Study on Bearing Mechanism of Split Grouting Pile Based on Finite Element Simulation

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Abstract. In order to realize the directional and controllable splitting of splitting grouting, the field grouting test was carried out. Using a new grouting pipe designed, the splitting direction and size of the branch vein are effectively controlled through the control of grouting pressure and grouting amount. In order to explore the bearing characteristics of split grouting pile and provide necessary parameters for the design of split grouting pile composite foundation in engineering practice, the field static load test and indoor geotechnical test of split grouting pile are designed, and the ultimate bearing capacity of single pile and necessary soil parameters are obtained. In order to make up for the limitations of field static load test, the three-dimensional finite element model of pile, soil and branch vein of split grouting pile is established by using the finite element analysis software ABAQUS. The finite element analysis results are compared with the measured values of field test, and the variation laws of pile shaft axial force, stress and displacement of branch vein at different depths, pile side friction, etc. are further explored. Through these changes, the interaction and load transfer mechanism between pile and soil are analyzed, which provides a reference for optimal design.

Keywords. Split grouting pile; a spur; Directional control; Static load test; Finite element method; Pile side friction.

1. Introduction
At present, split grouting technology [1-2] is widely used in the reinforcement projects of loess foundation, subgrade, uneven settlement of existing buildings, wind power facilities in mountainous areas, rock mass, tunnels, dams, etc. through the grouting machine, the slurry can fill the stratum and rock mass cracks under the action of high pressure, consolidate the foundation soil into a whole, improve the bearing capacity of the foundation soil and strengthen the foundation. Split grouting pile is a new type of pile formed after drilling and grouting in the proposed site by using split grouting technology, which is composed of pile core and branch vein. Firstly, holes shall be drilled in the proposed site. The design pile length is the drilling depth and the design pile diameter is the hole diameter. Then assemble the grouting steel pipe in sections and insert it into the hole. The upper end of the steel pipe is connected with the grouting hose, which is connected with the grouting machine. In order to ensure the pressure in the hole, the hole shall be sealed with a hole sealing device at the hole orifice, as shown in figure 1.
Start the grouting machine and inject the slurry mixed in advance into the grouting steel pipe at high pressure. The slurry in the steel pipe is sprayed out from the small hole on the steel pipe wall at high speed. The slurry is sprayed on the soil on the grouting hole wall to exert an additional compressive stress on the soil. The soil produces splitting cracks under this pressure. After the slurry enters the crack, it develops along the crack and finally fills the crack. After the designed grouting amount is injected, pull out the grouting steel pipe and wait for the slurry to set and harden. The pile core is formed after the slurry in the grouting hole is solidified and hardened, and the branch vein is formed after the slurry in the soil crack is solidified and hardened, and the pile core and branch vein are condensed into a whole, that is, the split grouting pile is formed, as shown in figure 2. Through the special structure of pile core branch vein, the splitting grouting pile can consolidate the adjacent pile and pile, pile and soil as a whole, improve the integrity of reinforcement and soil in the composite foundation, and give better play to its bearing capacity.

In the early 19th century, Charles berlghy [3], a French engineer, hydraulically injected clay slurry into the stratum in some repair works, which is considered to be the first appearance of grouting technology in history. In the mid-19th century, Gini Poole, an Englishman, successfully used cement slurry as grouting material for grouting test for the first time, marking the advent of cement grouting technology [4]. Since the 20th century [5], with the progress of science and technology and the improvement of grouting equipment, split grouting technology has been gradually developed and widely used in engineering practice. The research on splitting grouting technology in China began in the 1980s. Han Zhongcun and others [6] formulated the construction scheme of “drainage and pressure reduction and grouting water plugging” in view of the large amount of underground cement flow in the tunnel, and achieved good results. The effects of grouting pressure, grouting materials, grouting volume and drilling structure on splitting grouting effect were discussed for the first time. It lays a foundation for the engineering application of splitting grouting. Lu Chao et al. [7] used the splitting
grouting technology for anti-seepage reinforcement of the dam. The results show that this technology can not only form the anti-seepage curtain to block water, but also greatly reduce the seepage deformation of the dam due to the extrusion of the slurry on the surrounding soil and the filling of the original holes and cracks. Since the 21st century, with the continuous growth of national economy and the continuous progress of science and technology, the theory of splitting grouting has also been further developed. Zhou Mingru et al. [8] studied the mechanical mechanism of splitting grouting by using elastic-plastic mechanics and large deformation theory, obtained the calculated value of splitting grouting pressure, and found that it is very close to the measured value, which provides a theoretical basis for the grouting pressure of splitting grouting. Guo Han et al. [9] combined splitting grouting with anchor bolt technology, effectively increased the contact area between anchor section and rock mass, and significantly improved the bearing capacity of anchor bolt. P. Li et al. [10] proposed an empirical model varying with time to describe the propagation process of cracks in soil, and carried out splitting grouting test to verify the applicability of the model.

