Surface Settlement Analysis of an Ultrashallow Buried Large Span Rectangular Pipe-jacking Tunnel Under a Crossing Expressway

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Abstract

During the construction of a supershallow large-section rectangular pipe jacking tunnel underneath an expressway, due to the repeated disturbance of pipe jacking construction cycle jacking to the stratum and the mutual influence of adjacent tunnels, excessive cumulative deformation of expressway pavement easily occurs, resulting in engineering disasters and safety accidents. Therefore, this paper discusses the settlement deformation law of highway pavement during jacking construction through on-site monitoring and numerical simulation based on the rectangular pipe jacking tunnel project of the Liuye Avenue West Extension. In this case, the research results of surface subsidence can provide a reference for similar engineering construction designs.

Keywords

Shield tunnel; Energy method; Ground settlement; Soil arching effect; Ground loss.

1. Introduction

The high-level development of urbanization has put forward higher requirements for urban transportation infrastructure, and urban underground space development has become an inevitable choice. The underground excavation method is generally used to reduce the impact on the surface environment during the construction of urban tunnels. The underground excavation method includes the shallow excavation method, shield method, pipe jacking method and other trenchless construction methods. Compared with the traditional excavation method, the pipe jacking method can cross obstacles such as roads and buildings on the ground without excavating the ground. In addition, the pipe jacking method does not require large excavation to damage the environment, which can effectively save resources and reduce carbon emissions. Furthermore, the soil cutting of the pipe jacking method is also relatively easy, and the construction control is simple, but the disturbance to the soil will be greater. All kinds of engineering examples show that the pipe jacking process will inevitably produce different degrees of disturbance to the surrounding soil, and it is easy to cause construction safety problems such as excessive jacking force, soil stress concentration[1] and soil deformation overrun[2]. Although rectangular pipe jacking technology is relatively mature, there are relatively few examples and studies on the use of rectangular pipe jacking technology to build underground tunnels or channels of existing expressways under the conditions of large sections and shallow overburden. Therefore, it is urgent to study the series of environmental effects caused by the construction of ultrashallow large-span rectangular pipe jacking tunnels.

Aiming at the problem of surface deformation in the environmental effect of rectangular pipe jacking tunnel construction, many scholars have conducted in-depth research on the causes of rectangular pipe jacking tunnel deformation, mainly including geological conditions [1], tunnel burial depth, tunnel spacing and formation loss and other influencing factors, and formation loss is a key factor in the formation deformation caused by rectangular pipe jacking construction [2-4]. The existing research methods of soil deformation caused by rectangular pipe jacking tunnel construction mainly include the empirical formula method [5], analytical theory method [6], model test method [7], artificial intelligence method [8] and numerical simulation method [9]. Although the numerical simulation method simplifies the complicated construction process to a certain extent, it is difficult to select the model parameters. However, the numerical simulation method not only considers the soil properties and the interaction between the pipe jacking and the soil but also considers the influence of the construction on the surrounding environment, and the reliability of the analysis and prediction of the surface deformation is high. To reduce the disturbance of the rectangular pipe jacking construction process to the stratum and improve the reliability of analysis and prediction, scholars at home and abroad have carried out useful explorations by using numerical simulation methods.[10, 11]

On the basis of fully considering the geological conditions and construction steps, this paper uses the finite element numerical simulation method to simulate the construction process of the supershallow buried large-span rectangular pipe jacking tunnel on the west extension of Liuye Avenue. At the same time, combined with field monitoring data, the formation deformation is compared and studied, and the variation law of surface settlement is discussed to provide a reference for similar projects in the future.

2. Engineering overview

This project is located at the intersection of Changsha with the Zhangjiajie Expressway and Liuye Avenue West Extension Line. The terrain here is low, and the Chang-Zhang Expressway is a high-filled section. The embankment is approximately 20 m high, and the road center elevation is 55.012 m. Therefore, to minimize the impact of construction on the traffic of the Chang-Zhang Expressway, the west extension line of Liuye Avenue adopts two-hole rectangular pipe jacking with a net span of 18.2 m × 6.2 m, jacking through the Chang-Zhang Expressway at an oblique angle of 63.881°.

