Optimization of Jacking Sequence of Shallow-buried Pipes in Saturated Soft Soil

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Abstract. In order to extend the method of undercutting to the construction of metro stations in soft soil, Shanghai takes a section ofGuiqiao Road Station on Shanghai Metro Line 14 as trial engineering, and applies the pipe-roof method novelly to this engineering. Based on this project, the numerical simulation was used to optimize the construction sequence of pipe groups, with the purpose of reducing the disturbance to the soil stratum from pipe jacking. First of all, the stress release ratio, one of the most important parameters in the numerical model, was calibrated according to the on-site measured ground surface displacement, so that the established numerical model was validated. On this basis, a series of modellings with different jacking sequence were carried out and their disturbance degrees to the surrounding soil were comparatively analyzed. It shows that the construction sequence of the horizontal pipe groups is the decisive factor of the construction disturbance degree, and giving priority to lower pipes will reduce the ground deformation; and the less the number of steel pipes in the jacking construction, the smaller the deformation will be. Furthermore, the construction scheme of pipe groups was optimized, leading to reductions in the total and maximum surface deformation by 12% and 11.5% respectively. This study is of great significance for the further realization of micro-disturbance construction control when adopting pipe-roof method.

1. Introduction
With the continuous development of the city, the development intensity of the central urban area is increasing day by day. The environmental problems of constructing metro stations in dense traffic and construction areas are becoming more and more prominent. The traditional open cut method has a great impact on the surface traffic[1], while the undercutting method is more suitable for the downtown area due to its advantages of light environmental pollution, small demolition and relocation, and less traffic interference. However, it has higher requirements on the independence and stability of the excavated soil. Shanghai is a typical soft soil area with high groundwater level and low soil strength[2]. For many years, the construction of metro stations in Shanghai has been using the open cut method. Now, contradictions between urban construction and environment and traffic are increasingly sharp. Therefore, it is of great practical significance to introduce undercutting method to construct metro station in soft soil area. For this reason, Shanghai took the Guiqiao Road Station of Metro Line 14 as an experimental project, and tried to apply the pipe-roof method in the soft soil.

The specific process of the pipe-roof method is to first push steel pipes into the periphery of the planned excavation position to form a closed pipe-roof ring, and then carry out the excavation under the
protection of the pipe-roof to form an underground space. The pipe-roof method has the characteristics of flexible and diverse sections, high trenchless proportion and less pipeline relocation, etc. It is suitable for sandy soil and soft clay strata[3], and can be used for water-rich soil layers with freezing reinforcement.

The design scheme and process technology of the pipe-roof directly affect the degree of construction disturbance. Many scholars have conducted in-depth research on this. Yang Xian et al.[4] analyzed and modified Peck formula to predict the earth surface settlement. Fan Lei[5] studied the supporting effect of pipe-roof method in rich water pebbles and fine sand layer. Zhang Peng[6] analyzed soil disturbance during curved pipe jacking construction of Gongbei Tunnel. Zhu Hehua et al.[7] studied construction risks for pipe-roof tunnel in saturated soft soil. Most of these studies are aimed at interval tunnel, but the construction of metro station in soft soil has not been mentioned. There are a lot of technical problems that need to be tackled and a lot of research needs to be put in.

To this end, some preliminary work is done in this paper, focusing on optimizing the jacking sequence of pipe groups to control the construction disturbance of the pipe-roof with rectangular section. It is hoped that it will provide reference for related projects, which will help accelerate the formation of underground excavation technology system in the construction of metro station in the complex environment of the central city in soft soil.

2. Project Overview

Shanghai Metro Line 14, which is distributed along the east-west direction, is an important urban-level route in the new round of construction planning[8], and its terminal station is Guiqiao Road Station. The proposed site of Guiqiao Road Station is located in Pudong New Area. Since the surrounding environment of the station crossing section is relatively simple, the crossing section is set as the test section of the pipe-roof method in the saturated soft clay formation.

The test section is 100m in length with a buried depth of about 5.4m. It is a reinforced concrete box culvert structure with an outer dimension of 21.99m×7.2m (Fig. 1(a)). The construction scheme is as follows. Firstly, 52 steel pipes are inserted into the outer periphery of the excavation position by the pipe jacking machine to form a closed horizontal pipe-roof (Fig. 1(b)). Secondly, horizontal MJS piles are adopted to reinforce the excavation palm face so as to prevent the palm face from instability and overturning (Fig. 1(c)). Then, the pipes are frozen and reinforced to form a closed curtain. Next, the soil is excavated by the step method. After the completion of all excavation, the main structure is constructed.

