Model test for the simultaneous injecting of super-large rectangular pipe jacking

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Abstract: In the construction of pipe-jacking tunnels, simultaneous injecting is a key in controlling surface deformation and jacking force. At present, the traditional simultaneous injecting research is mainly limited to the study of slurry materials and the friction coefficient, while research on the flow of the slurry itself and its filling mechanism is rarely involved. By building a pipe-slurry-soil system and model test platform, this paper presents the results of a laboratory reduced-scale model test on the simultaneous injection of slurry of super-large rectangular pipe jacking. Results show that different slurries have varying effects on the quality of protective slurry screen, which contains traditional thixotropic slurry (consisting of bentonite, carboxymethyl cellulose (CMC), and soda ash) as well as HS-3 compound slurry and polyacrylamide compound slurry. Furthermore, the injection pressure, injection flowing path, and toroidal injection pressure distribution were visually and accurately measured and analyzed by installing 22 miniature soil pressure gauges on the surface of the organic glass model pipe and arranging 12 cameras inside the organic glass segment. Meanwhile, the settlement of different parts of soil and pipe-jacking force was measured to observe the influence of protective slurry screen on the ground settlement and pipe-jacking force. The injecting pressure distribution and the flow filling process of the shallow overburden large-section rectangular pipe-jacking tunnel were also explored.

Keywords: model test, pipe-slurry-soil system, mud screen, simultaneous injection, pipe jacking
1. Introduction

With the constant development of urban underground space and an increasing number of tunnel engineering projects, the amount of urban underground space available for use is shrinking. As a result, the rectangular pipe-jacking tunnel was recently introduced because of its superior utilization of space. The rectangular pipe-jacking method uses special techniques in the construction of pipelines and passages; furthermore, it excavates the ground as little as possible to minimize the damage to the urban underground space\[1\]. However, it is difficult to control the construction of rectangular pipe-jacking tunnels, and the resulting deformation is not easy to control, especially in areas with weak soil layers. Thus, simultaneous injecting is carried out at the same time during the pipe-jacking process by injecting holes on the pipe segment through the simultaneous injecting system. The slurry forms a mud screen in the gap between the pipe-jacking machine and the pipe segment to support the surrounding soil. Therefore, this process can effectively control the surface deformation and greatly reduce the frictional resistance during the jacking process. For this reason, in the construction of the pipe-jacking tunnel, simultaneous injecting is very important in controlling ground deformation and reducing frictional resistance.

Most of the experiments related to simultaneous injection are based on the slurry material, specifically analyzing the material parameters, including the selection of slurry and the determination of the material mix ratio\[2\] \[3\] \[4\]. Some scholars have also studied the influence of mud screen on jacking force, surface deformation, and soil splitting through laboratory experiments\[5\]. Other researchers used pressure sensors to detect the pressure of the segment during the synchronous grouting process; to analyze the distribution law and the dissipation of the grout pressure in the gap of the shield tail in order to investigate the flow path and diffusion mode of the grout, respectively; and to verify the rationality of flow-and-diffusion model of synchronous grouting\[6\]. Meanwhile, some scholars used plexiglass materials to make a scaled model of a rectangular shield tunnel to conduct a visual simulation test of the simultaneous grouting process, thus serving as an important basis for the establishment of a quasi-rectangular shield grouting pressure model\[7\].

Through a three-dimensional (3D) model test, the variations of jacking force and ground settlement inside a jacking pipe tunnel in silt stratum are simulated under testing conditions that include non-injection and different synchronized injections of slurry. The goal is to study the effect of traditional thixotropic slurry (consisting of bentonite, carboxymethyl cellulose (CMC), and soda ash) and HL compound slurry to decrease frictional resistance and ground settlement. Then, their mechanical properties are investigated according to the different slurry micro-structure features, which are captured by an electron microscope. The tests and analyses suggest that further attention should be given to slurry parameters in the actual engineering processes\[8\].

However, due to the special shape of the rectangular pipe, the flatness in the top of a rectangular shield tunnel disrupts the flow of slurry, which may cause silting at the top and bottom parts of the segment\[9\]. Therefore, investigating the behavior of the simultaneous injecting of a super-rectangular pipe tunnel (particularly the injection pressure and properties of injection-the injection volume) is essential.

This test is based on the Luxiang Road Pipe-Jacking Tunnel Project, whose scaled model is simultaneously injected. Specifically, the variation law of injecting pressure is analyzed through the
collection of injecting pressure data. Meanwhile the collection of jacking force and surface deformation data can help in analyzing the influence of injecting pressure and injecting volume on surface deformation and jacking force.

