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Ground Settlement Law, Jacking Force Prediction, and Control Countermeasures for Large-Section Rectangular Pipe Jacking of National Highway Underpass

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Abstract: The rectangular pipe jacking method is an efficient, green, trenchless technology for constructing urban underground space. However, some problems, including the high jacking resistance, the instability of the tunneling face, and excessive ground settlement during the large-section rectangular pipe jacking for the underpass of national highways, seriously affect construction safety and traffic. Based on the engineering background of the large-section rectangular pipe jacking in constructing the subway entrance tunnel of Guangzhou Metro Line 7, this work adopts the methods of theoretical calculation, numerical simulation, and engineering application. Five kinds of mechanical models for pipe soil slurry interactions in rectangular pipe jacking are analyzed. An evaluation of the applicability of the jacking force prediction of the different models is conducted. Moreover, the ground settlement law for the large-section rectangular pipe jacking for the underpass of national highways under different influencing factors, including slurry sleeve thickness, grouting pressure, and earth chamber pressure, is revealed. The control countermeasures of the ground settlements, such as installing a waterproof rubber curtain for the tunnel portal, pipe jacking machine receiving techniques, thixotropic slurry for reducing friction resistance, and soil stability at the tunneling face, are carried out. The results show that there is no need to install an intermediate jacking station in the large-section rectangular pipe jacking project with a jacking distance of 63 m. The most reasonable thickness of the thixotropic slurry sleeve is about 150 mm. The most reasonable grouting pressure range is 600–700 kPa. An earth chamber pressure of about 153 kPa is more reasonable to control the soil stability of the tunneling face. The engineering practice shows that the maximum ground settlement of the national highway during jacking is 10 mm. The maintenance effect is excellent, and the traffic operates normally.

Keywords: subway entrance; rectangular pipe jacking; jacking force; slurry sleeve; grouting pressure; earth chamber pressure; ground settlement; control countermeasures

Citation: Qian, D.; Jiao, H.; Li, Z.; Zhu, Y.; Liu, J.; Chen, Z.; Gao, X.; Liu, H.; Tao, B.; Xu, Z. Ground Settlement Law, Jacking Force Prediction, and Control Countermeasures for Large-Section Rectangular Pipe Jacking of National Highway Underpass. *Sustainability* **2023**, *15*, 12888. https://doi.org/10.3390/su151712888

Academic Editor: Minghua Huang

Received: 20 June 2023
Revised: 3 August 2023
Accepted: 24 August 2023
Published: 25 August 2023

1. Introduction

The development and utilization of underground space have become an effective way to solve the two development bottlenecks of urban construction land shortage and traffic congestion. The rectangular pipe jacking method is an efficient, green, trenchless technology for constructing urban underground space, which plays a crucial role in the sustainable development of urbanization and metropoles. The rectangular pipe jacking method has a wide range of application prospects in the development of underground space, including pedestrian tunnels, subway entrance tunnels, underground transportation, underground commerce, comprehensive pipe galleries, and municipal facilities. The approach has the advantages of green environmental protection, small construction sites, high cross-section utilization rates, and easy maintenance in the operation stage.