![Figure 1. Schematic diagram of pipe-roof section](image)

2.1. Pipe-roof configuration

As shown in Fig. 2, pipe-roof ring is composed of 44 customized steel pipes with locking orifice: 22 steel tubes at the top (numbered S1~S22), 4 steel pipes at the left and right sides (Z1~Z4 and Y1~Y4), and 14 steel pipes at the bottom (D1~D14). The middle partition is composed of 8 ordinary steel pipes.
(G1–G8) with no lock. According to the construction experience of several pipe-roof projects at home and abroad, and considering the feasibility of construction, the diameter of the outer and bottom steel pipes is selected as 1.6m. In order to reduce the buried depth of the station structure, the upper pipes’ diameter is 1m. The middle two columns of steel tubes are 1m in diameter. The steel pipe groups are constructed by three pipe jacking machines with diameters of 1 m and two diameters of 1.6 m, and the jacking distance is 100 m.

![Figure 2. Profile of pipe-roof section](image)

2.2. Project’s geological conditions

The survey results show that the proposed site belongs to the normal stratum distribution area of Shanghai, and there are 9 layers of foundation soil from top to bottom within a depth of 80m along the site. All of them are saturated, low strength and high compressibility soil layers. The thickness and physical and mechanical parameters of each soil layer are shown in Table 1.

| Soil Name               | Thickness Height H/m | Compression Modulus E/MPa | Poisson's Ratio μ/ - | Unit Weight γ/ kN/m³ | Cohesion c/ kPa | Internal friction angle φ/° |
|------------------------|-----------------------|----------------------------|----------------------|-----------------------|----------------|-----------------------------|
| Qml ①                 | 3.25                  | 4.92                       | 0.30                 | 17.3                  | 24             | 16.5                        |
| Qal ②                 | 1.50                  | 5.15                       | 0.32                 | 18.6                  | 22             | 23.2                        |
| muddy-silty clay ③    | 1.90                  | 3.34                       | 0.33                 | 17.3                  | 10             | 17.3                        |
| clayey silt ③         | 1.92                  | 9.69                       | 0.28                 | 18.4                  | 14             | 10.5                        |
| muddy-silty clay ③    | 5.68                  | 3.34                       | 0.33                 | 17.3                  | 10             | 17.3                        |
| mucky soil ④          | 6.90                  | 2.43                       | 0.37                 | 16.6                  | 12             | 13.5                        |
| clay ⑤1               | 6.50                  | 3.62                       | 0.34                 | 17.4                  | 19             | 18.1                        |
| silty clay ⑥          | 2.90                  | 6.92                       | 0.32                 | 19.3                  | 46             | 23.3                        |
| clayey silt ⑦1-1-1    | 5.45                  | 10.49                      | 0.28                 | 18.4                  | 12             | 23.3                        |

3. Numerical calculation model and stress release ratio calibration

3.1. Numerical calculation

The pipe-roof construction process was simulated using the finite difference software FLAC3D. In the actual construction, the pipe jacking is jacked up section by section, and there is the possibility of
misplaced construction of multiple pipe jacking machines, which has obvious space-time effect. It is more reasonable to establish a three-dimensional calculation model. Since this paper does not consider the working condition of multi-pipe jacking dislocation excavation for the time being, only preliminary exploration is made on the optimization of construction sequence of steel pipe groups. Therefore, the model is simplified to a plane strain model, which can significantly reduce the calculation amount and facilitate the simulation of more working conditions. The model is shown in Fig. 3. The steel pipes are simulated by shell elements; the foundation soil is simulated by solid elements, and the constitutive model is Mohr-Coulomb model. The calculation parameters of each soil layer are shown in Table 1. Assuming that the calculation boundary is not affected by the construction of the pipe curtain, that is, in the original stress state, the boundary condition is set as follows: the bottom boundary constrains the vertical displacement, the boundary on both sides constrains the horizontal displacement, and the surface is a free boundary.

![Figure 3. Numerical model](image)

3.2. stress release ratio calibration
The stress release ratio depends on the construction method, construction technology, formation characteristics and other factors, and is a difficult calculation parameter to determine[9]. However, to a certain extent, it determines the degree of formation disturbance caused by construction and has a great influence on the results of numerical calculation. Therefore, we first carried out inversion analysis on the stress release ratio in combination with the field measured data to make the established model reasonable and effective, so as to further carry out simulation of different working conditions.

