Study on the Mechanical Properties of Large Rectangular and Shallow Embedded Pipe-Jacking During Pushing-Process

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Abstract. With the continuous increase of urban population, the development degree of urban underground space is increasing, and the pipe jacking method has been widely used in the construction of urban underground space. This paper analyzes the disturbance mechanism of the pipe jacking construction on the surrounding soil, and analyzes the actual results of the surface subsidence in the rectangular pipe jacking project of Baima Road in Fuzhou Baolong Wanxiang Square and the civil defense project. By combining the three-dimensional finite element model, the law of ground surface settlement and deformation during the construction of shallow-buried large-section pipe jacking under the conditions of coastal stratum is studied. And through the on-site monitoring settlement data of the project and the finite element simulation, the ground surface subsidence deformation law and the pipe-tube stress variation law of the shallow-buried large-section pipe jacking under the coastal stratum are mastered, which can be used for the design and construction of related similar projects for reference in the future.

1. Introduction
At present, with the development of underground engineering, the scale and section of pipe jacking projects are gradually increasing, and showing expansive tendency in the future. Compared with other underground trenchless construction technologies, the large section rectangular pipe jacking method has the unique advantages of trenchless construction, less environmental impact, low comprehensive cost and high construction safety. Since April 1999, a 3.8 m×3.8 m rectangular cutter-head earth pressure balanced pipe jacking machine which is manufactured by Shanghai Tunnel Construction Technology Research Institute has been used for the first time in the rectangular passage at the entrance and exit of a station on No.3 Shanghai metro, it indicates that pipe jacking technology will be widely used in China. Compared with the original circular pipe jacking, rectangular pipe jacking has many advantages, such as larger area and higher efficiency. Scholars at home and abroad have done a lot of research and Discussion on the mechanical mechanism of pipe jacking construction, using theoretical analysis [2-6], model test [7-10], field measurement [11-13] and other methods. During pipe jacking construction, unloading arch can not be formed on top of pipe, which is unstable underground load, easy to arise ground surface subsidence and destroy road surface [14]. Therefore, it is of great significance to study the mechanical characteristics of pipe jacking. This paper relies on the rectangular pipe jacking project under Baima Road of Fuzhou Baolong Wanxiang Square in peacetime and wartime combined with civil defense project. Compared with the common pipe jacking project in...
the past, this project has the characteristics of complex coastal soft soil environment, shallow burial depth and large cross-section. It is a very characteristic project at home and abroad, and has very high research significance. On the basis of numerical simulation, the disturbance process of soil during jacking is simulated, and then the settlement data on both sides of the project are compared. The ground surface settlement law during jacking construction under this working condition is summarized, which has reference significance for similar projects in the future.

2. Project overview

2.1. General situation of engineering
This engineering is a large-scale underground space civil defense project combined with peacetime and wartime. It is situated underground in the core position of Fuzhou Marlboro Business Circle. It covers an area of 82,000 square meters and has a total building area of about 190,000 square meters. The ground is a commercial landscape square and urban road, including East-West Industrial Road (West Second Ring Road to White Road), north-south West Second Ring Road and Vientiane City Square, Baolong Square and Suning Square. It is surrounded by large commercial buildings and rail transit stations that have been built and are under construction. The main sites are roadways, pedestrian roads, and squares, which are not enclosed. The site is relatively flat, the undulation of the site is small, and the overall is relatively flat and open.

2.2. Engineering geological conditions
The upper Quaternary artificial accumulation soil, silt layer and underlying granite weathering layer in this interval. The main soil layers are miscellaneous fill, silt, medium sand, silty clay, soft rock and strong weathered granite. The highest groundwater level of the site is 5.8m in recent 3-5 years. The minimum cover depth of pipe jacking is 2.5m and the maximum cover depth is 6.0m.

2.3. Key and difficult points in engineering
In this project, the depth of pipe jacking is shallow, and the minimum overlying soil of box culvert at the outlet of pipe head is 2.5 meters, and because the box culvert is 9.26 meters high, the phenomenon of "head up" is easy to occur. And the total jacking force of pipe jacking in this project is expected to reach 23000kN. The reinforced foundation and anchorage balance system are adopted, which is different from the previous working mode of the working well and its back wall. Therefore, it is a difficult pipe jacking project for the current environment and geology.

In the process of pipe jacking construction, the soil around the pipeline is disturbed. Even when the soil deformation exceeds a certain range, it will seriously endanger the safety of adjacent buildings, foundations, pavement and underground pipelines, and cause a series of environmental and geotechnical problems. Studying the law of soil mechanics distribution and settlement deformation around pipe jacking is of great significance for minimizing the environmental impact around pipe jacking construction team and ensuring the smooth completion of pipe jacking construction, as well as for the construction of similar projects in the future.

