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Numerical Simulation Analysis of Deformation Characteristics in Existing Structures and Surface Induced by Large-Section Rectangular Pipe Jacking Construction

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Abstract: This study examines the impact of large-section rectangular pipe jacking construction on existing structures through the establishment of a three-dimensional model using MIDAS-GTS finite element software. The simulation analyzes surface deformation and displacement characteristics during construction. Results indicate that pipe jacking construction causes significant disturbances to the surface and surrounding structures, primarily resulting in soil settlement. The deformation range expands progressively as construction advances. By optimizing construction parameters such as grouting pressure and volume, the study effectively reduces surface settlement and structural displacement, providing valuable insights for similar engineering projects.

1. Introduction

As a trenchless underground engineering technology, large-section rectangular pipe jacking has been widely used in urban underground space development because of its advantages of small surface disturbance and high construction efficiency[1-3]. However, in the dense urban environment, pipe jacking construction may have adverse effects on the surrounding existing structures, especially when crossing complex geological conditions and adjacent important infrastructure [4, 5].

Researchers both domestically and internationally have conducted extensive studies on deformation control of soil and surrounding structures during pipe jacking construction. For example, He et al.[6] found that interlayer soil grouting is used to improve the strength of surrounding soil and steel bearing reinforcement is beneficial to control the relative deformation between segments. Qian et al.[7] assessed jacking force prediction for various models of pipe-soil-slurry interaction in rectangular pipe jacking. Their numerical analysis revealed that increasing the thickness of the mud-water liquid sleeve exacerbates overexcavation and surface settlement. Yan et al.[8] employed numerical simulation to model the construction of large-section quasi-rectangular pipe jacking, finding that viaduct piles significantly reduced the maximum positive and negative bending moments of the pipe section as well as the bending moments at the left spandrel and right arch foot.

Despite the progress in research, systematic studies on the impact of large-section rectangular pipe jacking on existing structures remain relatively scarce[9].This is particularly true under complex geological conditions, where developing effective optimization and control measures for construction parameters through the integration of numerical simulation and field monitoring remains a significant challenge in current engineering practice[10].

Using the construction of Changchun Urban Rail Transit Line 6 as a case study, this paper employs MIDAS-GTS finite element software to develop a three-dimensional model that simulates surface deformation and the displacement of surrounding structures during large-section rectangular pipe jacking construction.

2. Establishment of Numerical Model

2.1. Project Profile

This project involves the rectangular pipe jacking for the No. 1 and No. 2 transfer channels of the Fuzhi Road West Station, part of the Changchun Urban Rail Transit Line 6. The proposed rectangular pipe jacking for the No. 1 and No. 2 transfer passages is situated in the southwest quadrant of Linhe South Street and Fuzhi Road. The pipe jacking advances 3.3% downhill from east to west. During the jacking process, it is necessary to pass through the pier pile foundation of the Line 4 subway viaduct and the underground excavation section of the existing Line 6 subway. The primary pipelines within the influence area of the pipe jacking include a utility tunnel and two thermal pipelines. A schematic diagram of the project location is shown in Figure 1.