In the actual project, 52 pipe jackings were completed in October 2018. The actual jacking sequence of the jacking pipe group was determined according to experience and the site environment and equipment. As shown in Fig. 4, numbers in the figure represent the pipe jacking order. At the site, a surface subsidence monitoring cross section is set up every 5-6 meters, with 17 rows, and 5 monitoring points are evenly distributed in each section. Figure 5 shows the surface deformation curves of the five monitoring longitudinal sections after the construction of the pipe-roof. It can be seen from the figure that the formation has a large uplift deformation, with a maximum value up to 15cm. The main reason is that the buried depth of the pipe curtain is shallow, and the squeezing effect of the pipe jacking is more serious.
In order to invert the stress release ratio, the excavation of pipe jacking group is simulated according to the actual construction sequence, and monitoring points are arranged in the same position. By adjusting the stress release ratio, the calculated results of surface deformation fall within the 95% confidence interval of the mean value of the measured data, and it can be considered that the stress release ratio is consistent with the actual project. It can be seen from Fig. 5 that the front end of the pipes (monitoring cross-section number 1 to 6) is less deformed and the data is more concentrated. The excavation stress release rate is calibrated based on the measured data of the part, and the model is more accurate.

After repeated trial calculation, when the stress release rate is 11%, the model's vertical displacement calculation results fall within the 95% confidence interval, as shown in Fig. 6. It indicates that the calculated results of the numerical model are in good agreement with the measured data, so the stress release ratio is set as 11%. It can be seen that the stress release ratio caused by pipe jacking is very small, which reflects the advantages of mechanization.
4. Optimization of pipe groups' jacking sequence

After several calculations, it is found that if all steel pipes are jacked in at the same time or several pipe groups are constructed at the same time, the surface deformation will be too large. The less the number of steel tubes jacked together, the smaller the deformation will be. If every pipe is taken as a unit and total 52 pipes are arranged by the regulation of permutation and combinations ($A_{52}^{52}$), the workload is too heavy. Therefore, the optimal sequence within each pipe group is determined by taking every group as the unit, and then the sequence between each group is studied. The overall workload is greatly reduced, and the results are more reliable.

4.1. Jacking order of each pipe group

4.1.1. Jacking order of pipe groups S&D

Although the pipe groups S and D differ in the number, diameter and position of the tube curtains, the arrangement is horizontal, so the research methods are consistent. Considering the possible jacking order, calculating in turn, comparing the results, and selecting the optimal construction order. As shown in Fig. 7, taking 8 pipes as an example, the numbers in the figure represent the order of jacking, and 8 different construction sequences are considered from 1 to 8.

![Figure 7. Different jacking orders of pipe-roof groups S&D](image)

Table 2. Deformation statistics of pipe-roof groups S&D

| Orders | S       | D       |
|--------|---------|---------|
|        | Total deformation/mm | Standard deviation of deformation $\times 10^{-5}$ | Total deformation/mm | Standard deviation of deformation $\times 10^{-5}$ |
| 1      | 191     | 11.5    | -110   | 7.5     |
| 2      | 271     | 21.9    | -80    | 8.5     |
| 3      | 200     | 12.2    | -104   | 7.7     |
| 4      | 198     | 12.4    | -97    | 5.3     |
| 5      | 197     | 12.7    | -113   | 7.5     |
| 6      | 209     | 13.4    | -113   | 8.1     |
| 7      | 200     | 12.5    | -115   | 5.4     |
| 8      | 196     | 11.7    | -105   | 5.7     |

After calculating and comparing the images and various data indicators, it is found that although the configuration of the two groups is similar, the optimal jacking sequence is different due to the difference
in position and diameter. It can be seen from Table 2 that for the pipe group S, the total surface deformation amount and the deformation standard deviation caused by the jacking sequence ① are the smallest; for the pipe group D, the total surface deformation amount and the deformation standard deviation caused by the jacking sequence ⑦ are the smallest. Therefore, the optimal jacking sequence of groups S and D are ① and ⑦, respectively.