3. Mechanical characteristics during the whole pushing-process

3.1. Establishment of three-dimensional models and assumptions
In order to analyze the mechanical characteristics of pipe jacking construction and study the characteristics of surface settlement and deformation during construction, the finite element analysis software ABAQUS is used to analyze and summarize the law of soil deformation caused by pipe jacking construction by establishing model and setting parameters. The model size is 80 ×47.25 ×50 (length ×width ×height), model nodes are 32016, unit number is 34932, jacking starting plane of pipe jacking is x-z plane pipe jacking direction is Y axis positive direction, Z axis negative direction is depth direction, jacking direction is shown in Figure 1. The parameters of the soil layer are set by the
actual parameters of the site. Detailed parameters of the soil layer are shown in Table 1. According to the incremental plasticity theory, the Drucker-Prager criterion is used to analyze the soil, and the solid unit simulation is used to simulate the precast pipe jacking.

| Item                      | Bulk density (kN*m$^{-3}$) | Yong's modulus (MPa) | Poisson's ratio | Internal friction Angle (°) | Cohesive force (kPa) |
|---------------------------|-----------------------------|----------------------|----------------|----------------------------|----------------------|
| Prefabricated pipe jacking| 27                          | 3.54×10$^4$         | 0.2            | —                          | —                    |
| Pipe-jacking machine      | 78                          | 2.07×10$^5$         | 0.2            | —                          | —                    |
| Miscellaneous fill        | 17                          | 15                   | 0.35           | 10                         | 10                   |
| Silt                      | 15.9                        | 10.5                 | 0.38           | 5.4                        | 10.9                 |
| Medium sand               | 18                          | 30                   | 0.27           | 20                         | 3                    |
| Silty clay                | 16.9                        | 15.5                 | 0.39           | 4.1                        | 13.6                 |

Before calculation and analysis, some necessary assumptions are adopted: (1) In the course of jacking, the front thrust of super-shallow pipe jacking is set as rectangular uniform load. (2) Considering only the additional deformation stress of the soil layer, the calculation does not consider that the deformation caused by the self-weight of the soil has already been settled after construction. (3) In the course of pipe jacking, only the change of jacking space distance is considered, and the time effect of soil is not considered. (4) The upper surface of the model is the surface of the earth, which is a free interface; the side and bottom of the model are set as unique boundaries, which restrict the horizontal movement of the side and the vertical movement of the side. (5) The excavation simulation is carried out by "killing" the soil elements that need to be excavated in the direction of pipe jacking. (6) In the pipe jacking construction of this project, the reinforced foundation and anchorage balance system are adopted. The jack's jacking force is constantly changing in the jacking process. It is difficult to solve this problem by using finite element simulation analysis. In this paper, the displacement penetration method is used to exert load, and the jacking process of pipe jacking is simulated by applying displacement to pipe jacking.

3.2. Analysis of model result

3.2.1. Analysis of ground surface settlement results
According to the layout rules of settlement monitoring points, the measuring points within 20 meters on both sides of pipe jacking central axis are selected for analysis. The monitoring section is selected at the position x=13m from the beginning of pipe jacking. The horizontal coordinates indicate the
distance between the two sides of the pipe jacking central axis, the vertical coordinates indicate the ground surface settlement, and the L represents the jacking distance of the pipe jacking machine.

Fig. 3 shows the ground surface settlement at the section x=13 m when the pipe jacking head does not pass through the section x = 13 m. It can be seen that when the head of pipe jacking machine just jacked into the soil, there was a slight uplift on the surface of the soil. With the continuous jacking of pipe jacking, the earth pressure in front of the pipe jacking is increasing, resulting in the "squeezing effect". When the pipe jacking head is closer to the x=13 m section, the squeezing earth pressure becomes larger and the uplift of the surface becomes larger. It can be seen from the figure that when pipe jacking is 3 m, the maximum uplift of the surface is only 2.19 mm, but the maximum uplift of the machine head is 7.85 mm when it reaches 13. The maximum uplift of the surface is located at the central axis of pipe jacking.

Fig. 4 shows the ground surface settlement at the section x=13m when the pipe jacking head passes through the section x=13 m. From the figure, it can be seen that the settlement curve of the monitoring point of the transverse section presents a normal distribution gathered around the central axis above the pipe jacking, and the maximum settlement is above the central axis of the pipe jacking. With the increase of jacking distance of pipe jacking, the distance between excavation section and monitoring section is farther and farther, and the maximum cumulative settlement value is also increasing. When the jacking distance is 15mm, the maximum surface settlement is 7.05 mm; when the jacking is completed, the maximum ground surface settlement is 18.61mm. The lateral influence range of ground surface settlement is 2B (B is the width of pipe jacking). The settlement value of the axis of pipe jacking accounts for more than 90% of the total settlement. After the pipe jacking machine passes through the section x=13m, the ground surface settlement continues to increase. This is due to jacking.
with pipe jacking, the gap between pipe jacking head and pipe jacking body, and the convergence of soil due to stress relaxation. The grouting fluid should be added reasonably to increase the strength of soil, slow down the settlement and stabilize the settlement.

Fig. 5 shows the trend of uplift and settlement of the point on the central axis of pipe jacking along the jacking distance at x=13m section. In the jacking process, the general trend of the points on the central axis of pipe jacking is to rise first with the gradual jacking of pipe jacking, then settle after the pipe jacking passes, and the settlement rate gradually slows down with the further jacking.

