

## Article

# Study on Ground Deformation Induced by Square Pipe Group Jacking and Optimization of Key Jacking Sequences

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## Abstract

This study investigates the ground settlement behavior induced by square pipe group jacking construction using the pipe-roof structure method. The research is based on the Yifeng Gate undercrossing project in the east extension of the Jiangnan connecting line of the Jianning West Road River Crossing Channel. Field monitoring data and numerical simulation were employed to analyze the settlement patterns. The key results are as follows: (1) In the horizontal direction, the “skip construction” sequence results in slightly less ground settlement compared to the “sequential construction” method. However, the difference is minimal. Considering construction efficiency rather than ground deformation control, the “sequential construction” method is recommended. (2) In the vertical direction, the “top-down” construction sequence generates significantly less ground settlement than the “bottom-up” approach. Provided that jacking equipment installation is feasible, the “top-down” sequence is recommended for settlement control. (3) Areas under high surcharge loads (e.g., beneath the city gate tower) and regions with densely arranged pipes are prone to larger settlements during jacking. Corresponding deformation control and compensation measures should be implemented in these zones. The findings of this study provide a valuable reference for similar pipe-jacking projects in urban sensitive areas under soft ground conditions.

**Keywords:** pipe-roof structure method; square pipe jacking; jacking sequence; field monitoring; numerical simulation

## 1. Introduction

With the rapid development of urban construction, above-ground space in cities has become increasingly congested. The cut-and-cover method is gradually failing to meet the demands of urban underground engineering and may endanger the safety of surrounding existing structures [1]. Pipe jacking, characterized by its rapid construction speed, non-excavation requirement, and minimal impact on the surrounding environment, has been widely adopted in urban underground projects [2,3].

The pipe-roof structure method is an urban underground construction technique derived from pipe jacking [4]. The main structure and ventilation ducts of the Xinle Ruins Station on Shenyang Metro Line 2 marked the first domestic application of the pipe-roof method in China. Subsequently, this construction method was further adopted in the underpass project beneath Taiyuan Railway Station along Yingze Street in Taiyuan City, Shanxi Province [5]. It involves jacking steel pipes from a working shaft to predetermined

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positions along the pipe-roof perimeter, cutting the pipe walls, excavating the soil between pipes, reinforcing with steel bars, and casting concrete to form a tunnel structure within the pipes, followed by internal soil excavation. In China, this method is also referred to as the “new pipe-roof method” [6–8] or “pipe-roof pre-construction method” [9–12]. The jacking process inevitably disturbs the soil, leading to ground deformation and potential impacts on adjacent structures. Inadequate control measures may result in damage to both underground and above-ground buildings. The pipe-roof method involves multiple disturbances to the ground due to group pipe jacking, making ground deformation a key focus in both design and construction.

Regarding ground deformation induced by pipe jacking and its impact on surrounding structures, extensive research has been conducted by scholars both domestically and internationally. Taking the construction of the Xinle Ruins Station of the Shenyang Metro as a case study, Yang et al. [13], based on soil arching theory, derived the relationship between the constraint reaction force at the arch axis support and the geometric parameters of the model. By combining the strength control conditions at the arch crown and arch foot, they established a system of equations for solving the optimal pipe spacing. Li et al. [11,12], aiming to study the mechanical response of the tunnel lining structure and the law of ground settlement deformation during earth excavation in pipe-roof pre-construction method tunnels, conducted research on relevant projects using a combination of field monitoring and experimental methods. Han et al. [14], focusing on the pipe-roof structure method applied in the underpass project beneath Taiyuan Railway Station on Yingze Street, employed numerical simulation to investigate different jacking sequences for pipe groups and proposed a group-pipe construction scheme conducive to deformation control.

Sun et al. [15], based on the “pipe-roof and box culvert” jacking construction of the North Hong Road Underpass Project on Shanghai’s Middle Ring Road, systematically studied the deformation characteristics induced by construction using three-dimensional numerical software combined with the elastic foundation beam method, laboratory model tests, and the field monitoring data analogy method. Hu et al. [7] employed numerical simulation to model construction processes, including group pipe jacking, steel pipe cutting, and concrete casting. They analyzed the settlement patterns of station tracks and platforms and established allowable settlement control standards for the tracks based on the characteristics of ground surface settlement curves during pipe-roof structures. Jia et al. [9] investigated ground deformation induced by jacked pipes with flanges, considering factors such as pipe-soil interaction, distribution of pipe-soil friction, and face support pressure, and proposed a predictive method for surface settlement caused by such construction. Regarding large-diameter, densely arranged pipe jacking, Wang et al. [10,16] studied three typical construction schemes through model tests, analyzing the influence of construction sequence on surface settlement during dense pipe jacking. They proposed that the optimal sequence is to jack the upper row first, followed by the lower row and side pipes. To examine the impact of curved pipe-roof construction on surrounding strata of metro stations, Li et al. [17] analyzed key technologies for curved pipe jacking through field tests, proposed corresponding measures for attitude and alignment control of curved pipes, and derived the variation patterns of surrounding strata during curved pipe-roof construction. Yang et al. [4] investigated three different pipe-jacking sequences through numerical simulation, validated by large-scale laboratory model tests. The results indicated that the micro-arching effect can reduce the influence of subsequent pipe jacking on ground deformation. Md et al. [18] conducted a parametric study using three-dimensional finite element analysis to explore settlement behavior and the interaction between side-by-side twin tunnels during construction. They analyzed the total settlement after excavation and the settlement induced solely by the new tunnel construction. The findings suggest that simultaneous excavation of parallel tunnels leads to greater settlement, with a deeper and wider settlement trough. Previous studies have investigated ground deformation induced by pipe

jacking through theoretical, numerical, and field monitoring approaches, yielding significant results. However, research on ground deformation caused by square pipe group jacking remains relatively limited.