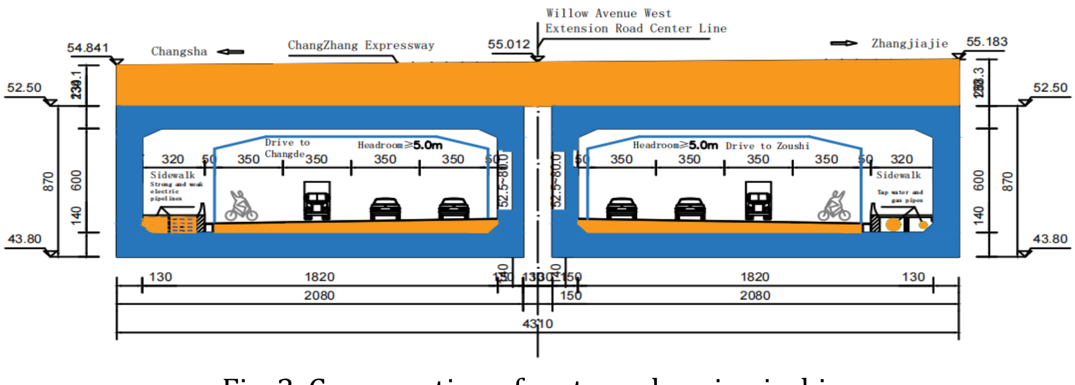


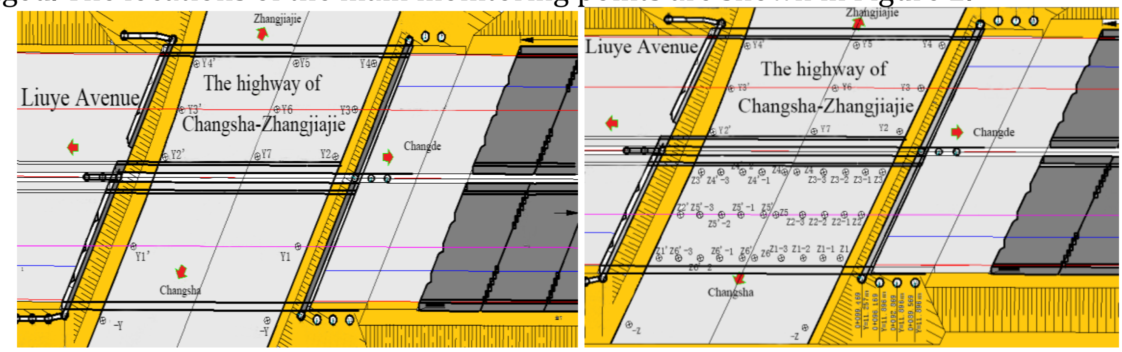
Fig. 3. Cross section of rectangular pipe jacking

To facilitate the jacking operation, the pipe jacking is prefabricated in four sections of 12, 13, 13 and 13 m, and a relay room is set between each section of the pipe jacking. To ensure that the front and rear of the pipe jacking are aligned and connected, positive pins are set on the roof and sidewall of the rectangular pipe jacking. In addition, to minimize the impact on expressway operation, this project adopts the rectangular pipe jacking method, which combines the principle of rectangular pipe jacking and the shield method. In addition, to minimize the impact on highway operation, this project adopts the rectangular pipe jacking method, which combines the principle of rectangular pipe jacking and the shield method. At the same time, to reduce friction, the width of the steel shield is wider than that of the pipe jacking on both sides. The preparation work of this project is basically the same as the general construction of rectangular pipe jacking, including excavation and reinforcement of working pits, back walls, chutes, pipe jacking construction and installation of jacking devices.

3. Deformation analysis

3.1. Monitoring scheme

To ensure that the elevation and midline deviation of the rectangular pipe jacking after the jacking are up to the excellent standard of the standard index and no cracks are not allowed in the jacking construction, very strict construction monitoring and control are carried out during the jacking process, and the measuring points are arranged at the edge of the guardrail of the emergency lane on both sides and the middle separation zone, and 3 ~ 4 test sections are arranged. The locations of the main monitoring points are shown in Figure 2.



a) Left b) Right

Fig. 2. Layout of pavement deformation observation points

3.2. Monitoring data

Analysis of monitoring results The following figure shows the monitoring results and simulation results of the Y2, Y3, Y4, Z1, Z2 and Z3 monitoring points on the highway axis. The above monitoring points are distributed on the edge line of rectangular pipe jacking, and a relatively complete rectangular pipe jacking process can be monitored, which is representative. The following points can be summarized from the figure:

(1) In the jacking process, the settlement value of the right monitoring point is greater than that of the left monitoring point, and the maximum settlement value of the right monitoring point is 78.07 mm.