At present, split grouting technology has been widely used in engineering practice as a relatively mature technology, but the research on the application of split grouting pile formed after grouting in the field of composite foundation has just started. Engineering application mostly depends on practical experience. The bearing characteristics, load transfer mechanism and load settlement change law of single pile composite foundation are not clear. Therefore, it is necessary to further study the split grouting pile on the basis of the existing research.

2. Overview of Test Site
The main strata of the test site are as follows from top to bottom:
- Plain fill (Q4ml): containing broken brick chips and block stones, it is formed by manual leveling and backfilling. The thickness of this layer is 1.50 ~ 5.30 m, with an average thickness of 3.16 m.
- Silty clay (Q4al + pl): it is deposited after recent manual sand extraction in the river channel. The thickness of this layer is 5.70 ~ 8.60 m, with an average thickness of 6.95 m.
- Loess like silt (Q4al + pl): uniform texture and porous. The thickness of this layer is 3.40 ~ 8.10 m, with an average thickness of 5.58 m.
- Mudstone (n): solidified from mud and clay, with obvious bedding structure. The thickness of this layer is 6.40 ~ 9.20 m, with an average thickness of 7.46 m.

3. Field Test

3.1. Design Test Pile
In order to carry out the static load test of split grouting pile, it is necessary to design the test pile and use the split grouting technology to form the pile at the test site. See table 1 for main parameters of test pile and grouting.

| Test pile parameters | Grouting parameters |
|----------------------|---------------------|
| Pile length /m       | Pile diameter /m     | Pile spacing /m | Slurry (water-cement ratio) | Cement paste (1:1) | Grouting quantity /m³ | Grouting pressure /Mpa |
| 10                   | 0.1                 | 0.8             | PO.42.5                       | 0.3834              | 0.6~0.8               |

In order to realize directional splitting, make each branch vein of adjacent piles better overlap, optimize the mechanical performance of splitting grouting pile, and make the upper branch vein of pile core grow densely and the lower branch vein grow sparsely, the grouting pipe is designed as follows:

The shotcrete holes on the pipe wall are distributed along the depth direction of 0.5 m, 0.5 m, 1 m, 1 m, 1 m, 2 m and 2 m respectively. There are 3 holes on each floor with a horizontal included angle of 120 °, and the upper and lower 10cm are staggered, as shown in figure 3.
The equipment required for the construction of splitting grouting pile include crawler down the hole drill, grouting machine, air compressor, generator, slurry mixing bucket, Baume's hydrometer, etc. In order to ensure the quality of test pile, the grouting test shall be carried out in strict accordance with the following process: drilling grouting hole → slurry preparation → connecting grouting pipe → starting grouting. During grouting, the principle of "drilling one hole, injecting one hole, and injecting every other hole" shall be strictly followed to prevent hole string between adjacent pile holes from affecting the quality of test pile. The on-site grouting test is shown in figure 4.

3.2. Static Load Test
After the grouting is completed and the test pile reaches the design strength, the on-site static load test shall be carried out to detect the ultimate bearing capacity of the test pile. The test device is shown in figure 5.
The static load test of single pile composite foundation adopts the slow maintenance load method, and three piles with good quality are selected for the test, with numbers of DZ80-1, DZ80-2 and DZ80-3 respectively. The test loading method refers to the technical code for the testing of building foundation piles (JGJ 106-2014) [11], and the test loading is shown in figures 6 and 7 respectively.