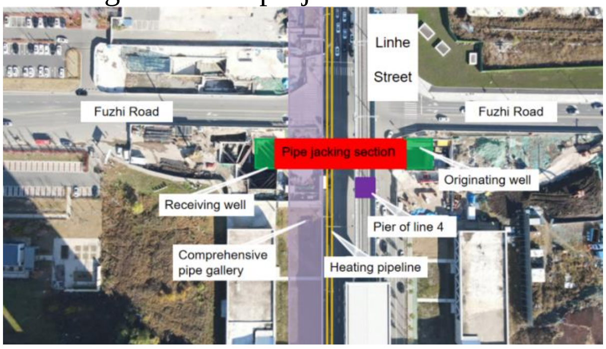


Figure 1.Schematic diagram of the project location

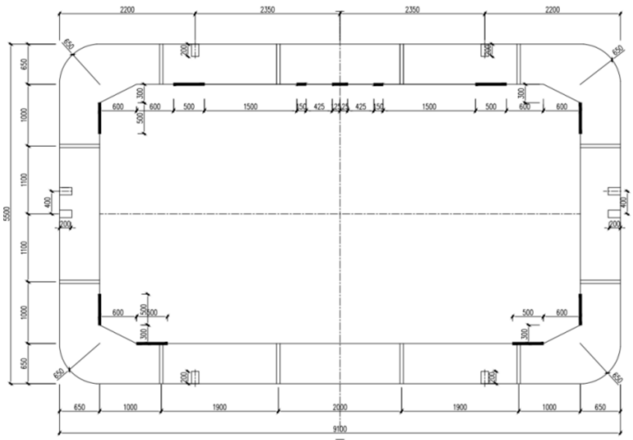


Figure 2. Schematic diagram of the pipe jacking section

The project employs pipe jacking with a cross-sectional dimension of 9.1 × 5.5 m and a thickness of 1.5 m. The weight of each pipe segment is 70 tons, and C50P10 concrete is used for construction. The average covering depth of the pipe jacking is 7.0 m, while the excavation depth is approximately 14.037 m. The design incorporates an earth pressure balance rectangular pipe jacking machine, consisting of a total of 41 pipe sections. A schematic diagram of the pipe jacking section is shown in Figure 2.

2.2. Model boundary setting

To ensure that the numerical simulation results accurately reflect the conditions of the construction site throughout the process, the geometric dimensions of the model were determined based on relevant drawings and construction experience. The model's width was set to 80 m, while the height was determined to be 40 m to accommodate the depth requirements of the bridge piles. Consequently, the geometric dimensions of the model are 80 m × 61.5 m (length of the pipe jacking section) × 40 m. The boundary conditions were defined as follows: the upper surface of the model is an unconstrained free surface; the front and rear surfaces are constrained in the longitudinal direction; the left and right surfaces are constrained in the lateral direction; and the bottom surface is fixed in all directions.

2.3. Selection of model material parameters

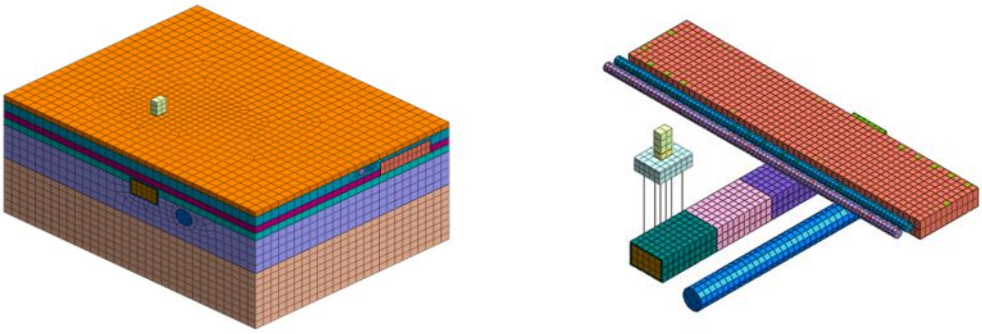
In the finite element numerical simulation analysis, the model was appropriately simplified to ensure that the simulation results align closely with the field-measured data. The soil in the model was defined as a 3D solid element. Similarly, the pipe jacking segment, existing buried tunnel, pipe gallery, and thermal pipeline were also modeled as 3D solid elements, with material properties assigned accordingly. The pipe jacking casing was represented using 2D plane elements, while the bridge piles were modeled as 1D beam elements. The pier, cap, and grouting were defined as 3D solid elements. Based on the relevant survey report, the physical and mechanical parameters of materials, including the soil layers and concrete, are summarized in Table 1.

Table 1.Table of physical and mechanical parameters of materials

Serial Number	Soil Layers and Materials	Thickness (m)	Constit-utive model	Poisson ratio	Natural Density (g/cm3)	Force of Cohesion (kpa)	Angle of Internal Friction(°)
1	Miscellaneous fill	1.8	M-C	0.29	1.75	5	8
2	Silty clay	3.4	M-C	0.33	1.96	27	17
3	Medium coarse sand	2.2	M-C	0.26	1.98	0	28
4	Fully weathered mudstone	2.5	M-C	0.25	2.08	32	14
5	Highly weathered mudstone	11.2	M-C	0.24	2.12	60	25
6	Moderately weathered mudstone	18.9	M-C	0.21	2.22	120	35
7	Tube segment	0.65	Elasticity	0.20	2.50	-	-

2.4. Model meshing

To balance calculation accuracy and efficiency, the grid size in key areas requiring detailed analysis was refined to achieve higher resolution. The grid size for the pipe jacking tunnel was set to 1 m, while the grid size for the thermal pipeline, buried tunnel, existing underground pipe gallery, and light rail viaduct was set to 1.5 m. For the 1–6 soil layers, a grid size of 3 m was adopted. The model consisted of 24,254 elements and 42,408 nodes. The overall model mesh is illustrated in Figure 3.



