Study on the Effect of Parallel Pipe Jacking Spacing on Surface Subsidence Deformation in the Pre-Construction Method of Tube Curtain

Jie Zhang¹,a, Xinyue Zhao¹,b, Yue Li¹–c, Junjie Zhang²,* and Guohui Ren¹,d
¹College of civil engineering and architecture, Shandong University of science and technology, Qingdao 266590, China
²Geotechnical and structural engineering research center, Shandong University, Jinan 250061, China
*Corresponding author e-mail: 27686942@qq.com, ¹1246294617@qq.com,
b478227454@qq.com, c1360141107@qq.com, d1198793792@qq.com

Abstract. In view of the feasibility of the pre-construction method of the tube screen, the paper makes a comprehensive and in-depth study on the law of the ground subsidence and deformation by means of theoretical analysis, numerical simulation and engineering test. The mechanism of parallel pipe jacking distance on surface settlement and the settlement calculation formula of parallel pipe jacking are studied. By means of numerical simulation, the law of surface subsidence with different jacking intervals is analyzed, and the accuracy of simulation is verified by combining with the monitoring of surface subsidence in actual engineering. The main conclusions are as follows: (1) By studying the subsidence mechanism of parallel pipe jacking distance to the surface, the necessity of controlling the surface subsidence by controlling the pipe jacking distance is expounded; (2) By comparing and analyzing the numerical simulation results of different pipe jacking distances, the vertical displacement values of the ground under different working conditions were obtained; (3) By comparing the engineering monitoring data with the numerical simulation results, it is proved that it is feasible to control the surface settlement by adjusting the pipe jacking distance.

1. Introduction
In solving the problem of urban underground space utilization, especially in cities with complicated pipelines, traffic congestion and limited space, controlling surface settlement is the primary problem. As a new technology, the pre-construction method can effectively control the soil disturbance around the steel tube and reduce the surface settlement. Therefore, it is necessary to study the feasibility of the pipe screen pre-construction method applied to the project of the downtown road.

Dao Wei Wang et al [1]. Established the test model of parallel pipe jacking, and analyzed the mechanical properties of parallel pipe jacking and the influence between pipes. Verruijt et al [2]. Analyzed the basic deformation mechanism of soil caused by double-hole pipe jacking under shallow burial conditions, and studied the ground settlement caused by pipe jacking. Jie Chen et al [3]-[4]. Analyzed the construction principle and process of pipe jacking, and conducted a multi-angle study on
settlement caused by construction. Yun jie Zhang [5] analyzed the stress and strain states of soil around the pipe during pipe jacking, and studied the surface settlement during pipe jacking.

Although many scholars at home and abroad have studied the deformation of parallel pipe jacking spacing on the surface settlement in the method of pipe curtain construction, there is no comparative analysis on the effect of parallel pipe jacking spacing on the surface settlement deformation, so the optimal steel pipe spacing cannot be determined. Therefore, it is necessary to study the deformation of surface settlement caused by parallel pipe jacking distance in the pre-construction method of tube curtain. By studying the mechanism of the parallel pipe jacking distance on the surface settlement deformation in the pre-construction method of pipe curtain, the settlement calculation formula of the parallel pipe jacking is derived. Combined with numerical simulation, the soil deformation under different pipe jacking spacing is studied. Through the analysis of the actual project, the accuracy of the simulation test is verified, and the feasibility of controlling the surface settlement by controlling the distance between parallel pipe jacking is proved.

2. Action mechanism of steel pipe jacking distance on soil mass

2.1. Influence of steel tube jacking distance on stress field
The distance between the steel pipes is very small. During parallel pipe jacking, the gap outside the pipe caused by the diameter difference between the pilot pipe and the subsequent pipe and the overbreak or undercut of the pipe head and the pipe side will disturb the formation, and the repeated disturbance to the formation will affect each other, resulting in the change of the underlying stress field, the formation loss is large, and the ground will show settlement. The superimposed settlement caused by parallel pipe jacking is much larger than that caused by superimposed settlement of the steel pipe and much larger than that caused by superimposed settlement of a single steel pipe. At the same time, during the construction process, the later jacking pipe will cause additional load on the adjacent pipelines that have been built, resulting in hazards [6].