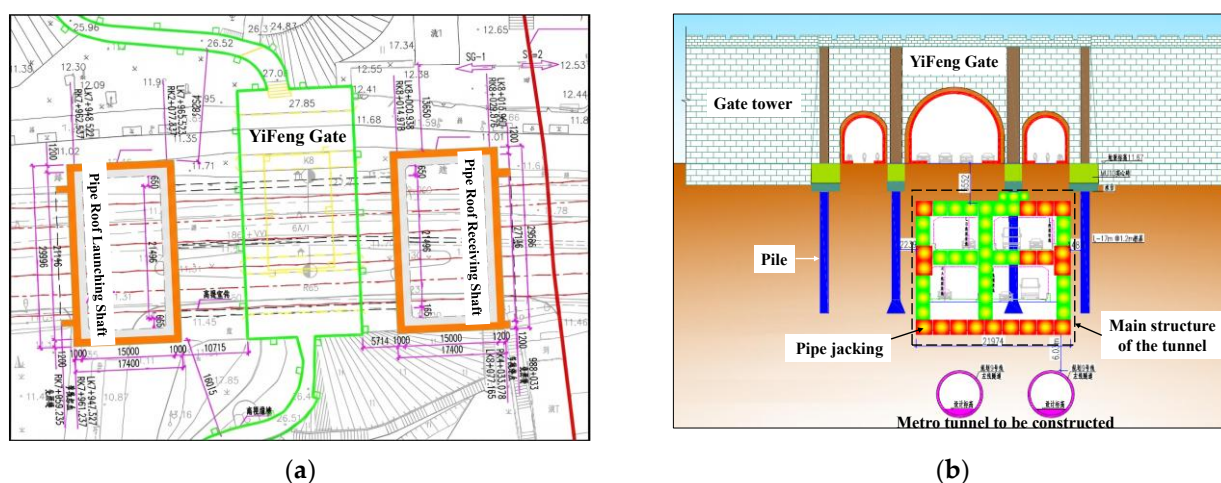
Since group pipe jacking is a dynamic and complex three-dimensional process, it is difficult to resolve specific engineering problems through theoretical research alone. Combining field monitoring analysis with numerical simulation is thus more effective for understanding the impact of construction on the surrounding environment and for providing reasonable solutions to issues encountered during construction. In the pipe-roof structure method, the jacking of square pipe groups causes repeated ground disturbances, leading to surface settlement. This study combines field monitoring with FLAC3D numerical simulation to analyze ground deformation induced by square pipe group jacking in the Yifeng Gate undercrossing project in the east extension of the Jiangnan connecting line of the Jianning West Road River Crossing Channel. The influence of the jacking sequence on ground deformation is emphasized. The findings provide a theoretical reference for similar engineering applications.

## 2. Project Overview

The Yifeng Gate undercrossing project features a main tunnel with dimensions of 21.48 m in width, 17.38 m in height, and approximately 37 m in length. The tunnel is covered by about 5.6 m of overlying soil and comprises two levels vertically, with a central partition wall dividing it into left and right sections horizontally, yielding a total excavation area of approximately 373.32 m<sup>2</sup>. Constructed using the pipe-roof structure method, the tunnel passes beneath a framed-structure gate tower while also running laterally adjacent to an existing Ming Dynasty city wall in the plan layout. The project imposes stringent deformation control standards and entails high construction risks.

### 2.1. Introduction to Tunnels Constructed Using the Pipe-Roof Structure Method

As shown in Figure 1, the main tunnel structure was constructed using the pipe-roof structure method with a concealed excavation technique, underpassing the existing above-ground structures. A total of 50 rectangular pipes with dimensions ranging from 1.2 m to 2.3 m were employed. The construction sequence primarily included pipe jacking, pipe cutting, inter-pipe connection, reinforcement bar binding, structural concrete casting, and earth excavation. T-shaped and C-shaped interlocks were installed between pipes to ensure watertight connections.



**Figure 1.** Schematic of construction using the pipe-roof structure method: (a) plan layout for construction using the pipe-roof structure method; (b) cross-sectional layout for construction using the pipe-roof structure method.

## 2.2. Ground Conditions

Based on the field investigation data, the site strata from top to bottom are as follows: miscellaneous fill layer (thickness: 1.4 m–3.6 m), silty clay (thickness: 13 m–18 m), silty clay mixed with gravel (thickness: 0–3.7 m), and completely weathered tuff (thickness: 4.2 m–9.7 m), underlain by strongly weathered tuff. The tunnel primarily traverses the silty clay, silty clay mixed with gravel, and strongly weathered tuff layers. The main physical and mechanical parameters of the key strata are presented in Table 1.

**Table 1.** Physical and mechanical parameters of key strata.

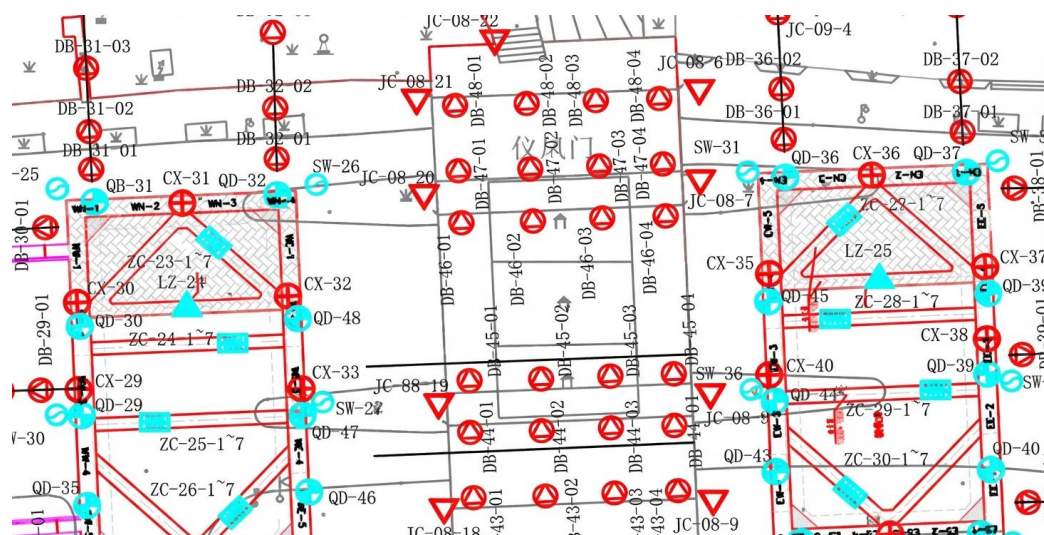
| Stratum No. | Unit Weight<br>kN/m <sup>3</sup> | Compression Index<br>MPa <sup>-1</sup> | Constrained Modulus<br>MPa | Cohesion<br>kPa | Friction Angle<br>° | Hydraulic Conductivity<br>cm/s |
|-------------|----------------------------------|----------------------------------------|----------------------------|-----------------|---------------------|--------------------------------|
| ①-1         | 19.0                             | --                                     | --                         | 15.0            | 12.0                | $2.00 \times 10^{-3}$          |
| ①-2         | 18.7                             | 0.437                                  | 4.45                       | 16.8            | 10.9                | $9.80 \times 10^{-6}$          |
| ②-4b2-3     | 19.4                             | 0.361                                  | 5.18                       | 20.1            | 13.0                | $8.30 \times 10^{-6}$          |
| ③-1b2       | 20.2                             | 0.22                                   | 7.75                       | 50.5            | 16.4                | $5.00 \times 10^{-6}$          |
| ④-3b1-2     | 20.6                             | 0.26                                   | 6.9                        | 62.0            | 16.3                | $5.00 \times 10^{-5}$          |
| ⑦-1         | 20.8                             | --                                     | --                         | --              | --                  | $4.0 \times 10^{-5}$           |
| ⑦-2         | 21.2                             | --                                     | --                         | --              | --                  | $3.0 \times 10^{-5}$           |

## 3. Field Monitoring

To systematically understand and address issues encountered during construction, ensure project safety, and enable timely adjustments to construction schemes and schedules, it is essential to monitor the surrounding environment and provide timely feedback with monitoring data. The combination of a level and monitoring points forms the foundation for high-precision vertical displacement monitoring, with these two tools being the most core and classic measurement instruments. Prior to construction, monitoring points were arranged on the ground surface and adjacent structures within key areas affected by pipe-jacking disturbances. After installation, a stabilization period was observed before initial measurements were taken to establish baseline elevation data. During construction, Trimble levels were used as the primary measurement tool, supplemented by total stations, to conduct regular monitoring of the relevant points. Monitoring data were collected promptly to capture the deformation behavior of the ground and surrounding structures, thereby providing data support for deformation control and analysis of deformation mechanisms.