(2) With the rectangular pipe jacking, the settling volume has experienced three stages of change. The first stage is the slow change in settling volume, the second stage is the rapid increase in settling volume, and the third stage is the gradual decrease in settling volume, which tends to be stable.

(3) According to the correlation analysis between the monitoring value and the simulated value (as shown in Table 1), there is a larger error between the monitoring value and the simulated value, but the trend is roughly consistent. In addition, the fitting degree between the right monitoring value and the simulated value is lower than that between the left monitoring value and the simulated value.

Table 1. Correlation analysis of the monitoring value and analog value of the monitoring point

Monitoring point	Y2	Y3	Y4	Z1	Z2	Z3
Root mean square	10.100	18.931	9.612	11.694	9.651	11.210

Correlation Coefficient	0.797	0.570	0.937	0.839	0.902	0.739
Average error	-27.649	-42.378	-41.624	-31.753	-38.611	-14.559
Average error	-27.649	-42.378	-41.624	-31.753	-38.611	-14.559

3.3. Error analysis

(1) The construction of the left and right pipe jacking is not at the same time, but after the completion of the right first jacking, the left began to jack. Therefore, jacking of the left pipe will inevitably cause a certain degree of soil disturbance to the right, thereby affecting its settlement value. Therefore, the cumulative settlement value of the right monitoring point is greater than that of the left monitoring point. In addition, due to the numerical simulation, some influencing factors, such as grouting parameters in actual construction, are not fully considered, resulting in the fitting degree of the right monitoring value and the simulation value being lower than that of the left. Although the factors affecting soil settlement are not fully considered, the monitoring values and simulation values of the left and right pipe jacking are basically consistent, and the reliability of numerical simulation prediction analysis is high, which has certain guiding significance for similar engineering construction.

(2) Since the construction does not interrupt the traffic of the existing highway, the monitoring points can only be deployed in the emergency lane, resulting in a limited number of monitoring points. Therefore, comprehensive data cannot be obtained. In addition, according to the simulation value, the maximum settlement appears at the edge of the road surface. However, no monitoring points are set up at the road edge.