2.2. Analysis of surface subsidence deformation by the jacking distance of steel tubes
In the construction of pipe jacking with the method of pre-construction of pipe curtain, the mutual disturbance of two pipes jacking at the same time is very big. If the distance between the two steel tubes is small, the settlement of the two steel tubes will interact with each other, further increasing the settlement, resulting in the movement of the first tube under the influence of the second tube. If the distance between the two steel tubes is large, the soil mass between the two "Windows" will sink to some extent without the support of the lower part. For example, the granary effect is similar, the soil mass at the upper part of this position will settle unevenly and shear stress will occur on the sliding surface.

2.3. Settlement calculation of pipe jacking
With the construction of pipe jacking, the original stress of soil will change and a new mechanical state of soil will appear. Because of the shear effect of the roadheader on the soil, the friction force between the roadheader and subsequent pipelines and soil during jacking drags the surrounding soil, a shear disturbance zone will be formed around the roadheader during pipe jacking. For the single jacking pipe, according to the limit equilibrium theory, it is considered that the excavation unloading disturbance area on both sides of the jacking pipe is tangent to the shear disturbance area, and the inclination Angle is about $45^\circ + \phi / 2$ (is the internal friction Angle of the soil), which is consistent with the active earth pressure Angle.
Figure 1. Ground subsidence caused by parallel pipe jacking

When the two pipelines are far apart, the mutual disturbance between them is small, and the ground settlement caused by parallel pipe jacking can be calculated roughly, that is, the ground settlement caused by multiple single pipe jacking construction can be predicted by vector superposition. For the final settlement of the ground, it can be assumed that the superposition method is still applicable. Therefore, the ground settlement of the parallel pipe jacking can be regarded as the vector addition of the ground settlement of the single pipe jacking, as shown in figure 1.

The superposition method is a rough calculation method. It is generally considered that the Peck formula is applicable to the front pipe and the back pipe respectively, and the maximum settlement value is located above the top of the pipe. Ignore any effect of the front tube on the rear tube. Then, the settlement curves of the two pipes were vector superimposed to obtain the total settlement of the surface soil [7].

The calculation formula takes the right side excavation as an example:

\[
S(x) = \frac{\pi R^2 \eta_f}{i_f \sqrt{2\pi}} \exp \left[ -\frac{(x - 0.5L)^2}{2i_f^2} \right] + \frac{\pi R^2 \eta_i}{i_i \sqrt{2\pi}} \exp \left[ -\frac{(x + 0.5L)^2}{2i_i^2} \right]
\]

(1)

Where, \(i_f\) and \(\eta_f\) are respectively the width coefficient of the ground settlement trough and \(\eta_i\) the soil loss rate of the forward tunnel; \(i_i\) and \(\eta_i\) are respectively after tunnel ground subsidence trough width coefficient and soil loss.

3. Numerical simulation analysis of steel pipe jacking distance

3.1. Establishment of model

The numerical simulation software ABAQUS was used to simulate and calculate the soil mass model, and the moore-coulomb model was adopted to study the deformation of the surface soil mass under the condition of pipe jacking, and the influence law of the pipe jacking on the surface soil mass was obtained. In order to simplify the calculation, the ABAQUS calculation model established selected the region with the length, width and height of 60m×30m×50m. There are 34320 solid cells in the soil grid, and the cell type is C3D8R. The pipe jacking model is shown in figure 2.
3.2. Model assumptions

(1) The initial stress field is evenly distributed between the ground and a certain depth below the ground, without considering the influence of the tectonic stress field.

(2) The effect of ground load and ground water on parallel pipe jacking is not considered; the deformation and stress distribution of soil under the action of dead weight have been completed before excavation, and the long-term deformation caused by soil consolidation has not been considered.

(3) In the process of simulation, the relevant physical and mechanical parameters of soil can be regarded as fixed values, and the influence of precipitation and underground seepage on it is not needed to be considered.