During the test, records shall be made according to the specifications, and the loading settlement results of each test pile are shown in table 2.

| DZ80-1 | DZ80-2 | DZ80-3 |
|--------|--------|--------|
| Hierarchical loading /kN | Cumulative settlement /mm | Hierarchical loading /kN | Cumulative settlement /mm | Hierarchical loading/kN | Cumulative settlement /mm |
| 120    | 2.51   | 130    | 2.76   | 104    | 1.94   |
| 180    | 4.14   | 195    | 4.37   | 156    | 3.63   |
| 240    | 6.09   | 260    | 6.84   | 208    | 5.51   |
| 300    | 8.13   | 325    | 9.57   | 260    | 7.35   |
| 360    | 10.76  | 390    | 12.49  | 312    | 10.11  |
| 420    | 13.25  | 455    | 15.21  | 364    | 13.15  |
| 480    | 16.18  | 520    | 20.64  | 416    | 17.86  |
| 540    | 22.64  | 585    | 25.85  | 468    | 22.07  |
| 600    | 28.14  | 650    | 31.27  | 520    | 29.95  |

The load settlement curve of each test pile is shown in figure 8.
Figure 8. Load settlement curve of each test pile.

It can be found from the above figure that DZ80-3 pile has excessive settlement rate and premature failure due to the influence of pile quality defects and soil around the pile. The composite load settlement curves of DZ80-1 and DZ80-2 piles are in good agreement. Within the loading range of 0 ~ 200kN, they are basically in the elastic stage. At this time, the load settlement curve increases linearly, and the pile-soil coordinated deformation bears the load together. Within the loading range of 200 ~ 480kN, it is basically in the plastic stage. At this time, the settlement rate begins to increase, the soil around the pile is compressed and plastic deformation occurs, individual branches of the pile appear shear failure, the deformation between the pile and the soil is no longer coordinated, and there is relative displacement. From 480kN, the "steep drop section" of the load settlement curve reaches the failure stage. At this time, the settlement increases suddenly, the original pile-soil structure is damaged, as shown in figure 9, and a large number of branches are shear damaged, as shown in figure 10. It can be judged that the ultimate load of DZ80-1 and DZ80-2 single pile composite foundation is 480kN, the ultimate bearing capacity is 955kPa, and the characteristic value of bearing capacity is 477kPa.

Figure 9. DZ80-3 pile after damage.  Figure 10. Broken branch.

4. Finite Element Simulation

Limited by the field test conditions, it is impossible to further explore the pile-soil load transfer mechanism of split grouting pile single pile composite foundation, and the stress conditions of pile core, branch vein and soil are also difficult to obtain. In order to make up for the deficiency of field test, the method of finite element numerical simulation [12-18] is adopted, and the three-dimensional model of pile-soil is established by using ABAQUS finite element analysis software [19]. Based on Mohr-Coulomb constitutive relationship, the finite element numerical simulation is carried out and the simulation results are analyzed.

4.1. Model Parameter

After the static load test, excavate the test area and observe the shape, size and size of the branch vein. Due to the limitation of site conditions, it is impossible to excavate the 10m long pile as a whole, so only excavate to the depth of 2m and observe the branch veins of the upper two layers. After excavation, it is found that the shape of branch veins is irregular plate shape, as shown in figure 11, and the quantity and size are shown in table 3.
Table 3. Statistics of number and size of branches in the upper two layers.

| Pile number | Number of branches | Branch length/m | Branch width/m | Branch thickness/m |
|-------------|--------------------|-----------------|----------------|-------------------|
| DZ80-1      | 4                  | 0.59            | 0.28           | 0.018             |
| DZ80-2      | 6                  | 0.75            | 0.34           | 0.024             |
| DZ80-3      | 6                  | 0.78            | 0.35           | 0.026             |

After on-site soil is taken back to the laboratory for geotechnical test, the soil parameters of the test site are obtained, as shown in table 4.

Table 4. Soil parameters of test site.

| Soil type   | Thickness /m | Bulk density /kN·m^{-3} | Elastic modulus /kPa | Poisson's ratio | Internal friction angle /° | Cohesion /kPa |
|-------------|--------------|-------------------------|----------------------|----------------|---------------------------|--------------|
| Plain fill  | 4.0          | 16.9                    | 3.27×10^{5}          | 0.40           | 8                         | 15           |
| Silty clay  | 7.5          | 18.3                    | 4.61×10^{5}          | 0.35           | 15                        | 36           |
| Loess silt  | 8.5          | 18.6                    | 5.01×10^{5}          | 0.32           | 17                        | 32           |

4.2. Model Establishment

(1) Soil mass

The soil model is set as a cuboid, with length and width of 10 m, height greater than twice the pile length, and the specific size is 10 m×10 m×21 m. At the center of the soil, the pile shall be excavated by cutting.