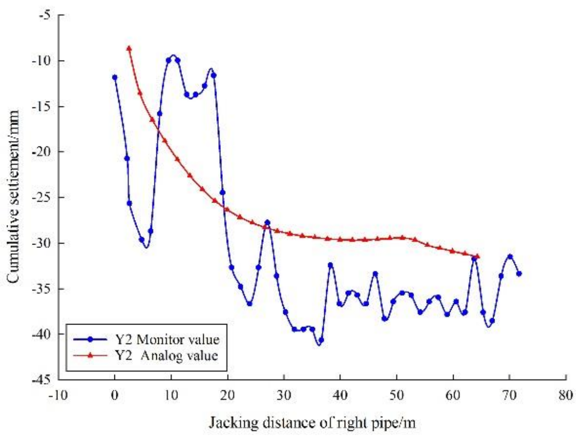


Fig. 3. Comparison of monitoring value and analog value of monitoring point Y2

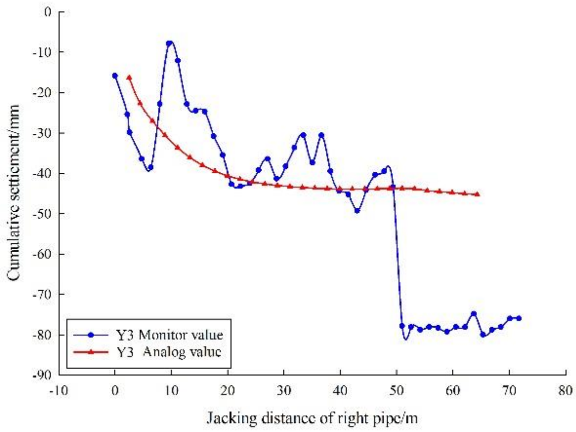


Fig. 4. Comparison of monitoring value and analog value of monitoring point Y3

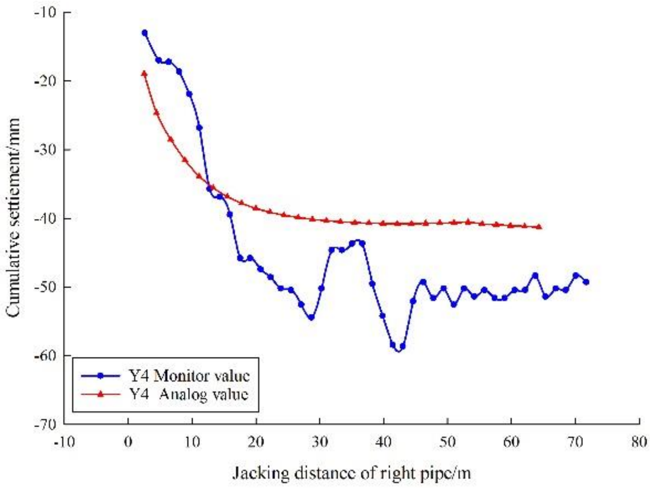


Fig. 5. Comparison of monitoring value and analog value of monitoring point Y4

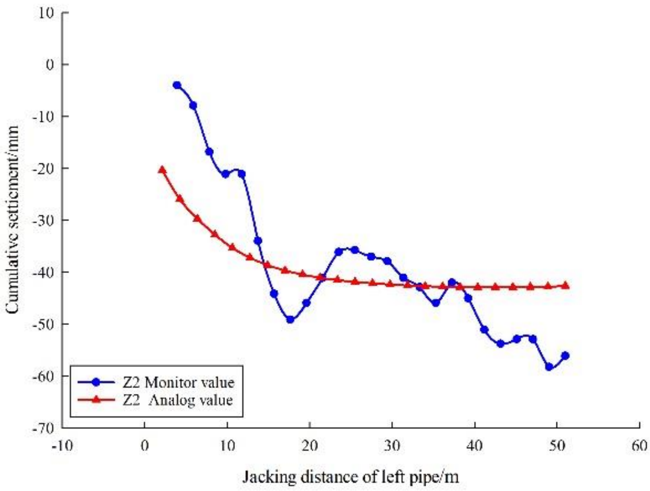


Fig. 6. Comparison of monitoring value and analog value of monitoring point Z1

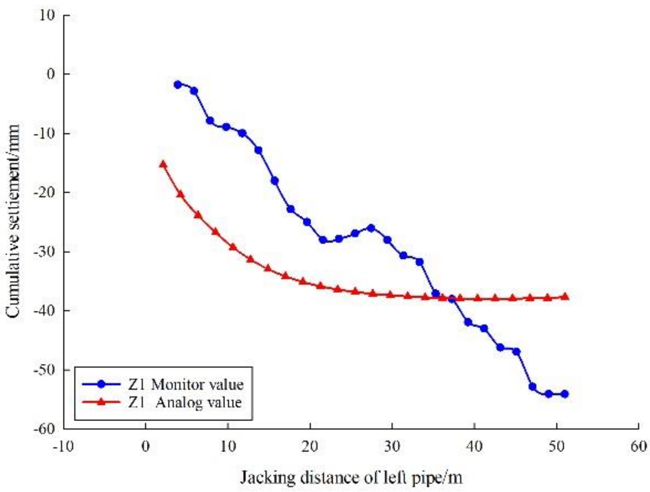


Fig. 7. Comparison of monitoring value and analog value of monitoring point Z2

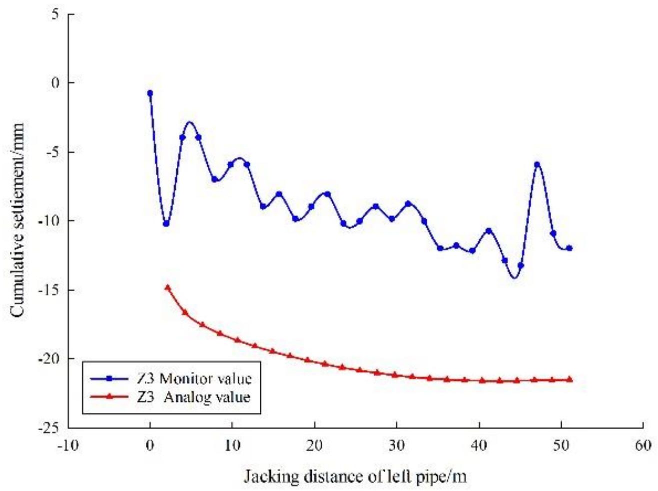


Fig. 8. Comparison of monitoring value and analog value of monitoring point Z3

4. Numerical simulation

4.1. Numerical model

To simulate the complete construction process and further consider the interaction between the soils, the Midas GTS-NX program was used to establish a three-dimensional numerical model of the rectangular pipe jacking process with a longitudinal dimension of 171.85 m, a transverse dimension of 86.2 m, and a vertical dimension of 25.91 m, as shown in Figure 9 below. In addition, since the elastic modulus cannot be directly obtained from the test, the initial elastic modulus of the soil layer and other soil parameters are derived from the design documents and engineering experience. The structural parameters of the pipe jacking and steel shield are obtained from the design documents, as shown in Table 2 and Table 3.

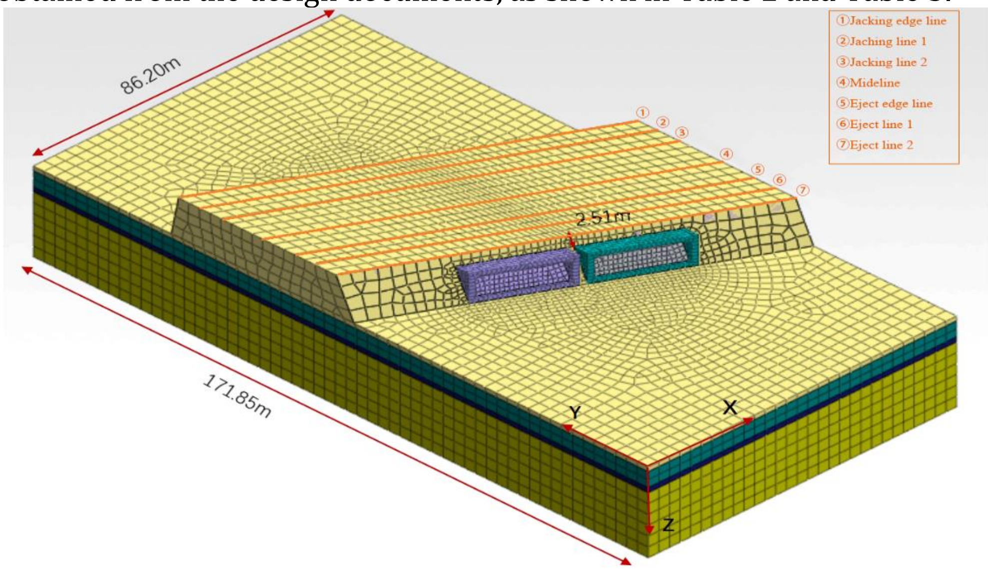


Fig. 9. 3D numerical modelling model diagram

Table 2. Physical parameters of the model soil

Soil	Volumetric weight(kN/m^3)	Elastic modulus (MPa)	Poisson ratio	Cohesion （KPa ）	Angle of internal friction（°）