### 3.1. Layout of Monitoring Points

To monitor ground surface deformation during pipe jacking, a total of 24 monitoring points (e.g., DB-43-01, DB-43-02, DB-43-03, DB-43-04, DB-44-01, DB-44-02, DB-44-03, DB-44-04, DB-45-01, DB-45-02, DB-45-03, DB-45-04, DB-46-01, DB-46-02, DB-46-03, DB-46-04, DB-47-01, DB-47-02, DB-47-03, DB-47-04, DB-48-01, DB-48-02, DB-48-03, and DB-48-04) were installed beneath the gate tower, as shown in Figure 2. The ground deformation in the pipe-jacking zone serves as critical data reflecting soil disturbance during construction, which can directly or indirectly indicate the impact of the jacking process on both the ground surface and the historic structure.



**Figure 2.** Schematic diagram of monitoring points.

### 3.2. Monitoring and Emergency Protection Measures

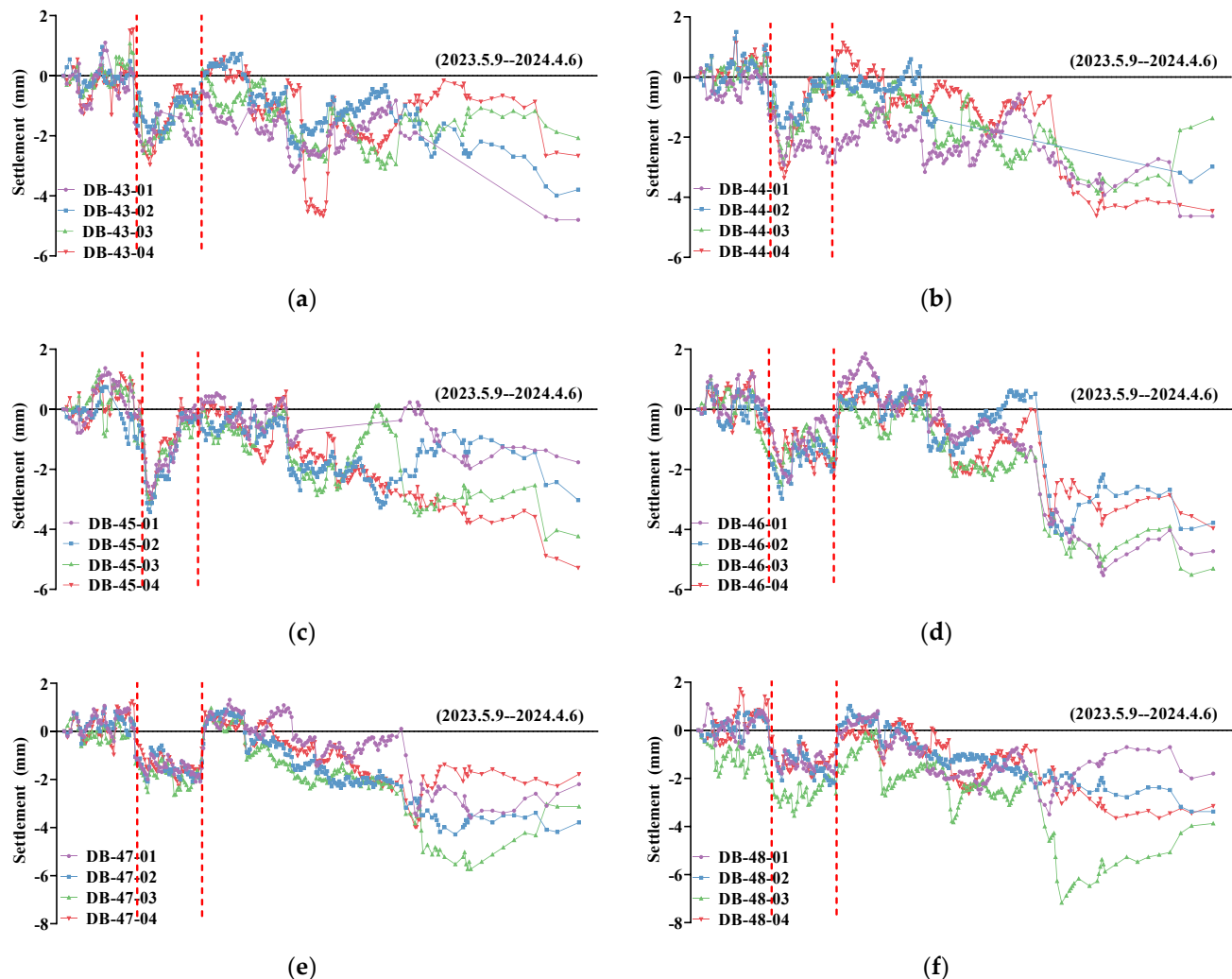
To prevent emergencies during pipe-jacking construction and mitigate potential losses caused by unforeseen incidents, corresponding technical measures should be implemented in advance:

- (1) Monitoring frequency shall be intensified. Once the warning value is triggered, construction must be halted immediately, and the relevant authorities shall be notified promptly. Corresponding reinforcement and deviation correction measures shall be taken accordingly. To facilitate the timely protection of the city wall in the event of an emergency, double-layer scaffolding shall be erected on both sides of the wall during construction. Rigid vibration-damping and isolation pads shall be installed between the scaffolding and the wall to ensure the integrity of the historic structure.
- (2) To address potential uneven settlement or excessive deformation during construction, sleeve-valve pipe grouting shall be adopted to reinforce the soil mass surrounding the city wall. In the case of settlement exceeding the warning threshold, compensation grouting shall be carried out to uplift the stratum.
- (3) To ensure the integrity of the gate tower throughout the construction process, a steel structure support system shall be installed inside the gate tower to protect the historic structure and ensure the smooth progress of construction.

### 3.3. Analysis of Field Monitoring Data

#### 3.3.1. Settlement Trend of the East–West Monitoring Section

In the figure, the horizontal axis represents the monitoring date (from 9 May 2023 to 6 April 2024), and the intervals marked by the two vertical dashed lines indicate the time periods during which heavy rainfall was recorded in the meteorological data. As shown in Figure 3, the settlement curves of the six sections along the east–west direction exhibit generally consistent trends. A pronounced settlement mutation occurred in all sections at the end of June 2023, which can be attributed to the Meiyu (plum rain) season in Nanjing from mid-June to early July. According to rainfall statistics at the end of June 2023, several intense precipitation events occurred on 17–19 June, 25 June, and 29–30 June. In particular, the rainfall from 17 June to 19 June was relatively heavy, with the cumulative rainfall across the city generally exceeding 100 mm. Under the influence of rainfall infiltration, ground subsidence occurred beneath the city gate tower. Subsequently, grouting uplift was implemented to compensate for the ground settlement.



