Numerical analysis on surface settlement in parallel rectangular pipe jacking construction

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Abstract—In recent years, rectangular pipe jacking technology has been gradually applied in urban underground engineering. Based on a parallel rectangular pipe jacking project, a three-dimensional finite element model is established for numerical analysis, and the surface settlement caused by rectangular pipe jacking construction is studied. The research shows that the pipe jacking construction has the most obvious impact on the soil above the pipe jacking axis, and when the clear distance between parallel rectangular pipe is 1D (D indicates the pipe inner width), the main influence range of pipe jacking construction on soil mass is about 1D along the longitudinal direction of pipe jacking. With the increase of parallel rectangular pipe distance, the surface settlement trough becomes wider and the maximum surface settlement decreases. The main influence range of parallel rectangular pipe jacking construction at the outside of the pipe jacking is about 1D−1.37D along the lateral direction. When the pipe distance is greater than 2D, the interaction between parallel pipe jacking is weak, and the influence range at the outside of pipe jacking is almost the same as that of single pipe jacking construction. The research results can provide a reference for the design and construction of similar pipe jacking projects.

1. Introduction
In recent years, with the rapid development of economy and technology and the rapid growth of population density, the exploration and utilization of underground space has become an inevitable trend. Due to the influence of urban aboveground buildings and ground traffic, the construction technology of traditional open excavation method is limited, and the shallow mining method has gradually become a trend and is also necessary, including pipe jacking construction technology.

Pipe jacking is a kind of construction technology with no or less excavation [1]. The traditional pipe jacking section is mostly circular, and has been developed at home and abroad [2-5]. Compared with the circular pipe jacking, rectangular pipe jacking shows the advantages of high section utilization, low cost-effectiveness ratio and good applicability, and is gradually widely used [6]. Researchers have studied the jacking force, mechanical effect and ground settlement caused by pipe jacking construction, but mainly focused on circular pipe jacking [7-9]. Compared with circular pipe jacking, rectangular pipe jacking causes more complex ground settlement during construction [10]. The existing research on rectangular pipe jacking is far from meeting the needs of practical engineering, and the research on parallel rectangular pipe jacking is relatively insufficient.

Therefore, it is necessary to study the surface settlement caused by parallel rectangular pipe jacking and the interaction between pipes, so as to provide some reference for similar projects.
2. Project overview
A parallel rectangular pipe jacking project is 75 m long, the pipe inner width is 8m, the height is 5m, the distance between two pipe jacking is 8 m, and the average soil covering is about 10 m. The rectangular jacking pipe is C50 prefabricated reinforced concrete pipe, and the external dimension of pipe jacking is 9m × 6 m, the pipe wall thickness is 0.5 m, the impermeability grade is P12, and the length of a single pipe section is 1.5 m.

According to the survey report, the subgrade bed coefficient of the soil layer is 150 MPa/m, the unit weight is 20.5 kN/m³, the cohesion is 40.0 kPa, the internal friction angle is 23°, and the elastic modulus is 26.0 MPa.

3. Establishment of Numerical Model

3.1. Numerical model
The pipe jacking model size is based on the practice project, the pipe inner width is 8m, and the distance between the two pipes is 8m, which is 1 time of the net inner width (D). The model boundary is 4 times the pipe structure width, and the model size is 104 m wide(X), 40 m high(Z) and 30 m deep(Y). The soil layer adopts solid element, which conforms to Mohr-Coulomb criterion. The pipe jacking is simulated with plate element, which meets the elastic constitutive model [11].

The numerical model adopts spatial tetrahedral grid, which is divided into 16314 nodes and 37579 elements. The numerical analysis model is shown in Fig.1.

![Numerical analysis model of pipe jacking construction](image)

3.2. Calculation parameters
The physical and mechanical parameters of model materials are shown in Table 1.

| Items   | E/MPa | ν   | γ/kN·m⁻³ | c/kPa | φ/°  |
|---------|-------|-----|---------|-------|------|
| Soil    | 26    | 0.3 | 20.5    | 40    | 23   |
| Pipe    | 34500 | 0.2 | 27      | /     | /    |

In the numerical simulation analysis, the construction steps are reasonably simplified according to the actual construction process, and can reflect the basic problems concerned in the process of pipe jacking construction. The full face excavation method is adopted in the analysis model. The left pipe jacking is constructed first until it is completed, and then the right pipe jacking is constructed. A total of 25 construction steps are set in the process of construction simulation.
4. Results and Analysis

4.1. Surface settlement analysis

The contour diagram of vertical displacement of soil layer in rectangular pipe jacking construction is shown in Fig. 2. It can be seen from the figure that the soil mass above the rectangular pipe jacking has settled, and the maximum value appears directly above the pipe jacking axis.

![Fig.2 Contour diagram of ground vertical displacement in parallel pipe jacking construction](image)

Taking the middle section of the model (y=15m) as the research object, the law of surface vertical displacement with pipe jacking construction is studied. Take the first pipe jacking axis as the zero point of coordinate horizontal axis, and then the surface settlement trough curve can be drawn at the research section, as shown in Fig. 3.

