Simulation analysis of a shallow-covered large cross-section rectangular pipe-jacking crossing highway

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Abstract: In this paper, based on a large cross-section shallow overburden rectangular pipe jacking project, using numerical simulation method to analyze the impact of pipe jacking construction on the highway, taking into account the positive jacking force of pipe jacking machine head on the soil, grouting pressure of slurry sleeve, setting of isolation steel pipe concrete curtain, friction-reducing slurry sleeve and other factors. The main conclusions are as follows: (1) the front jacking force is between the theoretical Rankine active earth pressure and the Rankine passive earth pressure. With the increase of jacking force, the road surface appears different degrees of uplift. When the jacking force is set between the active earth pressure and the static earth pressure, the uplift rate is the largest. In order to facilitate the construction control, it is suggested to control according to the theoretical static earth pressure; (2) the theoretical grouting control pressure The top of the pipe jacking is taken as the overlying water and soil pressure at the top of the mud jacket, and the bottom of the pipe jacking is taken as the sum of the overlying water and soil pressure and the hydro-static pressure of the mud sleeve. Based on the analysis of 0.8 times, 1.0 times and 1.2 times control grouting pressure, with the increase of grouting control pressure, the pavement heave gradually increases. It is recommended to adopt 0.8 times theoretical grouting pressure to ensure the thickness of the slurry sleeve meets the requirements and reduce the impact on the pavement; (3) setting concrete-filled steel tube curtain or anti friction slurry sleeve can reduce the impact of pipe jacking construction. When the steel pipe curtain has been set up, there is no obvious back soil effect without the anti friction mud sleeve.

0 Introduction

In comparison with circular pipe jacking, rectangular pipe jacking features high space utilization, and has been increasingly applied in engineering in recent years. Both domestic and foreign scholars have carried out extensive research on the jacking thrust, friction resistance and friction reduction measures for pipe jacking construction, and have achieved certain results. As the pipe jacking section becomes
increasingly large, the environment around the construction is also increasingly complex, so the research on enhancing the post-work settlement of pipe jacking under deep overburden conditions and the back soil influence under shallow overburden conditions is the key to reduce the influence of large section rectangular pipe jacking project on the surroundings.

Gao Yi et al. investigated the overall damage process of the soil directly above the rectangular pipe by combining field tests of shallow overburden excavation and presented the concept of "overall back soil influence", damage mode and theoretical calculation formula. According to them, the back soil influence is mainly generated by the thickness of the overburden, the frictional resistance between the pipe and the soil, and the strength index of the soil. Dou Xiaotian et al. combined the overall soil backing theory with a shallow buried rectangular pipe jacking project in an underground car park and conducted an analysis of the causes from the actual overall soil backing phenomenon. Moreover, it showed that the "back soil influence" is influentially mitigated by reducing the friction factor of the pipe and soil. Based on the rectangular pipe jacking project under Baima Road in Fuzhou, Chen Yuexiang presented the control measures and methods for soil disturbance during rectangular pipe jacking construction by adopting a combination of indoor tests, finite element simulation and field monitoring. This paper adopts a numerical simulation method to analysis the influence of construction factors on the displacement of the overlying highway pavement for a rectangular pipe jacking construction in a shallow overburden large section in Shanghai, resulting in a number of laws that can be used as a reference for similar projects in soft soil areas.

1 Project Background

1.1 General description of the project

This paper refers to a large section of rectangular pipe jacking construction under a highway project in Shanghai, which is a 55m wide highway.

As the distance between the top of the pipe jacking and the highway shoulder and the surface of the road arch are respectively 3.30m and 3.95m, it is a shallow overburden underpass project, and the pipe jacking is primarily located in the typical silty soil layer of Shanghai with poor soil properties. Inappropriate control of construction parameters may result in the "back soil influence" problem, thereby causing the pipe jacking construction to produce more serious adverse consequences such as cracking and deformation of the highway above. Therefore, a detailed construction plan has been developed before the project to control the influence of pipe jacking on the highway deformation.

1.2 Construction plan

It mainly consists of the design of pipe jacking parameters and protection measures, which specifically refers to the setting of the frontal jacking pressure, the control of the friction resistance of the slurry jacket, the control of the slurry pressure and the setting of the concrete curtain of the isolated steel pipe.

1.2.1 Frontal jacking pressure setting. In this project, earth pressure balancing type pipe jacking machine is applied to balance the soil on the excavation surface by using earth pressure to achieve the purpose of supporting the soil on the excavation surface and controlling the surface settlement. The frontal jacking pressure is calculated using Rankine static earth pressure strength, the top static earth
pressure strength is 51.8kPa, the bottom static earth pressure strength is 178.5kPa. Therefore, the average value of frontal jacking pressure is set at 115kPa.

1.2.2 Grouting friction reduction setting. In the process of jacking, in order to minimize the frictional resistance between the soil and the pipe joint, a reliable mud sleeve is created to reduce the frictional influence around the pipe joint by injecting frictional mud from the grouting hole inside the pipe joint, meanwhile the surrounding disturbed soil also has a certain enrichment influence. In addition, the mud jacket features no water loss, no sedimentation and no consolidation. It is required that the slurry jacket has a frictional resistance of 2–3kPa after preparation.