(a)Mesh division of each component (b) Mesh division of Stratum

Figure 3 Model meshing

2.5. Simulation of pipe jacking construction process

The actual construction site for rectangular pipe jacking undergoes dynamic and continuous changes. However, finite element numerical simulation software cannot fully replicate these evolving site conditions. Therefore, the model is simplified to simulate the jacking-grouting process of excavation segments in the actual construction project. The specific construction steps are as follows:

(1) Initial stage: Activate all mesh groups, add boundary conditions and dead weight, check the displacement clear option, and start the initial stage analysis.

(2) Construction stage 1: Activate the bridge pile grid group, open the bridge pile displacement boundary and the upper load of the bridge. At the same time, the system should activate the thermal pipe, pipe gallery, and buried tunnel grids, and open the boundary conditions to ensure optimal functionality and efficiency.

(3) Displacement clearing: This step does not activate the data, nor does it passivate the data, only checks the displacement clearing option.

(4) Normal cycle excavation process: in the first construction step, the excavation grid 1 is passivated, the excavation force static load 1 is activated, and the grouting layer grid 1 is activated; in the second construction step, the grouting layer grid 2, the pipe jacking segment boundary condition 1, the static load jack force 1, the excavation force 2 and the friction resistance 1 are still activated; the passivation data is the excavation grid 2; And so on until all excavation and support complete the whole construction process of pipe jacking (total length 61.5 m).

3. Analysis of numerical simulation results

3.1. Analysis of surface deformation

During rectangular pipe jacking construction, the jacking project passes beneath the existing pipe gallery and thermal pipeline, while also advancing alongside the light rail pier. Consequently, strict control of surface deformation is essential. In this analysis, vertical displacement cloud diagram of the soil after excavations of 15 m, 30 m, 45 m, and 61.5 m were selected to study the vertical displacement behavior. The variation patterns of soil vertical displacement were then summarized based on these observations.

Figure 4 is the vertical displacement cloud diagram of soil with different excavation lengths. As shown in the numerical simulation results, when the jacking parameters do not change during the jacking process, the surface settlement exceeds the limit obviously, so it is necessary to adjust the jacking parameters such as grouting amount and grouting pressure during and after the jacking process. The established model parameters are adjusted according to the daily grouting records, pipe jacking records, unearthed records and pipe jacking measurement follow-up records recorded at the construction site, and simulated again. The simulation results are shown in Figure 5.

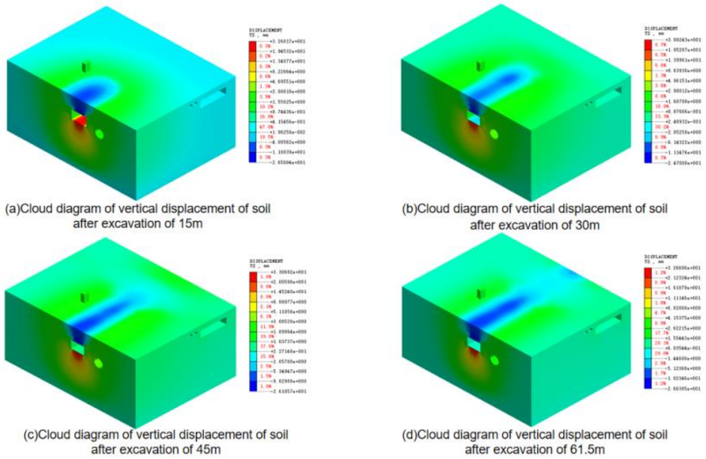


Figure 4 Cloud diagram of vertical displacement of soil with different excavation lengths

Figure 5 (a), (b), (c), and (d) show the vertical displacement cloud diagrams of the soil at excavation depths of 15 m, 30 m, 45 m, and 61.5 m, respectively, after optimizing the jacking parameters. The maximum surface settlement observed is 13.35 mm, which complies with the maximum allowable control value for surface settlement in pipe jacking tunnel construction projects. These results indicate that using the previous single set of jacking parameters increases the risk of exceeding settlement limits. Additionally, due to the 3.3% downhill slope of the tunneling line in this project, maintaining the proper alignment of the pipe jacking machine is challenging during steep jacking operations. Consequently, it is necessary to adjust jacking parameters based on surface settlement monitoring and deformation monitoring reports of existing structures throughout the jacking process.