**Figure 3.** Settlement in the east–west monitoring section: (a) Section DB-43; (b) Section DB-44; (c) Section DB-45; (d) Section DB-46; (e) Section DB-47; (f) Section DB-48.

During the jacking process, except for a slight increase in settlement at Sections DB-43 and DB-45, the ground settlement at the other sections remained nearly unchanged, indicating that the ground settlement was effectively controlled during jacking construction. For Sections DB-43 and DB-44, the maximum cumulative settlement occurred at Monitoring Point 01. Specifically, at Section DB-43, the settlement at Monitoring Point 01 remained the largest throughout the entire jacking process. In contrast, at Section DB-44, the maximum settlement initially occurred at Monitoring Point 04 during the early stage of jacking, whereas the settlement at Monitoring Point 01 exceeded that at Monitoring Point 04 in the later stage.

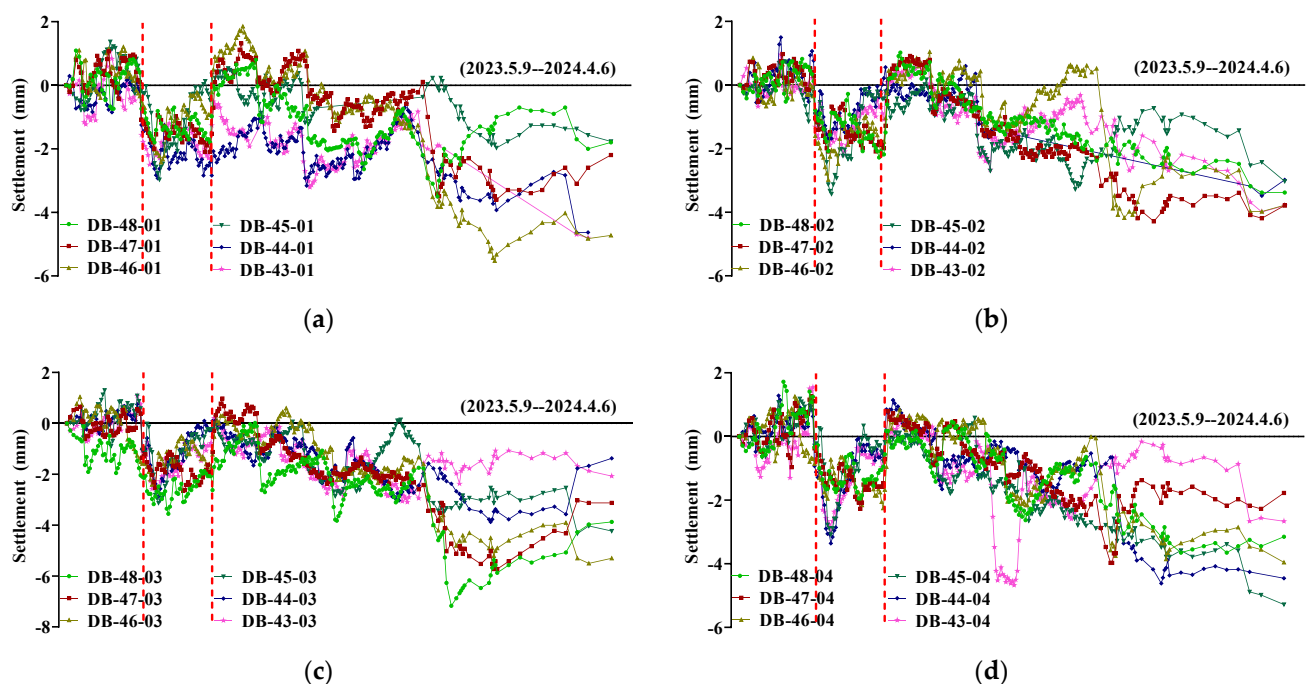
At Section DB-45, the settlement at Monitoring Point 04 remained the largest throughout the jacking process. For Section DB-47, greater settlement was observed at Monitoring Point 03 during the early stage, while in the later stage, the settlement at Monitoring Point 02 exceeded that at Monitoring Point 03. At Section DB-46, the settlement at Monitoring Point 01 was larger in the early stage of jacking, whereas the settlement at Monitoring Point 03 became dominant in the later stage. For Section DB-48, Monitoring Point 03 consistently exhibited the maximum settlement during the jacking process.

These results indicate that the locations of maximum settlement are mainly concentrated in the central part of the city gate tower and at the junction between the city gate

tower and the southern city wall. Therefore, enhanced monitoring should be implemented at these locations, and corresponding settlement control measures should be formulated.

### 3.3.2. Settlement Trend of the North–South Monitoring Section

In the figure, the horizontal axis represents the monitoring date (from 9 May 2023 to 6 April 2024), and the intervals marked by the two vertical dashed lines indicate the time periods during which heavy rainfall was recorded in the meteorological data. The settlement variation trends of the four sections in the north–south direction are illustrated in Figure 4. These trends are generally consistent with those observed for the six sections in the east–west direction. It can be clearly observed that, under the influence of heavy rainfall, ground settlement occurred beneath the city gate tower, followed by a subsequent uplift induced by grouting.

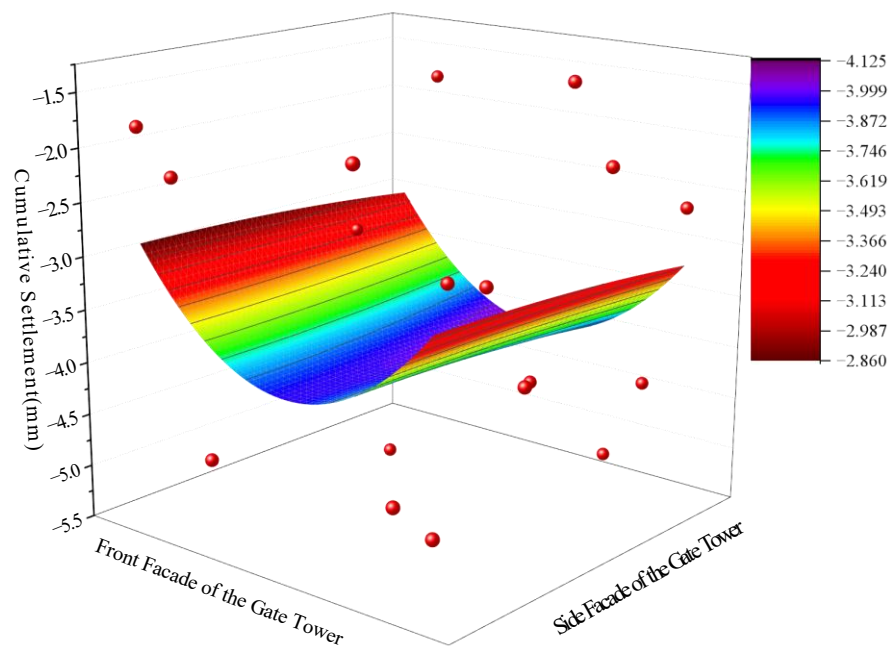


**Figure 4.** Settlement in the north–south monitoring section: (a) Sections DB-(43 to 48)-01; (b) DB-(43 to 48)-02; (c) Sections DB-(43 to 48)-03; (d) Sections DB-(43 to 48)-04.

