Deformation analysis of pipe-jacking process for a large-section shallow-covered project crossing highway

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Abstract: This paper introduces an engineering example of a large cross-section shallow soil covered rectangular pipe jacking of East-West double track crossing expressway. The cross-section size of pipe jacking is 9.90m × 8.15m, the length of single section is 1.5m, the through length of east line and west line is 80m, and the thickness of soil covering is 2.48 ~ 3.13m. In order to reduce the impact of pipe jacking construction on the expressway, measures such as setting of the frontal jacking pressure, the control of the friction resistance of the slurry sleeve, the control of the slurry pressure and the settings of φ 824 × 12@1100 steel pipe concrete curtain. The vertical displacement of the steel pipe curtain and the displacement of the highway pavement was monitored. The results show that the road surface heave is controlled within 3cm: the maximum heave of the north shoulder near the pipe curtain launching shaft is 27.8mm, the heave of the central road arch is 16.2mm ~ 19.1mm, the maximum heave of the south shoulder near the receiving shaft is 12.7mm, and the maximum heave of each section is less than 1.5mm. The position is the axis of pipe jacking machine. From the cross-sections of pipe jacking crossing, the range of transverse influence area of 5mm road uplift is about 2.0 ~ 3.0 times the width of pipe jacking machine, and the range of transverse influence area of 10mm road uplift is 1.0 ~ 2.0 times the width of pipe jacking machine. The monitoring results show that the construction parameters of pipe jacking are reasonable.

0 Introduction

In recent years, due to its high space utilization rate compared with circular pipe jacking, rectangular pipe jacking has been widely used in engineering, and the section of pipe jacking has become increasingly large, and the environment of its application has become relatively complex, especially for projects under existing roads or highways. According to the classification of pipe jacking section size, 3m × 5m is small section, 5m × 9m is medium section, 7m × 11m is large section, 13m × 16m is...
extra large section. Recently, large section and extra large section rectangular pipe jacking project has been developed in engineering practice, and engineering experience of large section rectangular pipe jacking construction has been accumulated progressively.\cite{1-6}

Rong Liang\cite{7} et al. present in detail the settlement control technology for the construction of rectangular pipe jacking machine through Zhengzhou Zhongzhou Avenue project, which has a pipe jacking section of \(10.12m \times 7.52m\) and an overburden thickness of \(3.0\sim4.2m\). It belongs to the large section, shallow overburden rectangular pipe jacking project, the pipe crossing layer is mainly powder layer, using thixotropic mud synchronous grouting and secondary grouting technology, the grouting pressure is \(0.027\sim0.049\)MPa, the final road surface are subsidence, but the settlement volume are within 3cm.

Currently, the largest cross-sectional rectangular pipe jacking project successfully passed for Jiaxing Expressway through South Lake Avenue project, the cross-section reached equipment section size \(14.82m \times 9.446m\), crossing geology for plain fill, powdered clay, silty powdered clay, tunnel overburden thickness \(5.68\sim6.54m\). The specific settlement data has not yet been reflected in the literature.

This paper introduces the construction of a shallow overburden, large section, long distance rectangular pipe jacking tunnel under a highway in Shanghai. In contrast to the above two cases, a steel pipe and concrete pipe curtain has been constructed between the pipe and the motorway prior to the construction of the pipe crossing, which is used to block the impact of the pipe construction on the motorway. Due to the length limitation of this paper, only the analysis of the impact of the eastern line pipe jacking on the overlying motorway is presented.

### 1 Overview of the project

#### 1.1 General information of the project

This project is about a double rectangular pipe jacking project in Shanghai, which involves a large cross-sectional rectangular pipe crossing an operational motorway, with a jacking distance of 445m, currently it is the longest rectangular pipe jacking project. The size of the roof pipe section is \(9.90m \times 8.15m\), where the length of the control protection section through the motorway is 85m, the width of the motorway is 55m. The direction of the roof pipe crossing is nearly perpendicular to the direction of road traffic from north to south. The distance between the top of the roof pipe and the shoulder of the motorway and the road arch are \(3.30m\) and \(3.95m\) respectively, which belongs to the shallow overburden underpass project. Due to the top pipe crossing stratum is located mostly in the Shanghai typical silty soil layer with poor soil properties, if the construction parameters are not properly controlled, it may result in more serious consequences such as cracking and deformation of the highway above. Therefore, a detailed special construction plan is formulated before the project is carried out to control the influence of the pipe jacking construction on the highway deformation.

#### 1.2 Reduce the influence measures and construction parameters setting

In order to control the influence of pipe jacking construction on the upper highway, the project adopts control of pipe jacking parameters and isolation protection measures. Specifically, it refers to the setting of the frontal jacking pressure, the control of the friction resistance of the slurry sleeve, the
control of the slurry pressure and the setting of the isolated steel pipe concrete curtain.