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Filling	18	100	0.35	25	25
Silty clay	20	24	0.33	23	13
Highly Weathered Argillaceous Siltstone	24	500	0.23	50	30
Decomposed Argillaceous Siltstone	25	4000	0.18	175	35

Table 3. Model structure parameters

Structures	Unit weight (kN/m^3)	Poisson's ratio	Elastic modulus (MPa)
Pipe	25	0.28	32500
Steel shield	78	0.3	20000

4.2. Modelling results

Figs. 11 – 18 show the curves of highway settlement troughs at different jacking stages. In the process of rectangular pipe jacking, the highway pavement gradually sinks, and the highway settlement is concentrated in the area near the entrance. The numerical simulation results show that the vertical displacement settlement trough caused by this project is stable in the range of 30 ~ 40 m on both sides of the axis, and the settlement is small at the central axis. In addition, after 15 m of left pipe jacking, the settlement curve is roughly symmetrical along the coordinate axis, and finally, the vertical deformation tends to be stable.

The maximum settlement of the highway obtained by numerical simulation is 96.25 mm, and it appears on the western edge of the expressway. It can be concluded that the farther away from the entrance, the smaller the settlement. The main reasons for this phenomenon are as follows: (1) The embankment on the entrance side has experienced a complete jacking construction process, including the preparation stage and jacking stage. Therefore, there will be an intermediate settlement value between the starting point and the end point of pipe jacking. (2) At the beginning of jacking, it is difficult for the soil around the pipe jacking to establish a balanced state.