1.2.3 Isolated steel pipe concrete curtain setting. In order to control the influence of pipe jacking construction on the highway, a steel pipe with a wall thickness of 12mm is used above the position of 30cm above the pipe jacking, which is φ 824@1100. In order to improve the influence of pipe jacking construction on the highway, C25 concrete is used for repressurement of the soil after the completion of the construction of the steel pipe curtain. A gap of 276mm exists among the adjacent steel pipes. A total of 13 steel pipes are set at the top of the rectangular pipe jacking, with a single length of 85m. The top of the steel pipe curtain is approximately 2.18m from the highway shoulder and 2.83m from the highway arch.

1.3 Analysis

In order to investigate the influence of pipe jacking construction on the highway, the finite element calculation model of 11 different working conditions are established as shown in Table 1, and variable parameter analysis is conducted in consideration of 4 most significant factors: (1) The frontal jacking pressure of the pipe jacking machine head on the soil. (2) The grouting pressure of the slurry sleeve. (3) The presence or absence of isolated steel pipe concrete curtain. (4) The presence or absence of frictional resistance of the slurry sleeve.

| Condition number | Frontal top pressure setting | Grouting pressure setting | Isolation pipe curtain | Friction control of mud jacket |
|------------------|------------------------------|--------------------------|------------------------|------------------------------|
| 1                | 1.0                          | 1.0                      | yes                    | yes                          |
| 2                | 0.8                          | 1.0                      | yes                    | yes                          |
| 3                | 1.2                          | 1.0                      | yes                    | yes                          |
| 4                | 1.4                          | 1.0                      | yes                    | yes                          |
| 5                | 1.6                          | 1.0                      | yes                    | yes                          |
| 6                | 1.0                          | 0.8                      | yes                    | yes                          |
| 7                | 1.0                          | 1.2                      | yes                    | yes                          |
| 8                | 1.0                          | 1.0                      | no                     | yes                          |
| 9                | 1.2                          | 1.0                      | no                     | yes                          |
| 10               | 1.0                          | 1.0                      | yes                    | no                           |
| 11               | 1.0                          | 1.0                      | no                     | no                           |

Table 1 Calculation conditions

According to Table 1, condition 1 is the base condition for reference purposes and the frontal jacking pressure used is set at a static soil pressure of 51.2kPa at the top of the pipe jacking machine. The size of the bottom of the pipe jacking machine is 178.5kPa and the size of the static soil pressure...
located between the top and bottom is linearly interpolated by depth, with an average pressure of 114.8kPa. The grouting pressure setting is considered to be 0.1MPa to 0.18MPa based on the overlying ground pressure of the construction plan + 20kPa. The size of the top of the pipe jacking machine is 0.1MPa and the size of the bottom of the pipe jacking machine is 0.18MPa, with an average pressure of 0.14MPa. The average pressure is 0.14MPa. The mud jacket friction resistance for the base case is set at 2kPa.

Conditions 1-5 are used to investigate the influence of the head of the pipe jacking machine on the frontal jacking pressure of the soil. The frontal jacking pressure is set between the active earth pressure (0.8 times the static earth pressure) and the passive earth pressure (1.6 times the static earth pressure), and there are a total of 5 conditions set for 0.8, 1.0, 1.2, 1.4 and 1.6 times the static earth pressure.

Condition 6, condition 1 and condition 7 are used to investigate the influence of grouting pressure settings on the highway, with grouting pressure settings of 0.8 times, 1.0 times and 1.2 times the grouting pressure.

2 Simulation analysis for pipe jacking construction process

2.1 Mechanical analysis method of pipe jacking construction
By using ZSOIL.PC (V2018) software to simulate the process of pipe jacking, the process of pipe jacking adopts the method of "alive and dead" existence function and load function to reflect the disturbance stress path of the whole process of pipe jacking on the surroundings soil. The presence or absence of the presence function is used to 'kill' the unit to simulate the excavation. The application of a slurry sleeve or pipe piece assembly is simulated by replacing the material. The load function is used to simulate the frontal support jacking pressure, the slurry pressure around the pipe wall and the frictional resistance between the pipe wall and the slurry sleeve.

2.2 Calculation model
A total of 14 rings (21m) on both sides of the highway arch are selected as the model for the calculation and analysis (Figure 1). The ground layers are interpolated according to the nearby boreholes, and the pipe jacking is primarily located in the ③ grey silty powdery clay and ④ grey silty clay layers.
Fig. 2 illustrates a perspective view of the model through the road arch section, which is situated above the jacking pipe, with a steel pipe curtain, between the jacking pipe and the road structure.