![Horizontal distance from first pipe axis](image)

As can be seen from Fig. 3, with the jacking of the second pipe, the surface settlement trough gradually becomes wider, and the center line of the surface settlement trough gradually approaches the second pipe. When the jacking of the second pipe is completed, the center line of the settlement trough is about the center of the two pipe jacking.

When the first pipe is completed, the maximum surface settlement is 11.2 mm, which is located above the first pipe axis. After the second pipe is completed, there are two maxima in the settlement trough, which are respectively located above the two pipe axis, and the maxima are 10.6 mm and 10.2 mm respectively.

In addition, after the first pipe is completed, the settlement trough is about 30 m wide, which is about 3.75D, indicating that the influence range of single rectangular pipe jacking construction on the
outside of the jacking edge is about 1.37 D. After the jacking of the two pipes, the settlement trough is basically symmetrical, and its width is about 43 m (about 5.37D), indicating that the influence range of parallel rectangular pipe jacking construction on the outside of the jacking edge is about 1.18 D.

4.2. Longitudinal influence range analysis
Along the longitudinal direction of pipe jacking, the surface vertical deformation above the first pipe axis with pipe jacking construction, as shown in Fig. 4 (negative value indicates settlement).

From Fig. 4, the settlement value when the pipe jacking face crosses 1D from each monitoring section and the final settlement value of the monitoring points can be obtained, as shown in Table 2.

| Monitoring section | Crossing 1D settlement (A) | Final settlement (B) | A/B |
|--------------------|----------------------------|----------------------|-----|
| y=0 m              | 13.08                      | 14.30                | 91% |
| y=4 m              | 13.13                      | 13.90                | 94% |
| y=8 m              | 11.29                      | 12.42                | 91% |
| y=12 m             | 10.66                      | 11.50                | 93% |
| y=14 m             | 8.88                       | 11.19                | 79% |
| y=18 m             | 9.06                       | 10.81                | 84% |
| y=22 m             | 9.39                       | 10.20                | 92% |

It can be seen from Table 2 that when the pipe jacking construction face passes through the monitoring section 1D, the settlement value of the section reaches about 90% of final settlement and quickly tends to be stable. This shows that along the longitudinal direction of pipe jacking, the influence range of pipe jacking construction on surface vertical displacement is 1D.

4.3. Influence analysis of pipe distance
In order to study the influence range of different pipe distance on surface settlement, a series of simulation analysis are carried out at different pipe distance conditions: 0.0D (single pipe), 0.2D (1.6m), 0.5D (4m), 1.0D (8m) and 2.0D (16m). Fig. 5 shows the final surface settlement at section y=15m at different pipe distance conditions.
Fig. 5 Surface settlement trough curve of section y=15m at different pipe distance

It can be seen that under the conditions of 0.2D, 0.5D, 1.0D and 2.0D, the width of surface settlement trough is about 34 m(4.25D), 37 m(4.63D), 43 m(5.37D) and 54 m(6.75D) respectively. Therefore, the lateral influence range of pipe jacking construction on the outside of pipe jacking edge under different pipe distance can be calculated, as shown in Table 3.

| Pipe distance | Settlement trough width | Influence range from pipe outside |
|---------------|-------------------------|----------------------------------|
| 0.2D          | 4.25D                   | 1.02D                            |
| 0.5D          | 4.63D                   | 1.06D                            |
| 1.0D          | 5.37D                   | 1.18D                            |
| 2.0D          | 6.75D                   | 1.37D                            |

As can be seen from Table 3, with the increase of parallel rectangular pipe distance, the surface settlement trough becomes wider. The main influence range of parallel rectangular pipe jacking construction on the outside of the pipe jacking is about 1D~1.37D along the lateral direction. When the pipe distance is 2D, the influence range on the outside of pipe jacking edge is about 1.37D, which is basically the same as that of single pipe jacking. When the pipe distance is greater than 2D, the mutual influence of parallel pipe jacking is weak, and the influence of pipe distance on surface settlement can be ignored during the construction.

5. Conclusion

Based on the analysis results presented above, the conclusions are obtained as below:

(1) The surface settlement mainly occurs in the upper part of rectangular pipe jacking and the maximum value is at the pipe jacking axis. With the jacking of the second pipe, the surface settlement trough gradually widens, and the center line of the settlement trough gradually approaches the second pipe. When the jacking of the second pipe is completed, the center line of the surface settlement trough is about the center of the two pipes.

(2) When the pipe jacking construction face passes through the monitoring section 1D, the settlement value of the section reaches about 90% of its final settlement and reached stability soon. Therefore, the main influence range of pipe jacking construction on soil mass is about 1D along the longitudinal direction of pipe jacking.

(3) With the increase of parallel rectangular pipe distance, the surface settlement trough becomes wider. The main influence range of parallel rectangular pipe jacking construction on the outside of the pipe jacking is about 1D~1.37D at the lateral direction. When the pipe distance is larger than 2D, the interaction between parallel pipe jacking is weak, which is almost the same as that of single pipe construction.
Acknowledgments
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