3.2.2. Stress analysis of pipe jacking

Fig. 6 and Fig. 7 show the variation of the maximum principal stress of the upper and left axes of pipe jacking joint with the jacking process under the five sections of y=5 m, y=10 m, y=15 m, y=20 m and y=25 m. It can be seen from the figure that the variation law of the five sections is basically the same. When pipe jacking is just jacked in, the maximum principal stress increases rapidly. With the gradual jacking of pipe joints, the growth rate of maximum principal stress decreases gradually, but also increases slowly. By the end of jacking, the maximum principal stress on the upper side reaches about 950kPa, while the maximum principal stress on the left side reaches 1020kPa. The maximum principal stress on the side of pipe jacking is slightly larger than that on the top side of pipe jacking.

4. Analysis of on-site monitoring

4.1. Layout of settlement monitoring

The top of the pipe jacking construction area is Baima Road. Because the project is located in the core circle of Fuzhou Marlboro Merchants, the traffic volume is large and the population flow is intensive, the surface uplift or settlement should be paid special attention to in the construction process. Therefore, the settlement monitoring network points are arranged near the surface of the pipe jacking construction area, and theodolite is used as the testing instrument. The monitoring points are mainly located on the pipe jacking axis and between and on both sides of the pipe jacking. The layout of the monitoring points is shown in Figure 8.

The monitoring points are mainly located on both sides of the pipe jacking route and above the axis. There are 30 measuring points. The distance between D1 and D10 measuring points is 3m from the starting position of pipe jacking. The distance between the other monitoring points is about 5m, and the number of monitoring points is D1-D30. Two rows and two rows of measuring points are arranged. There are two rows of transverse measuring points at 13m and 28m from the starting position. There are two rows of longitudinal measuring points directly above the central axes of the two pipe jacking. (The lower side is the first tube, and the upper side is the second tube.)
4.2. Analysis of monitoring settlement data

Fig 9 and Fig 10 show the vertical ground surface settlement of two rows of transverse measuring points at the starting position of 13m and 28m during the jacking of pipes. The abscissa of the chart indicates the time course of pipe jacking, the longitudinal coordinate represents the vertical settlement value of the surface, the positive value represents the uplift, and the negative value represents the settlement.

![Figure 8. Ground settlement measurement point layout](image)

4.3. Analysis of monitoring data of surface settlement

The monitoring data are compared with the numerical simulation of the ground surface lateral settlement curve. As shown in Fig. 11 and Fig. 12 below, the contrast maps of ground surface settlement at the position x=13m of section are selected when jacking the pipe jacking machine into 13m and 15m respectively.

![Figure 9. Curve of settlement of section x=13m](image)  
![Figure 10. Curve of settlement of section x=28m](image)
Fig. 11 shows that when pipe jacking is 13m in depth, the ground surface presents uplifting trend. The maximum uplift value above the central axis of pipe jacking is 7.85mm, and the field monitoring data is 7.29mm. Fig. 12 shows that when jacking pipe into 15mm, the ground surface shows a sinking trend. The settlement value of the measuring point directly above the central axis of pipe jacking is the largest, the simulated value is -7.05mm, and the measured value is -17.85mm. The settlement curve on the section presents a normal distribution. The measured curve and the numerical simulation curve are approximately the same, but the field monitoring data will be larger than the numerical simulation data. The main reasons for this phenomenon are: (1) Simplifying the soil layer in numerical simulation, the parameters of simulated soil layer will be a little different from those of field soil layer; (2) In the process of field pipe jacking construction, there are still vehicles passing through the surface, which will generate certain vehicle loads, resulting in the ground surface settlement of the measured surface is larger than the calculated value of the model.

5. Conclusions
In order to better guide the construction of pipe jacking in the coastal layer in the future, this paper carries out numerical simulation by three-dimensional numerical simulation method, and proves the validity of the model by comparing the field measured data, and draws the following conclusions.

(1) The settlement curve of the monitoring point of the transverse section shows a normal distribution gathered around the central axis above the pipe jacking. The maximum settlement is above the central axis of pipe jacking, and the ground surface settlement increases with the distance of the monitoring section from the excavation section. The main influencing area of jacking construction is within the upper central axis of pipe jacking (±10m), and the volume of settlement trough is almost within this range. The surface subsidence is small in the range of (±10m) away from the axis, so it can be considered that this area is not within the influence range of pipe jacking.

(2) In the jacking process of pipe jacking, the general trend of the points on the central axis of pipe jacking is that they rise first with the gradual jacking of pipe jacking, and begin to settle after the pipe jacking passes, and the settlement rate gradually slows down with the depth of pipe jacking.

(3) When pipe jacking is just jacked in, the maximum principal stress increases rapidly. The growth rate of the maximum principal stress decreases with the gradual jacking of the pipe, but the stress increases gradually until the pipe jacking is completed. The maximum principal stress at the side of pipe jacking is greater than that at the top of pipe jacking.

(4) The measured data of the building site show that the soil mass begins to rise about 4-10m away from pipe jacking, and the point on the axis of pipe jacking is most disturbed by pipe jacking. When jacking pipe into soil, the disturbance range is about 10m.

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