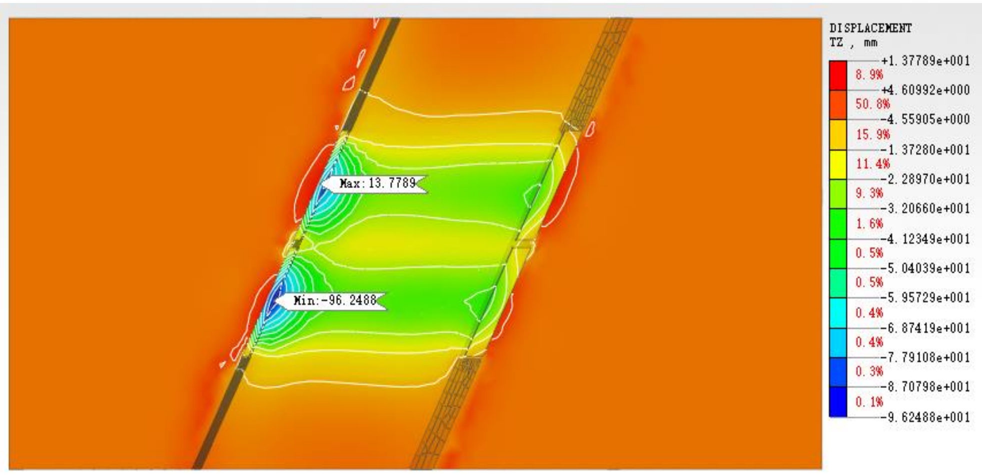

Fig. 10 Vertical displacement cloud diagram

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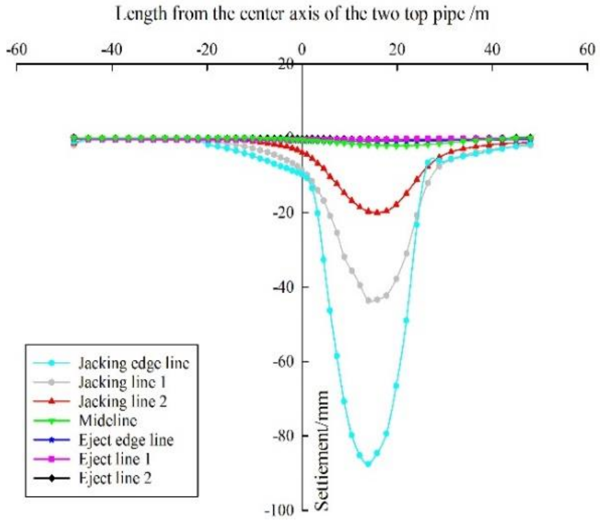