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

1.2.2 Grouting friction reduction setting. During the jacking process, in order to reduce the frictional resistance between the soil and the pipe joint, a reliable mud sleeve is generated around the pipe joint by injecting friction-reducing mud from the grouting hole inside the pipe joint to achieve the friction reduction effect, which also has a certain enrichment result for the surrounding disturbed soil. 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 Grouting pressure setting. Grouting pressure is dependent on the overlying soil and water pressure at the top of the mud jacket. If the grouting pressure is below the overlying soil and water pressure, the soil outside the pipe will collapse towards the gap in the outer wall of the pipe. If the grouting pressure is above the overlying soil and water pressure, it will lead to ground uplift. In soft soil areas, if the grouting pressure value is too great, it will also lead to thickening of the mud set, increase of the grouting volume and long duration of soil consolidation after finishing the pipe jacking. Generally, the grouting pressure value is greater than the overlying soil and water pressure value of 20 kPa. the grouting pressure is set to 0.1MPa~0.18MPa considering the change along the depth.

1.2.4 Steel pipe concrete pipe 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 installed above the top 30cm of the pipe jacking, and C25 concrete is adopted to fill the pipe curtain after the construction of the pipe curtain is completed, which forms a pipe concrete curtain and reinforces the soil to improve the influence of pipe jacking construction on the highway. The gap between adjacent steel pipes is 276mm. There are 13 steel pipes on top of the rectangular pipe jacking with a single length of 85m, and the top of the pipe curtain is about 2.18m from the highway shoulder and 2.83m from the highway arch.

1.3 General status of the construction of the east line pipe jacking

The major mileage of the east line pipe jacking under the protected section of the motorway of this project is X+360m~X+442m, which was advanced from April 26, 2020 to May 16, 2020, with a total time of 20 days, an advance distance of 82m and an average advance speed of 4.1m/day.

2 Monitoring items and arrangement of monitoring points

In order to implement the information construction and strengthen the protection of the highway, the main monitoring items of the pipe jacking section through the highway are the vertical displacement of the road surface and the vertical displacement of the pipe curtain. The east-west line surface vertical displacement monitoring section is illustrated in Figure 1, with 6 sections from S1 to S4, and the pipe
jacking direction is S4→S4'→S3→S2→S1'→S1. Among them, S4' is located on the asphalt shoulder on the north side of the highway. S1' is located on the asphalt shoulder on the south side of the highway. S3 and S2 are located on the highway arch, and S1 and S4 are located on the ground near the corresponding shoulder. There are 21 points in each section with a spacing of 3m between points, and point 1 is located on the east side. East line top pipe axis is located between measurement points 7~8, west line axis is located between measurement points 14~15 (this paper is not analyzed). There are 20 points in the steel pipe curtain arrangement, and they are numbered from 1 to 20. 20 points are located on the north side, and the pipe jacking direction is 20→1.

(a) Highway surface vertical displacement monitoring section
(b) Highway surface vertical displacement monitoring points

Figure 1 Layout of highway vertical displacement monitoring sections and points

3 Analysis of the effect of construction measures
Monitoring of pavement displacements starts as soon as the pipe curtain is constructed. In order to remove the interference of other factors and to study only the influence of pipe jacking on the motorway, the data is processed by deducting the part of the pavement displacement that occurred due to the construction of the pipe curtain before the pipe jacking.

3.1 Analysis of pavement displacement
As can be seen in Figure 3 (a~f), the vertical displacement of the pavement at each monitoring section is shown in the figure, during the jacking of the east line, the pavement basically shows a bulge, the shape of which is similar to an inverted Peck curve. The maximum bulge is located at the axis of the east line pipe jacking, the corresponding measurement point is No. 7. In order to reflect the size of the influence zone of the pipe jacking construction, the 5mm influence zone and the 10mm influence zone of the road surface uplift are defined, and the maximum uplift and lateral influence range are calculated as follows:

S4' section (the ground near the northern shoulder) shows a maximum rise of 30.2mm, located at measurement point S4-7. 5mm influence zone at S4' section has a lateral influence of 36m; 10mm influence zone has a lateral influence of 21m.

S4' section (north shoulder) pavement maximum bulge is 27.8mm, located in S4'-7 measurement point. 5 mm influence area of S4' section lateral influence area is 36m ; 10mm influence zone has a lateral influence of 18m.

S3' section (road arch) shows a maximum rise of 19.1mm, located at S3'-7. The lateral impact
area of the 5mm influence area of S3’s section is 18m laterally; 10mm influence zone has a lateral influence of 12m.

S2’ section (road arch) shows a maximum road surface uplift of 16.2mm at measurement point S2-7. 5mm influence area of S2’ section has a lateral influence area of 30m; 10mm influence area has a lateral influence area of 13.5m.

S1’ section (south shoulder) shows a maximum road surface uplift of 12.7mm, located at S1’-7. S1’ section. 5mm influence area lateral influence area is 27m; 10mm influence area lateral influence area is 12m.