(2) Pile

According to the test design, the pile length is 10m and the pile diameter is 0.1m. In order to facilitate grid division and branch vein installation, the pile core is set as a regular 12 prism, which approximately replaces the cylinder. Branch vein: according to the statistical results of excavation survey, the branch vein is approximately set as a thin plate with equal thickness, with a length of 0.767m. The short side is 0.05m wide, the long side is 0.33m wide and the thickness is 0.026m.

(3) Pressing plate

The pressing plate is set as a circular steel plate with a diameter of 0.8m and a thickness of 0.03m according to the actual situation.

The geometric model of each component is shown in figure 12.
Figure 12. Geometric model of each component.

(4) Load application

After the in-situ stress is balanced, apply loads of 50kN, 150kN, 250kN, 350kN, 450kN, 550kN, and 650kN in 7 levels in analysis steps 2 ~ 8 respectively, apply the above loads on the upper surface of the pressing plate in the form of pressure, and then submit the calculation.

4.3. Result Analysis

After all analysis steps of the model are calculated, the vertical stress and displacement of pile and soil are analyzed respectively.

(1) Soil in-situ stress balance results

The results of soil in-situ stress balance are shown in Figure 13.

It can be seen from Figure 13 that the displacement of the soil model after in-situ stress balance approaches 0, indicating that after in-situ stress balance, the soil does not produce displacement, and has the stress field under the action of gravity, and the in-situ stress balance has a good effect.

(2) Pile stress

The vertical stress nephogram of the pile core and branch vein is shown in Figure 14. For the pile core, the maximum vertical stress occurs at the pile top and decreases gradually along the pile body. For the branch vein, the maximum vertical stress occurs at the root and decreases gradually along the length of the branch vein. The whole pile body is a symmetrical structure, the stress of three branches in each layer is relatively uniform, and the stress of branches in the upper layer is greater than that in the lower layer. It should be noted that the vertical stress at the root of the branch vein of the first layer is the largest and greater than the vertical stress at the pile top.
The distribution curve of the vertical stress of the pile core along the length direction is shown in figure 15. Under the action of the first two levels of load, the vertical stress of the pile core is very small and almost distributed in a straight line. From the third load, the vertical stress in the pile core is distributed in a ladder shape, which is due to the existence of branches. When the load is transferred to the location of the branch vein, most of the load is borne by the branch vein, and a small part of the load continues to transfer downward. This phenomenon is reflected in the vertical stress distribution curve, and a "step" will appear. Moreover, it can be seen from the figure that under the action of each level of load, the vertical stress at the pile top is the largest, gradually decreases along the pile core, and almost decreases to 0 at the pile bottom, which indicates that the branch vein and pile side friction (as shown in figure 16) "consume" most of the load in the process of load transmission, which is the characteristic of typical friction pile.

The vertical stress distribution curve of the branch vein of each layer along the length direction of the branch vein is shown in figure 17. It can be seen that the vertical stress of the branch vein of the first layer is the largest and greater than the vertical stress at the pile top, reaching 40 Mpa, indicating that the branch vein of the first layer has been damaged long after loading. When the stress is transmitted down the pile core to the branch vein of the first layer, the stress begins to be borne by the branch vein of the first layer and increases continuously along the length direction of the branch vein, reaches the maximum when the branch vein length is 0.2 m, decreases sharply from the branch vein length of 0.3 m to 0.5 m. After 0.5 m, the stress begins to increase inversely and appears positive. This is because the radius of the pressing plate is 0.4 m and the pile diameter is 0.1 m. Therefore, the branch vein within the length of 0 ~ 0.3 m is under the pressing plate and has a positive stress, while the branch vein outside the range of 0 ~ 0.3 m is outside the pressing plate and is subjected to the reverse extrusion of the soil below, so the stress decreases sharply and produces a reverse stress. The 2nd, 3rd and 4th layers of branches bear large vertical stress and have been damaged to varying degrees. The 5th, 6th and 7th layers of branches bear small stress, and the 8th layer of branches has almost zero vertical stress.
Figure 17. Distribution curve of vertical stress along the length of branch vein of each layer.