Fig. 11. Settlement diagram of 20 m jacking on the right side

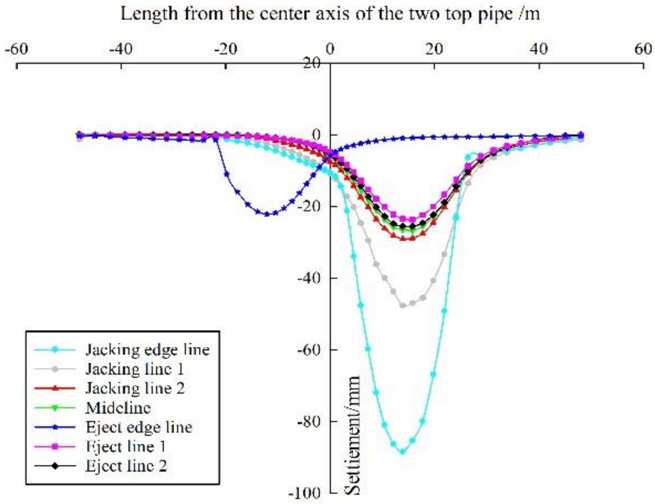

Fig. 12. Settlement diagram of 33 m jacking on the right side

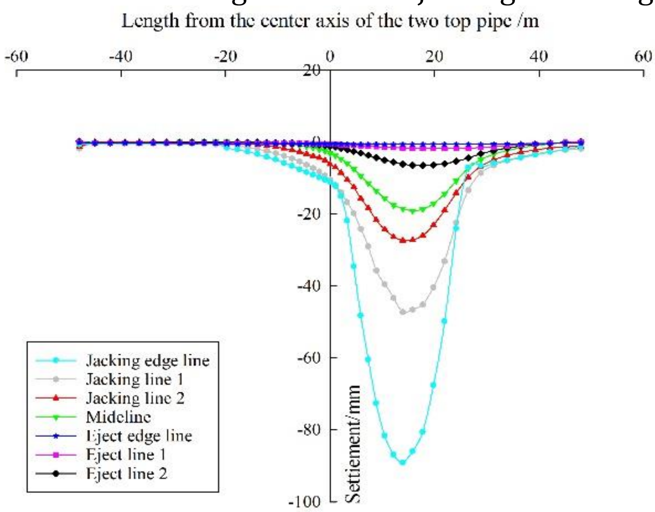

Fig. 13. Settlement diagram of 51 m jacking on the right side

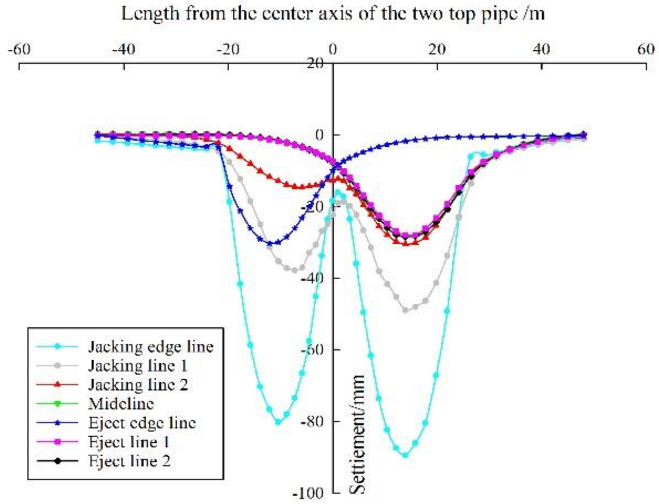

Fig. 14. Settlement diagram of 15 m jacking on the left side

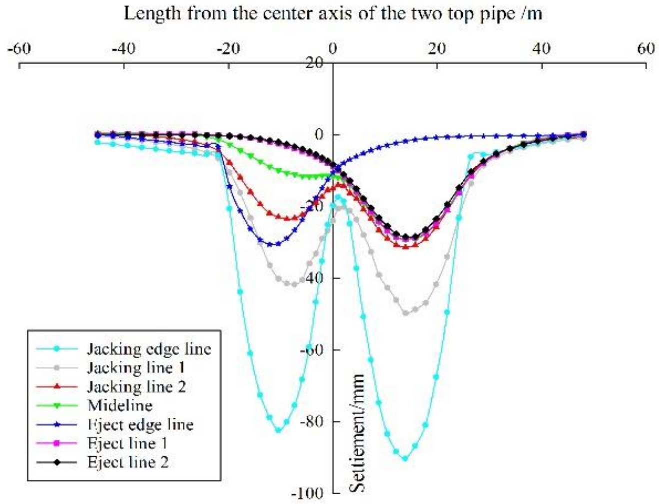

Fig. 15. Settlement diagram of 26 m jacking on the right side

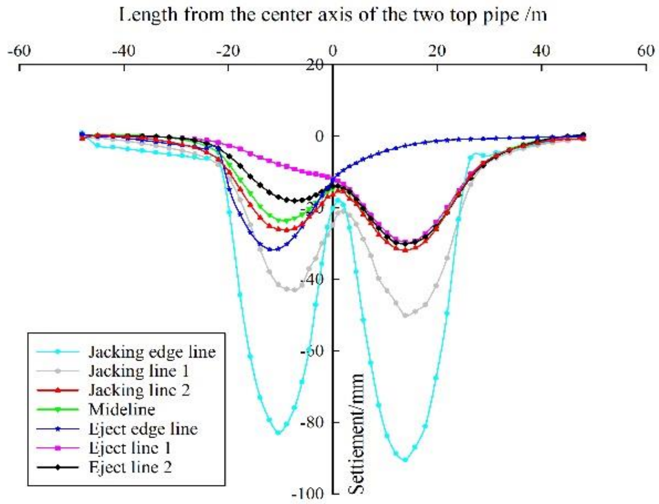

Fig. 16. Settlement diagram of 38 m jacking on the right side

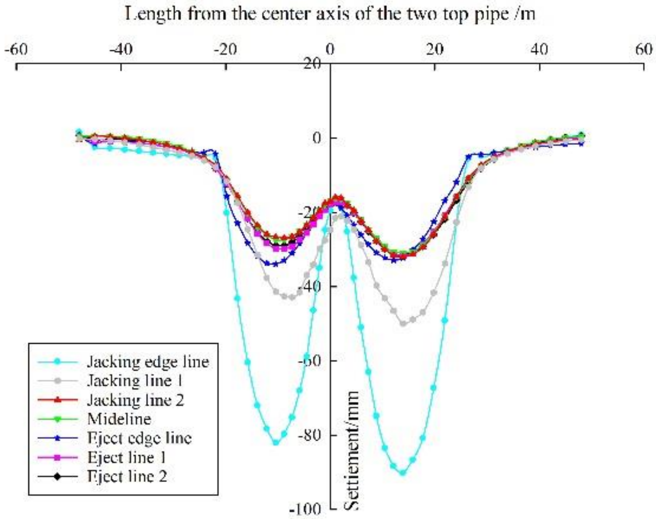

Fig. 17. Settlement diagram of 51 m jacking on the left side

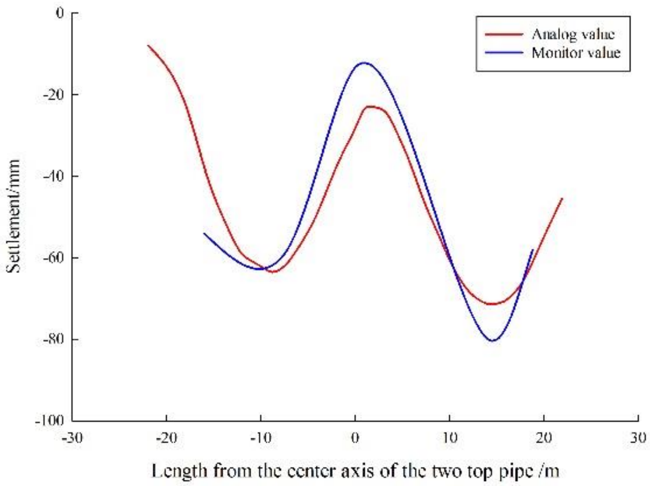

Fig. 18. Comparison between the numerical simulation value and monitoring value

Fig. 18 shows that there are some differences between the monitoring data and the numerical simulation data due to the simplification of the model and the complexity of the actual construction. However, the two settlement trough curves follow the same trend and are close to each other, which indicates that the numerical simulation data can reflect the main characteristics of settlement behavior in engineering practice and have certain guiding significance for similar projects in the future.

5. Conclusion

This paper introduces a project of a supershallow buried double-hole long-span rectangular pipe-jacking tunnel undercrossing an expressway. (total length 51 m, width 42.6 m, height 8.7 m). The construction scheme, monitoring scheme and three-dimensional numerical simulation in the jacking process are discussed in detail. The monitoring results are compared with the numerical simulation results.

(1) The settlement deformation is small during the initial pipe jacking, and the settlement increases sharply at approximately 10 m and then maintains a stable growth level. Until the jacking is approximately 30 m, the settlement velocity decreases, and the settlement tends to be stable.

(2) The vertical displacement at the starting point of pipe jacking is greater than that at the end point. The maximum vertical displacement occurs in the lagging jacking area, and the

settlement trough curve is stable in the range of 30 ~ 40 m on both sides of the axis. In addition, the advance jacking rectangular pipe jacking (right) compared to the latter jacking rectangular pipe jacking (left) on the road caused soil disturbance and greater settlement.

(3) By comparing and analysing the monitoring values and simulated values of vertical displacement and combining the correlation analysis, it can be seen that although there are some errors between the monitoring data and the simulated data, the two settlement trough curves follow the same trend and are close to each other. Therefore, this study has a high reliability in the analysis and prediction of a series of surface subsidence caused by the construction of ultrashallow buried large-span rectangular pipe jacking tunnels, which can provide a reference for the construction design of similar projects.

Acknowledgments

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