S1’ section (ground surface near the southern shoulder) shows a maximum uplift of 14.6mm, located at S1-7. 5mm influence area of S1’ section has a lateral influence area of 24m; 10mm influence area has a lateral influence area of 10m.

Figure 4 shows the temporal curves of pavement displacement development at the No. 7 point (the largest bulge point on the section) for a total of six sections from S1 to S4 (including S1’ and S4’). As can be seen, from 29 April 2020 to 30 April 2020, the pipe jacking advances to the vicinity of section S4 (mileage X+373m) and displacement changes (displacement changes from 0) begin to occur at section S2/S3 (X+400m to X+405m), which indicates that the longitudinal influence of the eastbound pipe jacking is approximately 27m.

Likewise, from 4 May 2020 to 5 May 2020, S1/S1’ section (X+425m) became displaced (displacement changed from 0), at which time the east line pipe jacking advanced to mileage X+400m, which indicates that the longitudinal influence of the east line pipe jacking is approximately 25m.
Figure 4 Time history of highway surface heave at the maximum heave points

On the basis of the previous pavement displacement analysis, from the perspective of each cross section of the pipe jacking crossing, the size of the transverse impact area where the pavement rises up to 5mm is 18~26m, which is approximately 2.0~3.0D (D is the width of the pipe jacking machine). The size of the transverse influence area where the pavement rises up to 10mm is 10~21m, which is approximately 1.0~2.0D (D is the width of the pipe jacking machine). From the vertical section of the pipe jacking crossing: the maximum influence area during the pipe jacking process is 25~27m from the head to the front of the head, which is 3.0D (D is the width of the pipe jacking machine).

3.2 Analysis of the displacement of the steel pipe and concrete pipe curtain

Figure 5 (a~e) illustrates the development curve of the displacement pattern of the pipe curtain measured by 20 static level measurement points from GM1-1 to GM1-20, during the jacking process of the east line pipe jacking in the section from X=365m to 441.8m. As can be seen, the pipe curtain in the pipe jacking process are manifested as bulging, the maximum amount of bulging is 18.5mm.

It can be seen from the changes in Figure 5(a) to Figure 5(e) that the displacement change pattern of the pipe curtain is similar to wave-like advancement. It specifically demonstrates a displacement pattern of rumbling first and then sinking, and finally (Figure 4.6(e)) the pipe curtain shows a uniform rumbling amount of about 10~15mm along the axis direction of the pipe curtain, which indicates that the steel pipe concrete pipe curtain has a significant influence on controlling the differential deformation of the highway.
Figure 5 Displacement pattern of pipe-roofing heave (example of east line pipe jacking)

3.3 Analysis of frontal earth pressure

Figure 4.6 illustrates the measured frontal earth pressure of the pipe jacking machine, which is based on the construction logs, during the jacking process of the eastern line. The range of the jacking mileage is \(X=360m \sim X=442m\). Therefore, it can be seen that the frontal earth pressure is between 103–123kPa, with an average size of 114.4kPa.

The theoretical calculation of the top of the jacking machine at the S20 road arch is 51.2kPa and the bottom of the jacking machine is 178.5kPa. The static soil pressure between the top and bottom is linearly interpolated by depth and the average pressure is 114.8kPa. Therefore, the measured frontal soil pressure approximates the static soil pressure at the highway road arch.
3.4 Analysis of slurry sleeve friction resistance

Figure 7 illustrates the measured friction between the side wall of the pipe jacking machine or pipe jacking sheet, and the mud sleeve during the jacking process of the east line according to the construction log, the mileage of the jacking is X=360m~X=442m. Therefore, it can be seen that the friction resistance of the mud sleeve is between 1.7~2.76kPa, and the average size is 2.03kPa, which indicates that the mud sleeve has good performance in reducing friction.

4 Conclusions

The paper introduces the construction of an east-west double-lane shallow overburden, large section, long distance rectangular pipe jacking tunnel under a highway in Shanghai. In addition, it provides a detailed description of the relevant construction measures taken to control the deformation of the highway and the setting of the construction technical parameters, and concludes the following based on the analysis of the monitoring data.

1. During the jacking process of the eastern line, the frontal earth pressure of the pipe jacking machine varied between 103~123kPa, with an average size of 114.4kPa, and the measured frontal earth pressure was close to the static earth pressure at the highway road arch.

2. The frictional resistance of the slurry jacket varied from 1.7 to 2.76 kPa, with an average value of 2.03 kPa, and the slurry jacket had a good effect in reducing friction.

3. The steel pipe and concrete pipe curtain plays a significant role in controlling the differential deformation of the highway.

4. The maximum uplift of the northern shoulder is 27.8mm. The uplift at the central road arch of the highway is 16.2mm ~ 19.1mm. The maximum uplift of the southern shoulder is 12.7mm. The location of the maximum uplift of each section is the location of the pipe jacking machine axis. Generally, the influence on the vertical displacement of the highway is within 3cm and the differential deformation is around 1.5cm under all construction parameters, which is effective in controlling the process of pipe jacking in the east line.

Acknowledgments

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