During the jacking process, the maximum settlement on Section DB-(43–48)-01 occurred at DB-46. For Section DB-(43–48)-02, the largest settlement was observed at DB-47. On Section DB-(43–48)-03, the maximum settlement initially occurred at DB-48; however, in the later stage of construction, the settlement at DB-46 became the largest. For Section DB-(43–48)-04, the maximum settlement initially appeared at DB-44, whereas in the later construction stage, the settlement at Section DB-45 exceeded that at DB-44.

### 3.3.3. Accumulated Ground Surface Settlement

The three-dimensional surface plot of cumulative ground surface settlement is shown in Figure 5.



**Figure 5.** The 3D surface plot of the ground surface settlement.

In Figure 5, the scattered points represent the final settlement values at various surface monitoring points, and the three-dimensional surface is generated by fitting these scattered points. This aims to provide a qualitative overall understanding of the surface deformation within the disturbed zone induced by pipe-jacking construction. Overall, the ground settlement at the central part of the city gate tower is more pronounced, which is consistent with the results of cumulative settlement shown in Figures 3 and 4. This phenomenon may be attributed to the fact that this area represents a key zone of construction-induced disturbance and is subjected to relatively large structural loads from the overlying city gate tower. Therefore, targeted ground reinforcement should be implemented in this area, corresponding settlement control measures should be formulated, and enhanced monitoring should be conducted throughout the pipe-jacking construction process.

#### 4. 3D Numerical Model

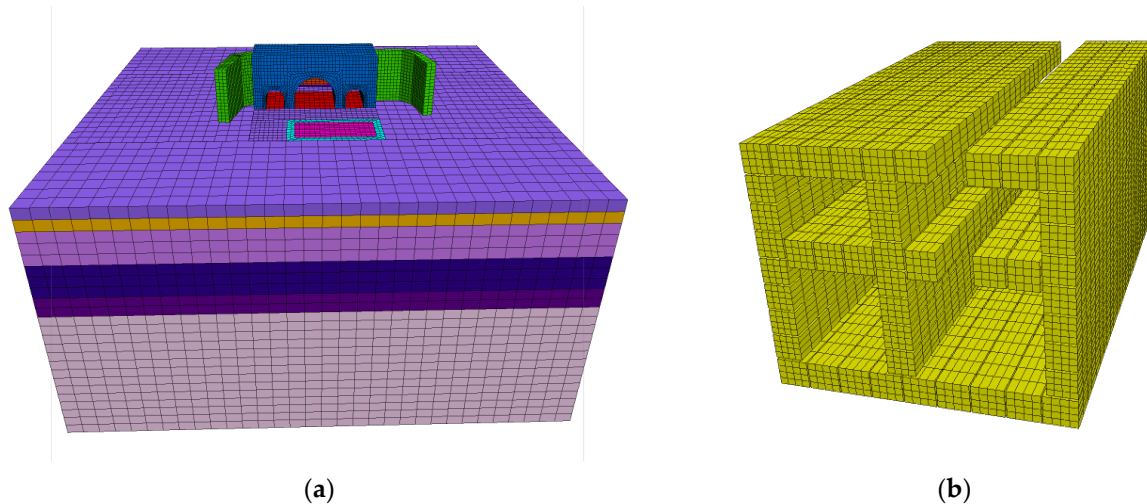
The square pipe-jacking process was simulated and analyzed using the FLAC3D 5.0 numerical simulation software. During construction, the main factors contributing to additional loads induced by the pipe-jacking machine include the additional jacking thrust at the cutter face, ground disturbance, ground loss, and grouting. The soil in the numerical model was assumed to be an isotropic elastoplastic material. In the simulation, time-dependent soil deformation effects and deformation rates under the initial self-weight stress field were not considered.

In actual construction, the pipe segments are connected by welding. Accordingly, shell elements were adopted in the numerical model to represent the steel pipes, which were advanced progressively as an integral structure during the jacking process [18,19].

##### 4.1. Dimensions of the Numerical Model

The dimensions of the numerical calculation model were determined as follows: the model has a length of 150 m, a width of 150 m, and a height of 75 m. The longitudinal excavation length of the pipe-jacking section was set to 36 m, as shown in Figure 6. The horizontal and vertical distances between the pipe-jacking and the model boundaries are greater than five times the characteristic dimension of the pipe so as to minimize the influence of boundary effects on the numerical results.

Regarding the boundary conditions, the upper boundary at  $z = 0$  m was defined as a free boundary, while the bottom boundary at  $z = -75$  m was constrained in the  $z$ -direction. The left and right boundaries were constrained in the  $x$ -direction, and the front and rear boundaries were constrained in the  $y$ -direction.



**Figure 6.** Numerical model: (a) the entire numerical model; (b) numerical model of the square pipe group.

#### 4.2. Parameters of the Numerical Model

The soil in the numerical model was represented by an isotropic elastoplastic constitutive model, with the Mohr–Coulomb failure criterion adopted as the yield criterion. All soil layers in the model were assumed to be homogeneous and uniformly distributed. When using FLAC3D for geotechnical numerical simulation, the Mohr–Coulomb model was selected as the constitutive model for the soil. This choice is primarily justified by the model's use of cohesion and internal friction angle as its core parameters, which carry clear physical meaning and effectively capture the elastoplastic response and failure criteria of soil under shear loading. The model is particularly suitable for simulating the progressive yielding and stress redistribution processes in soil during pipe-jacking construction. Furthermore, its parameters can be directly obtained through conventional laboratory tests, facilitating integration with site-specific engineering geological conditions and thereby enhancing both the reliability and applicability of the simulation. The Mohr–Coulomb model has been extensively validated by scholars in simulating soil deformation and stability problems associated with underground excavations such as foundation pits and tunnels. Its computational efficiency and stability satisfy the demands of large-scale three-dimensional simulations of construction processes. In actual construction, the wall thickness of the jacked pipes is relatively small compared with their overall dimensions. Therefore, the pipes were treated as thin-walled structures in the numerical model and simulated using shell elements.

The cross-sectional dimensions of the jacked pipe were taken as  $2\text{ m} \times 2\text{ m}$ , and the length of the pipe-jacking machine was set to 2 m. The depth of the pipe axis of the upper pipe from the ground surface was  $h = 6\text{ m}$ , and the center-to-center spacing between adjacent pipes was  $L = 3\text{ m}$ . The additional jacking thrust applied at the cutter face was taken as 20 kPa, the interface friction was set to 5 kPa, and the grouting pressure was specified as 20 kPa.