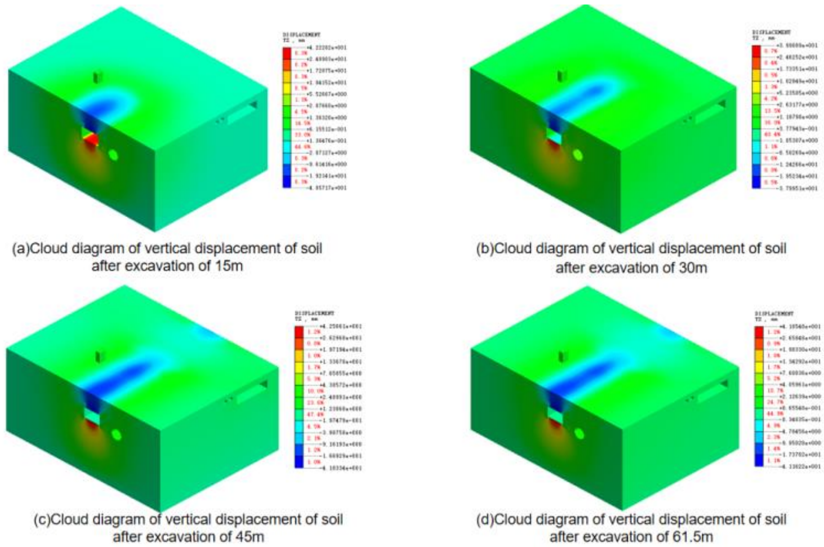


Figure 5 Cloud diagram of vertical displacement of soil with different excavation lengths after optimization of jacking parameters

3.2. Deformation analysis of existing structures

3.2.1. Deformation Analysis of Existing Light Rail Pier

During the construction of this pipe jacking project, measurements were taken on the pier side of the viaduct, necessitating an analysis of the pier's deformation. This analysis aims to identify and implement timely measures to prevent excessive settlement or tilting of the pier. In this section, the displacement cloud diagrams of the pier in the X direction (aligned with the pipe jacking direction) at distances of 15 m, 30 m, and 45 m from the pipe jacking excavation, as well as after the completion of pipe jacking construction, are analyzed. As shown in Figure 6, the closer the pier is to the pipe jacking operation, the greater the displacement observed due to the construction. When pipe jacking occurs within 10–20 m of the pier, it is critical to enhance monitoring of the pier and adjacent abutment on the pipe jacking side.

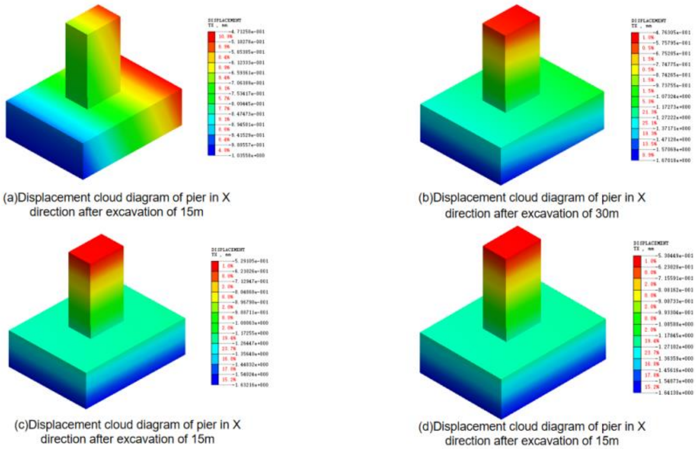


Figure 6 X direction displacement cloud diagram of piers with different excavation lengths

3.2.2. Deformation analysis of existing pipe gallery

Figure 7 presents the cloud diagrams of pipe gallery displacement at various excavation depths. As the excavation of the pipe jacking tunnel progresses, the vertical displacement of the existing pipe gallery exhibits a steadily increasing trend. The displacement intensifies with greater excavation depths, indicating a strong correlation between the vertical deformation of the pipe gallery and the depth of excavation.

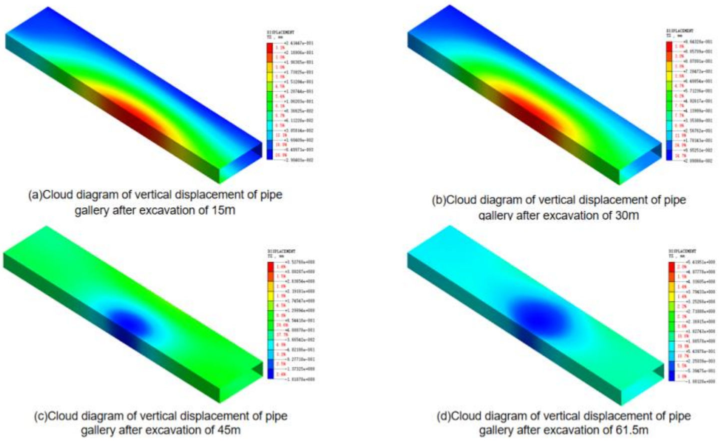


Figure 7 Cloud diagram of vertical displacement of pipe gallery with different excavation lengths