3.3. Model parameters

(1) Soil layer division and parameters

| Name of the geotechnical layer | Thickness H(m) | Cohesion C(Kpa) | Angle of internal friction $\phi$ (°) | Density $\rho$(kg/m$^3$) |
|--------------------------------|----------------|----------------|---------------------------------------|-------------------------|
| Grain filling                 | 3              | 10             | 6                                     | 1910                    |
| Silty sand                    | 17             | 23             | 15                                    | 1920                    |
| Silty clay                    | 30             | 43             | 27                                    | 2050                    |

| Name of the geotechnical layer | Bulk modulus K(MPa) | Modulus of elasticity E(MPa) | Shear modulus G(MPa) | Poisson's ratio $\nu$ |
|--------------------------------|---------------------|----------------------------|----------------------|----------------------|
| Grain filling                 | 17.92               | 8.1                       | 3.16                 | 0.39                 |
| Silty sand                    | 21.64               | 12                        | 9.57                 | 0.4                  |
| Silty clay                    | 62.75               | 35                        | 39.59                | 0.3                  |

(2) Simulation of steel pipe

A total of 20 steel tubes were used in the tunnel project of Yingze Street underpass railway station in Taiyuan. In order to facilitate the research, 2 steel tubes were selected for simulation in this paper. During the steel support simulation, a solid ring structure element is selected, and the following formula is used to calculate the parameters. See table 2 for the specific parameters.
Table 2. Calculation parameters of steel tube

| Name       | Modulus of elasticity (GPa) | Poisson's ratio | Inner diameter (m) | Outer diameter (m) | Density ρ(kg/m³) | Thickness (mm) |
|------------|-----------------------------|-----------------|--------------------|--------------------|------------------|----------------|
| Steel pipe | 300                         | 0.2             | 1.98               | 2                  | 2700             | 20             |

3.4. Analysis of simulation results

According to the established mathematical model, the vertical displacement and horizontal displacement of surrounding rock lining under the condition of 40cm, 30cm, 20cm and 10cm spacing were obtained by comparing and analyzing the pushing effect under different spacing, as shown in figure 3.

![Figure 3](image-url)

**Figure 3.** Vertical displacement cloud diagram of surface soil under the action of parallel pipe jacking at different distances
As shown in figure 3 and figure 4, according to the analysis of the above figure, the maximum vertical displacement of the overlying soil mass is 21.68mm, the maximum vertical displacement of the central position is 15.33mm, and the range of the overlying soil mass is 35m. With the shortening of the distance between the two steel tubes, the vertical displacement of the overlying soil presents an increasing trend, respectively 22.05mm, 22.27mm and 22.4mm, in the case of plan 2, plan 3 and plan 4, respectively. The maximum value of the central position increases to 15.96mm, 20mm and 17.43. The maximum value at the center of plan 4 is 17.43mm, which is another form of the pack curve. At the same time, in the case of plan 1, plan 2, plan 3 and plan 4, the influence range of the overlying soil is shortened from 35m to 30m. As the distance between the two steel tubes is gradually reduced, the influence range of the overlying soil is also reduced.

The four kinds of scheme, two horizontal distance are smaller than the pipe jacking pipe jacking axis horizontal disturbance zone, belongs to the small spacing problem of pipe jacking, built for pipe jacking before they are built in addition to the disturbance of soil, the influence of pipe jacking pipe jacking first built for soil deformation influence line edges of soil retaining wall, to prevent it from sliding to the excavation area, the influence of stratum deformation line inward, settling tank width is smaller, but always near central axis vertical displacement quantity is big. Plan one is most reasonable through comparative analysis.

4. Engineering application
The passage project of Yingze Street underpass railway station in Taiyuan city was studied, the jacking length of this section is 100m. By jacking 20 steel tubes into the soil successively, the project passes through the lower part of Taiyuan railway station and forms a certain support structure. The structure is 18.2m wide and 10.5m high. In order to facilitate the study, two steel tubes were selected for the study.
4.1. Construction process

![Flow chart of construction process]

Figure 5. Flow chart of construction process

4.2. Settlement point layout of roadbed

For monitoring the surface subsidence of subgrade settlement were arranged on the surface and roadbed settlement point layout in north and south to wear near the center line of the pipe jacking, respectively in the well, starting well received and middle position respectively the horizontal arrangement of a set of monitoring stations, 15 in each group decoration monitoring, spacing of 4 m north and south on both sides of the two, a total of 45 roadbed settlement can add monitoring. The monitoring frequency is 2 times /d. The real-time monitoring data is processed to obtain the data as shown in the figure.