#### 4.3. Pipe-Jacking Construction Process

Firstly, the numerical model was brought to equilibrium under the self-weight stress field to establish the initial in situ stress state. Subsequently, the overall displacement of the model was reset to zero in order to obtain the ground stress field prior to construction. The first pipe segment was then excavated, followed by a calculation to obtain the unbalanced nodal forces acting on the outer boundary of the excavated elements. These unbalanced nodal forces were multiplied by a reduction factor less than unity and applied in the opposite direction to the corresponding locations, thereby simulating the stress release during the pipe-jacking process.

A uniformly distributed load was applied at the tunnel face to represent the additional thrust exerted by the pipe-jacking machine, and shell structural elements were added to simulate the installed pipe segment. The model was then recalculated until equilibrium was reached. The excavation and jacking procedure was conducted in a stepwise manner with an excavation step length of 3.6 m, and the above process was repeated sequentially until completion of the pipe-jacking construction.

#### 4.4. Ground Settlement Induced by Single Pipe Jacking

Peck's formula [6,12], owing to its wide applicability, has been extensively used for predicting ground surface settlement induced by tunnel construction. This method assumes that surface settlement is primarily caused by ground loss and that the transverse settlement trough at the ground surface follows a Gaussian (normal) distribution. The surface settlement can be predicted using the following equation:

$$S(x) = S_{\max} \exp\left(-\frac{x^2}{2i^2}\right), \quad (1)$$

$$S_{\max} = \frac{V_i}{i\sqrt{2\pi}}, \quad (2)$$

$$V_i = D\eta, \quad (3)$$

In this equation,  $S_{\max}$  represents the maximum ground surface settlement,  $x$  is the distance from the pipe-jacking axis, and  $S(x)$  denotes the surface settlement at a given location. Additionally,  $D$  is the cross-sectional area of the jacked pipe.  $V_i$  is the ground loss per unit length, and  $\eta$  is the ground loss ratio, which depends on geological and construction factors. For cohesive soils, the ground loss ratio typically ranges between 0.5% and 2.5%.  $i$  is the trough width parameter (the width coefficient of the settlement trough), which can be determined by Formula (4) [4,18].

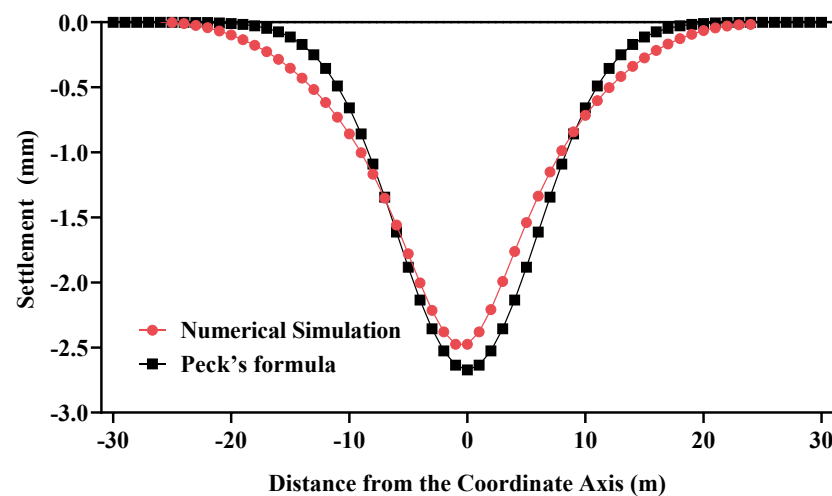
$$i = (1 - 0.02\varphi)h, \quad (4)$$

In the above equation,  $\varphi$  is the internal friction angle of the ground, and  $h$  denotes the burial depth of the pipe axis.

Taking the single-pipe-jacking construction at a buried depth of 6 m along the pipe axis as an example, a simulation was conducted using the FLAC3D numerical software. The transverse surface settlement curve after pipe jacking is shown in Figure 3. To verify the accuracy of the numerical results, the surface transverse settlement was also calculated using Peck's formula. Based on the actual construction conditions and ground characteristics at the site, a ground loss ratio  $\eta$  of 1.0% was adopted.

As shown in Figure 7, the transverse ground surface settlement curves obtained from the numerical simulation and Peck's formula exhibit similar overall trends. As the monitoring points move away from the pipe axis, the ground surface settlement gradually

decreases and tends to stabilize. The maximum settlement occurs directly above the pipe axis, with values of  $-2.47$  mm and  $-2.67$  mm, respectively. The difference between the two results is approximately 8.0%.



**Figure 7.** Transverse ground surface settlement curve.

#### 4.5. Ground Settlement Induced by Group-Pipe-Jacking Construction

Based on the fundamental principles of the group-pipe-jacking sequence employed at the construction site—namely, “bottom-up” and “from both sides toward the center”—a simulation was conducted using FLAC3D numerical software. The transverse surface settlement curve upon completion of the group-pipe construction is presented in the following figure.

Numerical simulation-1 and numerical simulation-2 correspond to the numerical simulation results without and with consideration of grouting reinforcement, respectively. The grouting reinforcement simulated in the model represents the field construction practice in which sleeve-valve pipes are used to reinforce the strata in the pipe-jacking zone prior to the commencement of construction. In the numerical model, this reinforcement is implemented by activating the equivalent layer within the reinforced zone and enhancing the material parameters. As shown in Figure 8, the transverse surface settlement curves obtained from numerical simulation and field monitoring exhibit broadly similar variation trends. As the monitoring points move away from the disturbance zone of pipe jacking, the surface settlement gradually decreases, with the maximum settlement occurring in the densely piped area beneath the gate tower. The maximum settlements from the numerical simulation-1 and field monitoring are  $-10.44$  mm and  $-5.31$  mm, respectively, representing a difference of approximately 49%. The maximum settlements from the numerical simulation-2 and field monitoring are  $-6.40$  mm and  $-5.31$  mm, respectively, representing a difference of approximately 17%. It can be seen that the application of pre-grouting reinforcement in the stratum can effectively control the settlement of both the ground surface and adjacent structures.

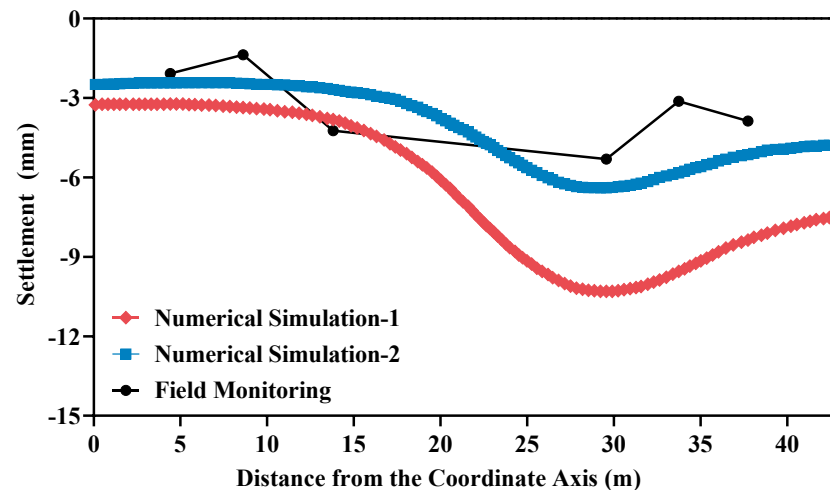


Figure 8. Transverse ground surface settlement curve.