3.2.3. Deformation Analysis of Existing Thermal Pipeline

Figure 8 illustrates the displacement cloud diagrams of the thermal pipeline at various excavation depths. The displacement of the pipeline near the excavation area exhibits a significant upward trend, while sections farther from the excavation remain relatively stable. This pattern indicates that as tunnel excavation progresses, changes in the stress state of the surrounding soil generate an upward thrust on the pipeline.

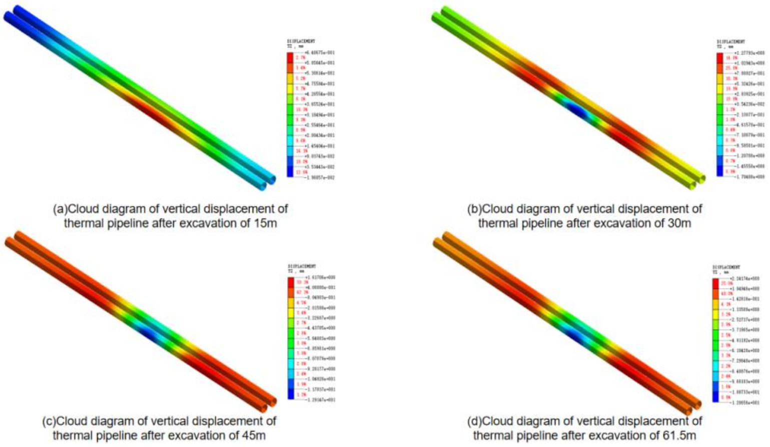


Figure 8 Cloud diagram of vertical displacement of thermal pipelines with different excavation lengths

3.2.4. Deformation Analysis of Existing Tunnel

Figure 9 presents the displacement cloud diagrams of the existing shield subway tunnel during rectangular pipe jacking construction. The displacement of the shield tunnel gradually increases as excavation advances. Initially, due to the shallow excavation depth, displacement changes are relatively minor. However, as the excavation depth increases, the vertical displacement of the shield tunnel becomes more pronounced due to the combined effects of soil deformation, groundwater infiltration, and construction disturbances.

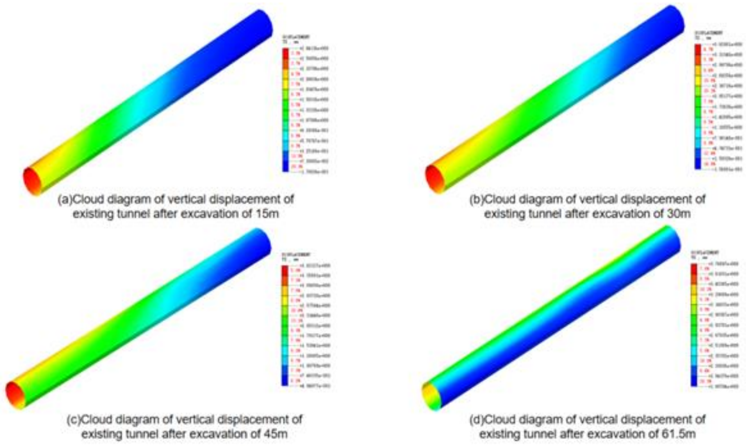


Figure 9 Cloud diagram of vertical displacement of existing tunnel with different excavation lengths

4. Conclusions

Based on finite element numerical simulation, this study systematically evaluates the impact of large-section rectangular pipe jacking construction on surface deformation and surrounding structures. The following conclusions are drawn:

(1)Large-section rectangular pipe jacking construction induces significant surface deformation, primarily manifested as settlement. Simulation results indicate that the degree of settlement increases progressively with the excavation length.

(2)Without optimization, surface settlement exceeds permissible limits. Adjusting jacking parameters effectively reduces maximum surface settlement to acceptable levels, highlighting the importance of parameter optimization in mitigating deformation risks.

(3)Surrounding structures, including light rail piers, pipe galleries, thermal pipelines, and shield tunnels, exhibit varying degrees of displacement. The extent of displacement is influenced by both the proximity to the excavation and the depth of the excavation.

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