2. Similar systems and relationships

Pipe jacking is a very complicated process, which involves the interactions among the segment, soil, and slurry, thus bringing great difficulties to their theoretical analysis. However, the model tests provide a good platform for investigating stratigraphic adaptability in the pipe-jacking process. Therefore, the current paper takes the pipe jacking, slurry, and soil as a system, that is, the “pipe-slurry-soil system.” According to similar theories, using the basic dimensional system represented by mass, length, and time (MLT), we can obtain all physical parameters involved in the simultaneous injecting test system\[10\].

\[
\begin{align*}
(1) \quad & \text{Pipe jacking characteristics: Cover thickness } H[L], \text{ Tunnel diameter } D[L], \text{ and Gap}\ d[L] \\
(2) \quad & \text{Soil characteristics: Cohesion } C_1[ML^{-1}T^{-2}], \text{ Internal friction angle } \phi_1[1], \text{ Volumetric weight } \gamma_1[ML^{-3}T^{-2}], \text{ and Compression modulus } E[ML^{-1}T^{-2}] \\
(3) \quad & \text{Slurry characteristics: Dynamic shear force } \tau[ML^{-1}T^{-2}], \text{ Thixotropy } p[ML^{-1}T^{-2}], \text{ Filtration rate } \psi[1] \\
(4) \quad & \text{Pipe jacking-injecting system: Jacking speed } v[LT^{-1}], \text{ injection pressure } p[ML^{-1}T^{-2}], \text{ and injection volume } q[L^3T^{-1}] \\
(5) \quad & \text{Dependent variable: Internal stress of soil } \sigma[ML^{-1}T^{-2}] \text{ and Soil deformation } \delta[LT^{-2}]
\end{align*}
\]

Given that the model and the prototype are in the same gravitational field, the acceleration of gravity is equal. Using the dimensional analysis method and the second theorem of similarity theory, the relationship between the similarity ratios of the physical parameters is finally obtained as follows:

\[
\begin{align*}
C_H &= C_I, \quad C_D = C_I, \quad C_d = C_I, \quad C_G = C_IE^2, \quad C_{\sigma} = C_I, \quad C_{C_1} = C_E, \quad C_{C_2} = C_E, \quad C_{C_3} = C_E, \quad C_{\phi_1} = 1, \quad C_{E} = C_{\gamma_1}, C_I = C_2C_1, \\
C_{v} &= 1, \quad C_{p} = 1, \quad C_{\tau} = C_E, \quad C_{\gamma} = 1, \quad C_{q} = C_1^2, \quad C_{\delta} = \sqrt{C_I}, \quad C_{\psi} = \sqrt{C_I}, \quad C_{\sigma} = C_E, \quad C_{q} = \left(\sqrt{C_I}\right)^5, \quad C_{p} = C_E, \\
C_{\varphi} &= C_E, \quad C_{\delta} = C_p
\end{align*}
\]

In the above formula, \( C_I \) is the geometrical similarity ratio between the prototype and the model \((C_I = 20)\), and \( C_E \) is the compression modulus similarity ratio of prototype soil and model soil and the rest can be derived.

As can be seen from the above formula, as long as \( C_I \) and \( C_E \) are selected, in theory, \( C_I \) and \( C_E \) are equal, but when the model soil is configured, it is difficult to achieve absolute similarity. Thus, as long as the approximate similarity is satisfied, we can first assume that an approximate \( C_E \) is close to \( C_I \), and then continue to make the adjustment. In this way, we can determine the similarity ratio of other physical parameters.

3. Preparation of model soil and model slurry

3.1 Preparation of model soil
The stratum referred to in the model test is the soft soil layer in Shanghai. According to the survey report, the soil layer and the overlying soil layer through which the pipe jacking is selected are chosen, and the four performance indicators of the prototype soil are obtained according to the weighted average of the thickness. After several attempts, we finally chose barite powder, double fly powder, bentonite, undisturbed soil, washing powder, fine sand, and water. According to a certain ratio, these were stirred evenly, after which the model box was filled with the samples in layers. After pressure treatment, the artificial model soil with stable performance was obtained. The four performance indexes of prototype soil and model soil are shown in Table 1.

At this time, \( C_{C_1} \approx C_E \approx C_I \) is approximately equal, because absolute similarity cannot be achieved; as long as the main similarity relationship can be satisfied, it can be considered that the model soil is similar to the undisturbed soil[10].

| Type of soil  | \( \gamma_1 / (\text{kN m}^{-3}) \) | \( C_{\gamma_1} \) | \( \phi_1 (^\circ) \) | \( C_{\phi_1} \) | \( C_{C_1} \) | \( E / \text{(MPa)} \) | \( C_E \) |
|--------------|---------------------------------|----------------|----------------|----------------|--------------|---------------|--------------|
| Prototype soil | 17.2 | 0.96 | 15 | 11 | 1.03 | 2.9 | 9.7 |
| Model soil    | 17.9 | 0.96 | 15.8 | 10.7 | 0.3 | 0.3 | 0.3 |

### 3.2 Preparation of model slurry

The model slurry is mainly aimed at the bentonite antifriction slurry commonly used in pipe-jacking tunnels. The raw materials used to prepare the model slurry are exactly the same as the prototype slurry, including bentonite, CMC, soda ash, and water. After a comprehensive comparison, three indicators of water loss, thixotropy, and dynamic shear were selected as reference quantities for describing the characteristics of the slurry. The performance indicators of the prototype slurry were measured on site, and after several attempts, a model slurry that approximately met the requirements was obtained. The four performance indexes of prototype slurry and model slurry are shown in Table 2.

| Type of slurry  | \( \psi / \text{l} \) | \( C_p \) | \( \tau / \text{pa} \) | \( C_r \) | \( p / \text{pa} \) | \( C_p \) |
|----------------|----------------|-------------|----------------|-------------|----------------|-------------|
| Prototype slurry | 0.044 | 12.3 | 1.07 | 9.5 | 4 | 10.5 |
| Model slurry    | 0.041 | 1.3 | 0.38 | 0.38 | 0.38 | 0.38 |

### 4. Description of the test system and method

The integrated testing equipment consisted of five parts: test chamber, load system, injecting system, visual system, and measurement systems. Their relationship and the overall experimental layout are illustrated in Figure 1.