## 5. Optimization of Critical Construction Sequences

To investigate the influence of the jacking sequence of square pipe groups on ground surface settlement, other construction factors were neglected, and a typical jacking sequence at a representative section of the square pipe group was selected to establish a numerical calculation model, as shown in Figure 9. The jacking construction of the pipes was taken as the main focus, and the effects of different jacking sequences on the ground deformation behavior were analyzed. From the perspective of deformation control, the advantages and disadvantages of different jacking sequences were compared, and the construction scheme was optimized accordingly.

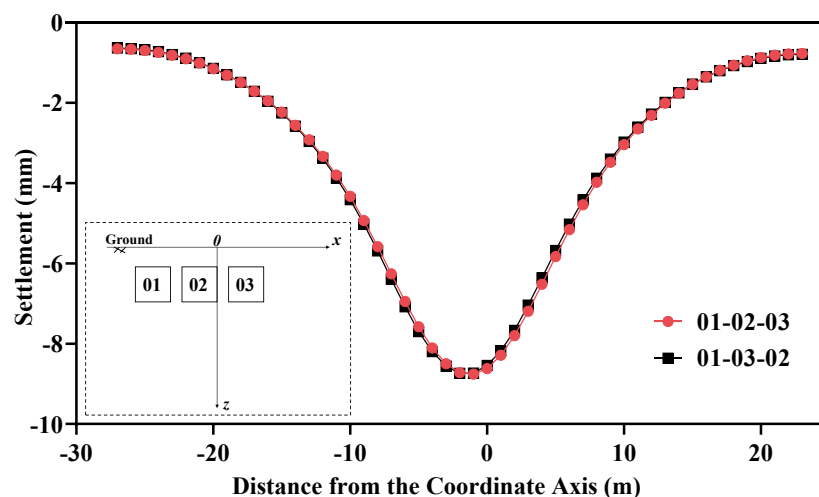


Figure 9. Transverse surface settlement curves.

### 5.1. Parallel Arrangement of Jacking Pipes

The analysis cases for the parallel arrangement of jacking pipes are illustrated in Figure 9. The primary cases include the following:

Case 1: Sequential construction from left to right (01 → 02 → 03).

Case 2: Skip construction from left to right (01 → 03 → 02).

Figure 9 shows the transverse surface settlement curves under different construction scenarios for the parallel arrangement of jacking pipes.

As illustrated in Figure 9, for the parallel pipe arrangement, the maximum surface settlements after construction under Case 1 and Case 2 are  $-8.76$  mm and  $-8.74$  mm, respectively. The “skip construction” sequence results in a slightly smaller maximum settlement compared to the “sequential construction” sequence, although the difference between the two is marginal. The locations of the maximum transverse settlement for Case 1 and Case 2 occur at  $x = -1$  m and  $x = -2$  m, respectively. Furthermore, the transverse settlement curves indicate that the overall influence ranges of surface settlement induced by the two different construction sequences are broadly similar.

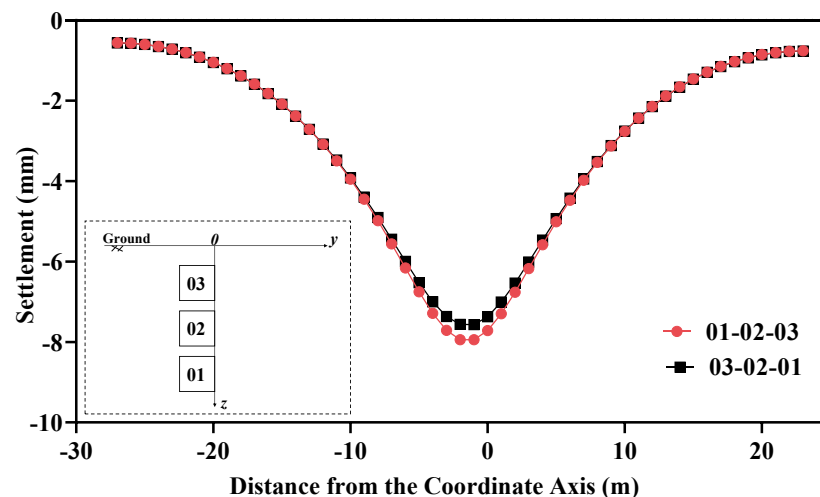
### 5.2. Staggered Stack Arrangement of Jacking Pipes

The analysis cases for the staggered stack arrangement of jacking pipes are illustrated in Figure 10. The main cases include the following:

Case 1: Sequential construction from bottom to top (01  $\rightarrow$  02  $\rightarrow$  03).

Case 2: Sequential construction from top to bottom (03  $\rightarrow$  02  $\rightarrow$  01).

Figure 10 illustrates the transverse surface settlement curves under different construction scenarios for the staggered stack arrangement of jacking pipes.



**Figure 10.** Transverse surface settlement curves.

As illustrated in Figure 10, for the staggered stack arrangement of jacking pipes, the maximum surface settlements after construction under Case 1 and Case 2 are  $-7.94$  mm and  $-7.57$  mm, respectively, with a difference of  $0.37$  mm. In both cases, the locations of maximum transverse settlement are situated directly above the pipe-jacking axis. A comparison of the transverse settlement curves between the two cases reveals that the settlement directly above the axis in Case 2 (“top-down” sequence) is significantly smaller than that in Case 1 (“bottom-up” sequence). However, the overall influence range of the settlement induced by the two construction sequences is broadly similar.

### 5.3. L-Shaped Arrangement of Jacking Pipes

The analysis cases for the L-shaped arrangement of jacking pipes are illustrated in Figure 11. The primary cases include the following:

Case 1: Sequential construction from bottom to top (01  $\rightarrow$  02  $\rightarrow$  03).

Case 2: Sequential construction from bottom to top (02  $\rightarrow$  01  $\rightarrow$  03).

Case 3: Sequential construction from top to bottom (03  $\rightarrow$  01  $\rightarrow$  02).

Figure 11 shows the transverse surface settlement curves under different construction scenarios for the L-shaped arrangement of jacking pipes.

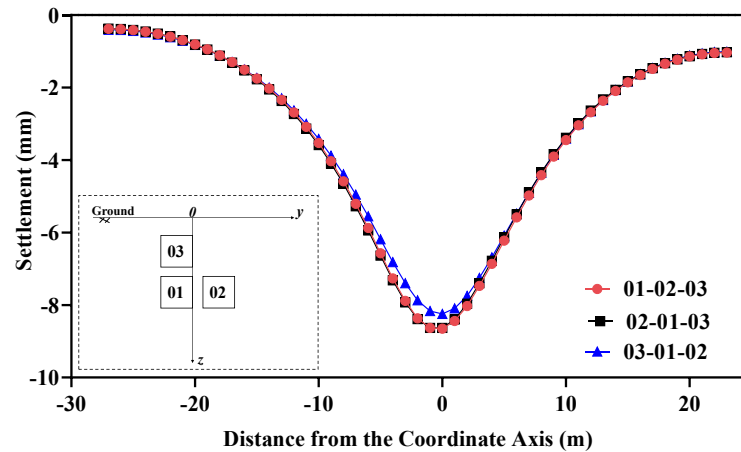


Figure 11. Transverse surface settlement curves.

