pile, which can eliminate the foundation collapsibility, turn the negative friction resistance of pile soil into positive friction resistance and improve side friction resistance of foundation after compaction. Rigid pile can be used to reinforce the composite foundation of soil compaction pile and then rigid pile can transfer the upper load to the harder stratum beneath the collapsible loess, which greatly improves the bearing capacity of the original compacted foundation and reduces the foundation settlement. Under the action of upper load, various parts of which multi-treatment system of the composite foundation is composed of soil compaction pile and rigid pile work together to jointly promote the improvement of bearing capacity of the foundation. Combining with the results of the
field test, the interaction mechanism of soil compaction pile and rigid pile composite foundation can be summarized as the following aspects:

1) Soil Compaction Pile
   During the soil compaction pile forming process, the soil around the pile hole is squeezed horizontally and vertically, resulting in disturbance and remodeling. With the increase of penetration resistance during the pore forming process, soil close to the pile body is damaged of deformation rapidly, plastic flow and squeeze lateral displacement of pile side soil appears and the soil below the pile tip is squeezed downwards and sideways. Meanwhile, the soil at the surface will rise up. Due to the pressure of overburden, the soil that in the depth of formation is mainly radial extrusion, so that the soil near the pile finally destructs, ratio of porosity decreases, dry density increases, collapsibility disappears, bearing capacity and water stability of the foundation and soil properties has been significantly improved. Due to the effect of superposition of the junction compaction, the soil dry density of the pile will be further increased after piles compacted.

2) Vertical Reinforcement of Rigid Pile Composite Foundation
   When the foundation is subjected to vertical load, the settlement of pile and pile soil will occur. When the load is constant, the load sharing between the pile and the soil is a constant value and does not change with time because of the coordinating action of the cushion. With the gradual increase of the upper load, the stress and strain between the pile and the soil in the composite foundation interact and restrain each other and coordinate with each other.
   Under the action of the upper load, the soil between the pile and the pile begins to be deformed by the stress. Because the compressive deformation modulus of the pile is much larger than that of the soil between the piles, the compressive deformation of the soil between the piles is larger than that of the pile, so that the pile soil displacement at the top of pile is bigger than that of pile body. This stress-strain coordination process is characterized by the stress in the soil between piles concentrated to the pile body, which is the stress concentration effect of the pile body.
   With the increase of load, the pile stress concentration effect is more obvious. As a result of the cushion layer arrangement, the pile begins to pierce into the upper cushion to coordinate the stress uncoordination between the pile and soil due to differential settlement, which will cause negative friction zone at the top of the pile and equal settlement section at a certain depth below the top of the pile. Pile soil above equal settlement section moves downward and appears negative friction resistance to pile that direction is downward. Meanwhile, pile below equal settlement section bear positive friction resistance that direction is upward.
   With the further increase of the load, friction resistance below the pile side is further developed. When the pile side friction resistance plays to the limit state, the pile begins to displace and pile end resistance develops well. After that, all the increment of stress in the pile body is borne by the pile soil and the bottom of the pile pierces downward. The soil near the pile top and end enters into plastic state (fig. 14).

3) Constraint Adjustment and Supporting System of Soil Compaction Pile and Rigid Pile
   Under the action of cushion layer, rigid pile, flexible pile and the soil between the piles will interact with each other and work together to form a multi-element composite foundation system after bearing upper load.
   At the initial stage of loading, the strength of pile soil that after compaction treatment is increased and close to soil compaction pile, and part of load transferred by the cushion is shared, so that the soil between the piles begins compressive deformation. As the rigid pile modulus is much larger than that of soil compaction pile and pile soil after compacted, stress concentration phenomenon appears at the top of rigid pile. At this time the stress...
ratio of pile soil gradually increased. With the shallow soil between the pile deformation compaction, its bearing capacity is improved. The compacted soil between piles has greater restraint effect on the upper deformation of rigid pile and flexible pile, so that the pile body bears bigger pile side friction resistance and its bearing capacity is brought into full play, which is also the reason that the pile soil stress ratio of rigid pile is always maintained at a high level. Because of the small material modulus of soil compaction pile that slightly higher than the soil modulus between the pile, so that the above-mentioned experimental results show that pile soil stress is relatively small and the decay is fast along the pile body. Hence, the role of the pile relative to rigid pile can be ignored. Load through the homogenization and diffusion of cushion, finally is beard by composite foundation consisting of rigid pile, soil compaction pile and pile soil improved by soil compaction pile, greatly improved the ultimate bearing capacity of the foundation.

6. CONCLUSION
In this paper, a new type of rigid pile - soil compaction composite foundation, which is a new treatment method to collapsible loess foundation has been deeply researched and analyzed theoretically. Through static load test during the construction and test, its bearing deformation and load transfer method are analyzed and summarized, and the following results are obtained:

(1) The p – s curve of soil compaction pile composite foundation is slowly deformed. The bearing capacity of foundation after compaction is large, which can reach over 250kPa. The stress ratio of soil-cement pile and pile soil in soil compaction pile composite foundation is small about 1.5. And the axial force of soil pile is fast decaying and the pile body effect is poor. The improvement mechanism of bearing capacity of the foundation is the improvement of pile soil, which make compacted soil between the piles responsible for about 80% of the upper load.

(2) The cushion layer improves the interaction of rigid pile, soil compaction pile and soil in the composite foundation of rigid pile-soil compaction pile. The cushion layer reduces the stress concentration of rigid pile, so that soil compaction pile and soil between piles bears load at the beginning, which improves the working performance of composite foundation and has significant role to ensure pile soil bear the load together. It is an important measure to ensure the pile soil interaction to form composite foundation.

(3) With the increase of load in rigid pile-soil compaction pile composite foundation, the rigid pile will pierce into cushion layer. At this time, the upper part of rigid pile appears negative friction resistance and the maximum axial force appears at a certain position below the pile top. As the modulus of soil compaction pile is small, slightly larger than the improved soil between the pile, so that both of them have same deposition and can not pierce upward into cushion. The maximum axial force of pile body appears at the top of the pile and there is no negative friction resistance on the pile side.

(4) The main action mechanism of rigid pile-soil compaction pile composite foundation is shown as below: The compaction of collapsible loess foundation was carried out by adopting soil compaction pile and replacing the collapsible loess with plain soil, which improves soil properties, eliminates the foundation collapsibility and initially improves the bearing capacity of foundation, finally turns negative friction resistance of pile soil into positive friction resistance. Meanwhile, side friction resistance of foundation after compacted has been improved. Rigid pile can be used to reinforce the composite foundation of soil compaction pile and rigid pile can transfer the upper load to the harder stratum beneath the collapsible loess, which greatly improves the bearing capacity of the original compacted foundation and reduces the foundation settlement.

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