#### 4.1 Test system and equipment

**4.1.1 Equipment.** Test chamber: The front, back, left, and right sides were made of transparent acrylic sheets with a thickness of 20 mm, and the bottom part was made of steel plates. The outer corners and the front and back sides were reinforced with steel bars. The size was 2500 × 1500 × 1500 mm (length
Model pipes: To simulate the annular gap between the tunnel structure and the soil at the actual construction site, the model pipes consisted of the front and back pipes made of transparent acrylic sheets. The front pipe was used to simulate the pipe-jacking machine, and the back pipe was used to simulate the real pipes. The size of the back pipe was 500×408×1500×20 mm (width × height × length × thickness). The front pipe was thicker than the back pipe by 2 mm.

(a) front pipe
(b) back pipe

Figure 1. Overall layout of the test system

Figure 2. Model pipes
4.1.2 Load system. Hydraulic jack: The rated lifting capacity was 6 t, and the rated hoisting height was 1000 mm. It can display real-time pressure and jacking distance. After setting the jacking speed, jacking can be done automatically, and the speed of this test was set to 0.046 mm/s.

4.1.3Injecting system. The injecting system included the injecting pump machine and pipelines. There were five injecting sections on the back segment, and each section had five injecting holes, two holes on the top, one hole on each side, and one hole on the bottom. The injecting process was actually controlled by the volume and the flow rate of the slurry.

4.1.4 Visual system

There were three sections on the back segment, each with four cameras, respectively, at the center of the side. These were used to observe the flow and diffusion of the slurry and to analyze the flow of the slurry with the data collected by the earth pressure sensor in the later stage.

4.1.5 Measurement system

There were three measurement systems used. First, 30 vertical displacement gauges were arranged above the soil to measure the deformation of the ground when the jacking pipe passes. Second, 22 miniature earth pressure gauges were arranged on the pipe slices to measure the change of the injection pressure on the pipe. Finally, FC-TJ01 standard S-type load cell was installed between the front and back pipes in order to measure the friction force of the front segment without grouting. Then, the total jacking force was used to calculate the friction force experienced by the segment under injecting, thus facilitating a comparison of the jacking force under injecting and no injecting situations.

4.2 Description of the method

First, the box was filled with the configured model soil in layers and then compacted. Next, the front pipe was placed into the model box, filled with soil, and then compacted, according to the soil pressure gauge on the front pipe to determine the compaction time. Then, the back pipe was installed after correcting the deviation and debugging the injecting, jacking, and monitoring equipment. Then, this was pushed in at a speed of 0.046 mm/s. When the injecting hole entered the soil, the injection
was initiated. According to engineering experience, the injecting volume was calculated according to the grouting rate of 200%. The interval between each ring was 200 mm, and the volume was 1440 ml. The different injecting volumes with the same grouting hole were set to compare the working conditions in Table 3.

| Injection flow | Upper left | Upper right | Left side | Right side | bottom |
|----------------|------------|-------------|-----------|------------|--------|
| Condition 1    | 40%        | 40%         | 10%       | 10%        | 0%     |
| Condition 2    | 30%        | 30%         | 15%       | 15%        | 10%    |

5. Analysis of test results

As demonstrated in the curves above, when the injecting method of working condition 2 is used, the fluctuation of the inject pressure on the four contact surfaces of the upper, lower, left, and right sides, respectively, is smaller than that under the injecting method of working condition 1, which is more effective for maintaining ground stability. Although it is a customary engineering practice to use
only top injecting and use the gravity of the slurry to make it flow to other parts, for pipe-jacking projects in shallow soil areas, injecting only at the top is likely to cause excessive local pressure and soil splitting. As a result, the slurry will penetrate the soil in large volumes, and the ground will experience problems in stability and construction safety.

6. Conclusion

In this paper, the pipe-slurry-soil system was established for the pipe-jacking tunnel. Through model tests of different injecting methods, the flow of slurry in the gap between the pipe jacking and the soil was studied, and the different injecting methods were assesses in terms of the quality of controlling the ground deformation. The following conclusions are drawn from this work. First, the distribution of the initial value of the slurry pressure is mainly affected by the injecting method, thus forming an irregular contour figure around the pipe wall. Second, engineers should try to avoid injecting only at the upper part. Rather, it is best to inject at the upper and side simultaneously and consider whether or not the bottom is injected according to the actual situation.

Acknowledgments

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