| Monitoring project            | The maximum /mm | The alarm value /mm | Make sure those goals are met |
|-------------------------------|-----------------|---------------------|------------------------------|
| The first row of monitoring points | 22.13           | 25                  | Yes                          |
| Second row of monitoring points  | 21.75           | 25                  | Yes                          |
| The third row of monitoring points | 22.15           | 25                  | Yes                          |

Table 3. Data of main surface monitoring points

It can be seen from table 3 that the maximum value of monitoring data in Taiyuan railway station is far less than the alarm value, and the test results have proved the rationality of plan 2. Combined with relevant data of tube curtain method and monitoring data, it can be seen that tube curtain pre-construction method can be used as an effective method to go down through existing buildings.

Comparison and analysis of simulation data and monitoring data (see figure 6-8).
Figure 6. Monitoring values and simulation values of the first row of monitoring points

Figure 7. Monitoring values and simulation values of the second row of monitoring points

Figure 8. Monitoring values and simulation values of the third row of monitoring points
The station ground subsidence monitoring points are widely distributed and numerous, mong which only three rows of representative monitoring points are selected for research. It can be seen from FIG. 6 ~ 8 that considering various complicated conditions such as construction site vibration and train running vibration, slight fluctuation of deformation amount is normal, so the numerical simulation results of ABAQUS are correct. It can be seen from the figure that the monitoring data curve of surface settlement is similar to the simulation curve of tube curtain construction method, and the law is consistent. The error is within the normal range, indicating the rationality of plan 1.

In conclusion, combined with engineering cases, the simulated deformation of surface settlement is less than the alarm value, indicating the safety of the tube curtain construction method. The monitoring data of surface subsidence conforms to the requirements of underground channel deformation monitoring, and the numerical simulation results are verified.

5. Conclusion
(1) In view of the feasibility of the pipe curtain construction method, the action mechanism of steel pipe jacking distance on the soil was studied, the failure pattern of steel pipe cutting “window” was studied from the perspective of damage mechanics, and the settlement formula of parallel pipe jacking was derived; The influence of pipe jacking distance on the stress field is analyzed.

(2) By establishing a numerical model and carrying out ABAQUS numerical simulation calculation, the displacement field under four types of horizontal jacking spacing was analyzed with known parameters. The displacement field under pipe jacking spacing was 10cm, 20cm, 30cm and 40cm. The results showed that the maximum settlement value of the overlying soil decreased from 22.4mm to 21.68mm with the increase of pipe spacing. The maximum settlement value at the center decreased from 20mm to 15.33mm. The influence range of overlying soil increased with the distance between steel pipes, from 30m to 35m.

(3) The design scheme was optimized for the construction project of Yingze Street underpass railway station, and the results showed the feasibility of the pre-construction method of tube screen; Combined with the comparative analysis of the data monitored in the actual project and the numerical simulation results, it is concluded that this method has played a significant governance effect, verified the accuracy of the simulation test, and provided reference for similar projects.

References
[1] Verruijt A, Booker J R. Surface settlements due to deformation of a tunnel in an elastic half lane [J]. Geotechnique, 1996, 46 (4): 753-756.
[2] Jie Chen. Study on mechanical effect of four-hole parallel rectangular pipe jacking construction [D]. Chengdu: southwest jiaotong university, 2015.
[3] Jianfeng Yu. Numerical simulation analysis of pavement subsidence caused by pipe jacking on guangqing expressway [J]. Guangdong civil & construction, 2011 (5): 55-56
[4] Gang Wei, Xinjiang Wei, and Yumin Tu. Analysis of ground deformation induced by parallel pipe jacking [J]. Journal of rock mechanics and engineering, 2006 (S1): 3299-3304.
[5] Yingjing Liu. Study on the additional influence of pipe jacking construction on the adjacent tunnel [J]. Highway, 2016, 61 (08): 233-239.
[6] Yunjie Zhang. Effect of double-hole pipe jacking with small spacing and large diameter on surrounding soil [D]. Harbin: Harbin Institute of Technology, 2013.