2.3 Calculation parameters
The soils use a small strain hardened soil HSS model and the soil parameters are shown in Table 2. The slurry jacket, steel pipe curtain, pipe jacking sheet and pavement structure are adopted as linear elastic models. The slurry jacket modulus of elasticity is 4MPa, Poisson's ratio is 0.49. The steel pipe curtain modulus is 30GPa, Poisson's ratio is 0.25. The pipe sheet modulus of elasticity is 30GPa, Poisson's ratio is 0.25. The pavement structure is regarded as a comprehensive modulus of elasticity of 1GPa, Poisson's ratio is 0.25.

2.4 Boundary condition setting
Frontal jacking pressure: It adopts a surface load, which acts vertically on the palm face and varies linearly from the top surface of the palm face to the bottom surface, the pressure value is set as described in the previous working conditions.

Friction between pipe and sleeve: It adopts surface load, which is set to 2kPa when using a friction-absorbing sleeve and 40kPa when not using a friction-absorbing sleeve, which is set to the ultimate frictional resistance of the surrounding soil.

Mud sleeve grouting pressure: It adopts surface load, which acts vertically on the outer surface of the equatorial layer and varies linearly from the top of the palm face to the bottom of the palm face, the size is set as grouting pressure 0.1MPa~0.18MPa, namely the pressure value is 100~180kPa.

Boundary conditions for ring-by-ring jacking are shown in the figure. Among them, the frontal jacking pressure is "killed" as soon as the next ring is excavated, while the grouting pressure of each ring and the lateral friction between the pipe wall and the slurry sleeve remain "active" until the pipe is passed.

3 Simulation results analysis
Eleven working conditions models from the previous section 1.3 have been calculated and the results have been classified and collated. The major contents of the collation are the pavement displacements of the four sections and the displacement field clouds etc.

Figure 5 illustrates the coordinate system, the jacking direction and the cross-sectional convention. Among it, y-direction is the gravity direction, z-direction positive direction is the jacking advance direction (from north to south) and XY-plane is the jacking section direction. A total of 4 sections from S1 to S4 are analysed for pavement displacement statistics, where sections S2 and S3 are located
in the road arch at a distance of 3.5m from the top of the jacking pipe, sections S1 and S4 are located at the boundary position, and the jacking sequence is S4\rightarrow S3\rightarrow S2\rightarrow S1.

**Fig.5** Convention of coordinate, pipe-jacking direction and monitored section

### 3.1 Influence of setting steel pipe curtain

Figure 6(a~d) illustrates the displacement of the pavement in sections S4~S1 respectively, when the jacking pressure is static earth pressure, and when the steel pipe curtain is set and no steel pipe curtain is set.

![Figure 6(a~d)](image)

**Fig.6** Vertical displacement with different grouting pressures at S1~S4 four sections

Figure 7 (a~d) illustrates the displacement of the pavement in sections S1~S4 when the jacking pressure is 1.2 times the static earth pressure, with and without the steel pipe curtain respectively.

![Figure 7(a~d)](image)
3.2 Influence of the friction-absorbing mud jacket

In order to investigate the influence of the back soil effect of the friction-resistant mud sleeve, two conditions with and without the pipe curtain have been analyzed: In the case of the pipe curtain, a comparison between working condition 1 and working condition 10 with and without the friction-resistant mud sleeve has been conducted; In the case without the pipe curtain, a comparison between working condition 8 and working condition 11 with and without the friction-resistant mud sleeve has been conducted.

Figure 8 (a) Back soil displacement cloud along the top pipe jacking axis when the pipe curtain is installed and the friction-resistant mud sleeve is set, with a maximum displacement of 4.3mm.

Figure 8 (b) Back soil displacement cloud along the pipe jacking axis with the pipe screen in place and without the friction-resistant mud sleeve, with a maximum displacement of 20.2mm, though the back soil effect is well attenuated above the pipe screen.

Figure 8 (c) Back soil displacement cloud along the pipe jacking axis without the pipe curtain and with the friction-absorbing mud jacket, with a maximum displacement of 4.3mm.

Figure 8 (d) Back soil displacement cloud along the pipe jacking axis without pipe curtain and without friction-resistant mud sleeve, the maximum displacement is 25mm, the back soil effect is significant.

According to the comparison between Figure 10(a) and Figure 10(c), the back soil effect can be reduced with or without the installation of the pipe curtain.

According to the comparison between Figure 10(a) and Figure 10(b), the back soil effect can be
reduced above the steel pipe curtain without the friction-absorbing mud jacket.

![Figure 8](image)

**Fig.8** Vertical displacement field of surrounding soil at different calculation condition

### 4 Conclusion

This paper is based on a large section of shallow overburden rectangular pipe jacking under a highway project, and uses numerical simulation methods to analyze the influence of pipe jacking construction on the highway, which takes into account the size of the frontal jacking pressure of the head of the pipe jacking machine on the soil, the grouting pressure of the slurry sleeve, the presence or absence of the isolated steel pipe concrete pipe curtain, and the presence or absence of the friction resistance of the slurry sleeve. The major conclusions are obtained as follows:

Set up steel pipe concrete curtain or set up anti-friction mud sleeve to reduce the back soil effect of pipe jacking construction, there are significant effects. When the steel pipe curtain has been set up, without setting up anti-friction mud sleeve, there is no significant back soil effect.

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