(3) Pile displacement

The vertical displacement nephogram of the pile is shown in figure 18. It can be seen from the figure that the vertical displacement within 1m above the pile core is large, and the maximum displacement occurs at the pile top. The maximum vertical displacement of the branch vein is about half smaller than that of the pile top, because the branch vein is embedded in the soil and is squeezed and supported by the soil below.

Figure 18. Nephogram of vertical displacement of pile.

The vertical displacement curve of pile core under various loads is shown in figure 19. With the increase of load grade, the vertical displacement of pile core increases uniformly, and the vertical displacement of pile top is the largest, which decreases gradually along the length of pile core and decreases to 0 at pile bottom. It shows that the branch vein plays a great role in the process of pile vertical settlement, so that the pile bottom basically does not have vertical displacement. During the action of the first four levels of load, the vertical displacement of the pile core increases slightly. From the fifth level of load, the vertical displacement of the pile core increases suddenly, indicating that the pile body begins to be damaged and gradually loses its bearing capacity from the current level of load.
Under the action of loads at all levels, the vertical displacement distribution curve of the branch vein along the length direction is shown in figure 20. The vertical displacement of the root of the branch vein is greater than that of the end, and it decreases gradually along the length direction. Under the action of loads at all levels, the vertical displacement of the first four layers of branches increases greatly. From the fifth layer of branches, the vertical displacement increases slightly and evenly. It can be seen that in the process of load application, the branches that play a role are mainly distributed in the upper 4 layers of the pile.

(4) Soil stress
It can be seen from the cloud diagram of soil vertical stress (figure 21) that the vertical stress of soil is symmetrically distributed as a whole. The soil under the pressing plate sinks after being pressed, resulting in reverse compression on the surrounding soil, so the top soil produces a small positive stress. With the increase of depth, the vertical stress increases gradually.
Figure 22 shows the distribution curve of vertical stress on the upper surface of soil along the axis of symmetry under various loads. It can be seen that under the action of loads at all levels, the vertical stress is basically symmetrically distributed along the axis of symmetry, which proves that the model parameters are set reasonably and the soil is stressed evenly. The pile body is located at the length of 5m of the symmetry axis, where the vertical stress is the largest, but it is subjected to the reverse extrusion of the soil below. In the area outside the pile head and within the pressing plate, the reverse stress is generated, so the vertical stress within this range is reduced. From the second level load to the fifth level load, the positive stress appears, and the positive stress gradually decreases with the increase of load. From the 6th load to the 7th load, the positive stress disappears, and the negative stress within the pressing plate increases continuously. At this time, the soil at the pile head and pile side has been damaged and lost its bearing capacity.

Figure 22. Vertical stress distribution curve along the axis of symmetry on the upper surface of soil.

5. Conclusion
Taking the field single pile composite static load test as the background, combined with the field measured data, the three-dimensional model of split grouting pile and soil is established through ABAQUS finite element simulation software. Combined with the numerical simulation results, the variation laws of stress and displacement of pile-soil model under various loads are analyzed and compared with the field test data. Finally, the following conclusions are drawn:
(1) The model size, material parameter setting, contact setting and grid division are relatively
appropriate. The load settlement simulation curve is basically consistent with the measured curve, and the characteristic value of bearing capacity is basically consistent. Therefore, the single pile composite foundation model of split grouting pile basically meets the practical needs, and can be calculated by numerical simulation without field test conditions, It provides a reference for optimal design.

(2) Under the action of loads at all levels, the pile core plays the role of friction pile, the pile side friction and branch vein "consume" most of the load, and the load transmitted to the pile bottom is basically 0.

(3) The branch vein is filled to compact the soil around the pile, which reduces the cumulative settlement of the soil around the pile, strengthens the connection between the pile and soil, and is conducive to give full play to the coordination role between the pile and soil. In the process of load transmission, the branch bears most of the load, and the load borne by the upper branch is greater than that of the lower branch. Therefore, in the engineering practice design, the dense layout of the upper branch should be controlled, and the sparse layout of the lower branch can be controlled.

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