As shown in Figure 11, for the L-shaped pipe arrangement, the maximum surface settlements after construction under Case 1, Case 2, and Case 3 are  $-8.65$  mm,  $-8.63$  mm, and  $-8.24$  mm, respectively. Regarding the maximum settlement values, Case 3 is  $0.41$  mm and  $0.39$  mm smaller than Case 1 and Case 2, respectively. In all three cases, the points of maximum settlement are located directly above the midpoint of the pipe-jacking axis. A comparison of the transverse settlement curves induced by the three construction scenarios indicates that the “top-down” sequence generally results in smaller surface settlements, whereas the choice between sequential and skip construction sequences has a relatively minor influence on the final settlement profile.

#### 5.4. T-Shaped Arrangement of Jacking Pipes

The analysis cases for the T-shaped arrangement of jacking pipes are illustrated in Figure 12. The main cases are defined as follows:

Case 1: Sequential construction from bottom to top (01  $\rightarrow$  02  $\rightarrow$  03  $\rightarrow$  04  $\rightarrow$  05).

Case 2: Sequential construction from bottom to top (01  $\rightarrow$  02  $\rightarrow$  04  $\rightarrow$  03  $\rightarrow$  05).

Case 3: Skip construction from bottom to top (01  $\rightarrow$  02  $\rightarrow$  04  $\rightarrow$  05  $\rightarrow$  03).

Case 4: Sequential construction from top to bottom (04  $\rightarrow$  03  $\rightarrow$  05  $\rightarrow$  02  $\rightarrow$  01).

Figure 12 illustrates the transverse surface settlement curves under different construction scenarios for the T-shaped arrangement of jacking pipes.

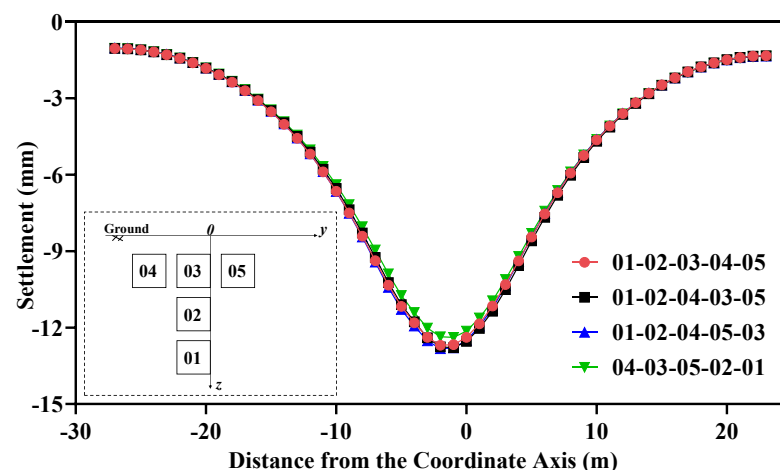


Figure 12. Transverse surface settlement curves.

As shown in Figure 12, for the T-shaped pipe arrangement, the maximum surface settlements after construction under Case 1, Case 2, Case 3, and Case 4 are  $-12.69$  mm,  $-12.78$  mm,  $-12.83$  mm, and  $-12.37$  mm, respectively. In all four cases, the maximum settlement point is located at  $x = -1.5$  m. A comparison of the surface settlement curves induced by the four construction scenarios indicates that the “top-down” sequence generally leads to relatively smaller settlements. Furthermore, comparing Case 1, Case 2, and Case 3 reveals that the choice between “sequential construction” and “skip construction” has only a minor influence on the final settlement profile.

### 5.5. Critical Construction Sequences

Through numerical simulation, a comparative analysis was conducted on the most common construction sequence variations encountered during pipe jacking, including sequential jacking, skip jacking, top-down, and bottom-up sequences. Due to the superimposed effects of disturbance induced by pipe jacking, continuous sequential jacking in the horizontal direction caused greater disturbance to the soil layer, thereby resulting in larger ground settlement. In contrast, skip jacking provided time and space for stress relief in the disturbed soil, effectively mitigating the degree of ground disturbance. In the vertical direction, when the top-down construction sequence was adopted, the previously installed upper pipes generated a soil arching effect in the stratum, which helped to share the loads from subsequent lower construction and thus improved overall settlement control [14,20]. Conversely, under the bottom-up sequence, the lower pipes constructed first caused disturbance to the surrounding soil, leading to greater ground settlement during the subsequent jacking of the upper pipes.

In terms of surface settlement response, the combination of “skip construction” and “top-down” sequences exhibited certain advantages in deformation control. However, this combination entails more complex construction organization on-site and imposes higher requirements on the spatial arrangement of equipment. Therefore, in pipe-jacking projects implemented in soft soil areas such as Nanjing and Ningbo, this construction sequence may be prioritized in deformation-sensitive zones, while in general areas, sequences more conducive to construction efficiency may be adopted.

## 6. Conclusions

Taking the Yifeng Gate undercrossing project as the engineering background, this study analyzed the ground deformation characteristics induced by the pipe-roof structure method using a combination of field monitoring and numerical simulation. Targeted investigations were conducted on the construction sequence of square pipe jacking at critical construction stages. By examining the influence of pipe-jacking operations on ground surface deformation, the advantages and disadvantages of different jacking sequences were compared. The main conclusions and recommendations are as follows:

- (1) The combined effect of substantial surcharge loads and construction disturbance is pronounced. Larger settlement values were observed in the central section of the gate tower and at the junction between the tower and the city wall. It is recommended to implement ground reinforcement in these critical areas prior to construction, formulate corresponding settlement control measures, and enhance monitoring throughout the pipe-jacking process.
- (2) When different pipe-jacking sequences are adopted, the variation trends of the surface settlement curves are similar, and the scopes of settlement influence are essentially identical upon completion of all pipe-jacking activities.
- (3) In the horizontal direction, although the “skip construction” sequence results in slightly smaller final surface settlements compared to the “sequential construction”

- sequence, the absolute difference between the two is relatively minor. In areas where settlement control requirements are not particularly stringent, the “sequential construction” sequence is recommended, considering construction efficiency and safety.
- (4) In the vertical direction, the “top-down” construction sequence produces smaller final surface settlements after pipe jacking than the “bottom-up” sequence. In settlement-sensitive areas, the “top-down” jacking sequence is preferred to better control ground deformation.
  - (5) Both the field monitoring data and numerical simulation results indicate that the soil in areas with densely arranged square pipe groups is repeatedly disturbed during the pipe-jacking process, resulting in generally larger ground surface settlements. Therefore, enhanced monitoring should be implemented in these densely distributed pipe-jacking areas, and appropriate settlement control and compensation measures should be adopted.

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