4.1.2. Jacking order of pipe groups G&Z&Y The pipe group G and groups Z & Y are all arranged vertically in two columns, so simulation methods of them are similar. As shown in Fig. 8, the numbers in the figure represent the order of jacking, and 8 different construction sequences are considered from 1 to 8. Because the two columns of group G are close to each other, they are considered together. The pipe groups Z and Y are far apart, so the order within each group is considered first. After several calculations, it is found that the surface deformation is the smallest when pipes of each group are jacked upward successively from the bottom to the top. If pipe groups Z and Y are combined for consideration, 8 different jacking orders are also simulated according to Fig.8, and it is found that the optimal jacking order is ③, which is consistent with the conclusion of separate simulation of two groups.

![Figure 8. Different jacking order of pipe-roof groups G&Z&Y](image)

4.2. Inner and outer pipe-roof jacking sequence
For the convenience of discussion and description, outer groups S, Z, D, Y and the inner group G (Fig. 2) are simulated separately. The pipe groups S, Z, D, and Y form a rectangular ring. In order to determine the sequence of the outer pipe ring, all possible situations are arranged with permutation and combination theory. Since the whole construction is completely symmetrical, the construction sequence of the groups Z and Y does not affect the calculation result. Therefore, there are 12 different jacking sequences of the four groups. To simulate 12 situations above, each group is simulated according to the optimal sequence obtained in Section 4.1, and the calculated results were shown in Fig 9. It can be seen from Fig. 9 that the main controlling factor affecting the surface deformation is the sequence of group D and group S. If group D is constructed before S, the surface deformation is significantly reduced. Six groups of data in this order are selected, and the total deformation amount and deformation standard difference of each group are compared. It is found that the indexes of the jacking order D-Z-Y-S is the smallest. Obviously, this is the optimal construction sequence of the pipe-roof.
After determining the jacking sequence of the outer ring, the construction order of the inner group G and the outer ring is discussed. There are two cases, respectively for simulation and comparison. The results show that the surface deformation is smaller when the outer pipe ring is jacked before group G.

4.3. Optimal jacking sequence of the whole pipe-roof

According to the above analysis, when the jacking sequence of the pipe group is D-Z-Y-S-G, and each pipe group is constructed in accordance with the optimal sequence within the group determined in Section 4.1, the surface deformation is minimal. Fig. 10 shows the optimal jacking sequence of the whole pipe-roof. Fig. 11 compares the surface deformation produced by the calculated optimal sequence with the actual construction sequence. As can be seen from the figure, after optimization, the total surface deformation is reduced by 12%, the maximum deformation is reduced by 11.5%, and the standard deviation of the deformation is greatly reduced. It indicates that the surface deformation is more stable, and the optimization goal has been achieved.

Figure 9. Simulation results of jacking order of lateral pipe-roof

![Simulation results of jacking order of lateral pipe-roof](image)

Figure 10. Jacking order of pipe-roof after optimization

![Jacking order of pipe-roof after optimization](image)
5. Conclusions and suggestions

1) The jacking sequence of the pipe-roof has a great influence on the formation deformation around the metro station. Numerical simulation calculation is an effective method to optimize the construction process, and the excavation stress release ratio is a key parameter of the numerical model. Based on the comparison between the actual monitoring data and the numerical simulation results, the excavation stress release ratio of the pipe-roof jacking in the saturated soft soil layer is determined, which provides a reference for similar projects in this type of stratum in the future.

2) This paper provides a set of analysis methods for the construction sequence of pipes jacking in metro stations. It uses the methods of comparative analysis and enumeration to consider various possibilities, finds the key factors affecting the surface deformation, and finally optimizes the construction plan. This approach simplifies the analysis step and greatly improves the optimization efficiency. The analysis shows that the jacking sequence of horizontal pipe groups is the decisive factor of the degree of construction disturbance, and jacking horizontal pipe group at the bottom preferentially will obviously reduce the surface deformation.

3) Different types of pipes’ sets have different optimal jacking construction schemes. The optimal scheme for the horizontal pipe group below is from the middle to the left and right sides alternately. The optimal scheme for the upper horizontal pipe group is to construct from left to right in turn. The optimal sequence of vertical pipe groups on both sides is to construct from bottom to top successively and the optimal scheme for the internal pipe group is to construct the entire column at one time.

4) The optimization sequence is the result of simulation under the ideal conditions without considering sites and equipment. In actual projects, the final construction plans need to be determined by integrating manpower, material resources and time limit. At the same time, different geological conditions, pipe diameters and buried depths will also affect the choice of construction sequence, so targeted simulation analyses are needed.

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