Many scholars have carried out research on the jacking force, strata disturbance law, and settlement control of rectangular pipe jacking, which provides a reference for the large-section rectangular pipe jacking constructing underground space. Zhou et al. [1] summarized the causes and main locations of strata loss through in situ observation results and calculated the formation loss rate of a project. Wang et al. [2] analyzed the causes of surface subsidence using field monitoring and numerical simulation and divided the ground deformation into four stages. The study found that the maximum ground subsidence occurred in the process of entering and leaving the tunnel. Gao et al. [3] proposed the "overall-carrying-soil effect" based on the rectangular pipe jacking test, proposed the preconditions and failure conditions of the overall soil effect, gave the corresponding prejudgment method, and analyzed the relationship among the overall soil effect, the jacking length, the segment width, the friction resistance of the pipe soil, and the buried depth. Dong [4] analyzed the monitoring data of Wuhan Metro and concluded that the ground subsidence caused by rectangular pipe jacking construction is unevenly distributed in the longitudinal direction. The settlement of the starting section is large, the settlement control in the middle is good, and the part near the reception shaft is uplifted. Zhang et al. [5] studied the surface deformation law caused by pipe jacking construction through numerical simulation and field monitoring. The monitoring points during pipe jacking construction mainly experienced three stages: rapid ground heave, a ground heave slowing stage, and a settlement stage. Liu et al. [6] analyzed the deformation law of an existing subway tunnel caused by the pipe jacking construction of an underground passage in Nanjing using numerical simulation and field testing. The results show that the subway tunnel structure presents horizontal compression and vertical tension. Zhang et al. [7] used Mindlin's solutions and stochastic medium theory to derive the analytical solution of the ground surface upheaval and settlement induced by rectangular pipe jacking considering the total influences of the additional excavation pressure due to the squeezing effect of the cutter head, softening and non-uniformly distributed shield skin–soil friction in soft soils, thixotropic mud-affected friction resistance between pipe segments and surrounding soils, grouting pressure, and soil loss. Ma et al. [8] studied the distribution characteristics of surface subsidence caused by buried depth and double-line pipe jacking construction through numerical simulation. In the range of about 1.6 times the width of the small section, the superimposed disturbance of the pipe jacking is obvious. Tang et al. [9] used the Peck formula and stochastic medium theory to calculate the surface settlement of rectangular pipe jacking in the Suzhou Chengbei Road Utility Tunnel. Compared with field measurements, the Peck formula is more accurate in predicting the settlement within 1.5 times the pipe jacking width, while the stochastic medium theory is more accurate in predicting the settlement beyond 1.5 times the pipe jacking width. Ma et al. [10] used the numerical simulation method to study the ground disturbance law for the jacking of four rectangular pipes under the same cross-sectional area and different height and width ratios. The results show that with the increase in the height and width ratio of the rectangular pipe jacking, the degree of disturbance to the ground decreases, and the required jacking force increases. Wang et al. [11] proposed a parallel rectangular pipe jacking stratum disturbance analysis model based on the Mindlin solution and random medium theory. The research shows that the disturbance range of the later pipe jacking construction is larger, and the maximum settlement value is close to the first pipe jacking. By analyzing the data of the earth pressure, pore water pressure, soil displacement, and surface settlement of a rectangular pipe jacking in Nanjing, Sun et al. [12] studied the law of surface settlement caused by rectangular pipe jacking construction and found that the surface settlement is mainly caused by the back soil effect. Hu et al. [13] proposed a method for predicting the surface settlement of a rectangular pipe jacking tunnel crossing an existing expressway. The improved particle swarm optimization (IPSO)–BP hybrid prediction model can predict the surface settlement law during the construction process in the ultra-shallow buried large-section rectangular pipe jacking tunnel project, and the results are more accurate, which can provide new ideas for settlement pre-control of similar projects. Li et al. [14] investigated a soil pressure balance rectangular pipe jacking project to find out the interaction of jacking control and ground settlement in Zhengzhou, China. Ground settlement increases during jacking, but the increasing amplitude decreases with the increase in cutter pressure, jacking force, and grouting. Ma et al. [15] explored the construction stability and reinforcement technology of the super-large rectangular tunnel when excavating under the operational high-speed railway in the composite stratums. Ma et al. [16] proposed a new pipe–soil contact model to predict the jacking force under grouting and verified the prediction results by numerical simulation and field monitoring data. Jiao et al. [17] proposed a jacking force calculation model coupling the finite difference method and jacking force–jacking control method considering influencing factors such as construction stoppages, pipe buoyancy, and lubrication volumes. Chen et al. [18] presented a case study of a 233.6-meter-long utility tunnel constructed by using a large-section rectangular box jacking in Suzhou, China. The box jacking passed through a silty sand layer with groundwater, and the minimum depth of overburden was only 3.5 m when crossing underneath the Yuanhetang River. An earth pressure balance (EPB) pipe jacking machine with a combined cutter plate was adopted to reduce the disturbance to the ground. At present, some progress has been made in the study of the pipe–soil contact model and ground settlement law in terms of rectangular pipe jacking. However, there are still some problems in the construction of large-section rectangular pipe jacking for underpass road engineering, such as large jacking resistance, easy instability of soil on tunneling face, and ground settlement control, which seriously restrict the construction safety of large-section rectangular pipe jacking and the traffic safety of national highways during pipe jacking.

Based on the rectangular pipe jacking project at the subway entrance and exit No.1 (subway entrance No.1) of Lintou Station, Guangzhou Metro Line 7, this paper analyzes the jacking force under five mechanics models of rectangular pipe–soil contact. The originality and novelty of this study include conducting the evaluation of the applicability of the jacking force prediction of the different models and revealing the ground settlement law of the large-section rectangular pipe jacking of a national highway underpass under different influencing factors, including slurry sleeve thickness, grouting pressure, and earth chamber pressure, using the geotechnical engineering finite element software MIDAS GTS NX 2021. The main objectives are to propose ground settlement control countermeasures, which can provide practical referable significance for similar pipe jacking projects.

2. Engineering Geological Profiles for Large-Section Rectangular Pipe Jacking

2.1. Engineering Profiles

Lintou subway station, on Guangzhou Metro Line 7, is located along the side of the national highway G105, i.e., G105 Jingzhu (from Beijing City to Zhuhai City) Line (Figure 1). The subway entrance No.1, an underpass of the G105 Jingzhu line, was opened at the same time as Lintou subway station and has an underground single-layer (local two-layer) frame structure. Subway entrance No.1 was constructed using the EPB rectangular pipe jacking method.

The length of the rectangular pipe jacking is 63 m, and the thickness of the overlying soil is 6 m. The section size is 7 m wide and 5 m high, and the wall thickness of the pipe segments is 0.45 m. The pipe segments are prefabricated using C50 concrete. The segments are connected using F-type sockets, and the length of each segment is 1.5 m.

Figure 1. Plan of pipe jacking at entrance and exit No.1 of Lintou station, Guangzhou Metro Line 7.

2.2. Geological Conditions

The terrain of this project is relatively flat, and the main strata from the top to the bottom are an artificial fill layer, a muddy silt fine sand layer, a muddy soil layer, silty clay, fully weathered argillaceous siltstone, and highly weathered argillaceous siltstone, respectively. The characteristics of the soil layers are shown in Table 1.

Table 1. Soil layer characteristics.

Number	Soil Name	Soil Layer Description
1	Artificial fill layer	Most are plain fill and a few are miscellaneous fill, mainly filled in the past 10 years. The plain fill is mainly composed of cohesive soil, medium–coarse sand, gravel, and other artificial fills. The miscellaneous fill contains construction waste such as bricks and concrete blocks.
2	Muddy silt fine sand layer	This layer is mainly muddy silty fine sand, silty fine sand, gray-black and dark gray in color. It is saturated, loose, and has good particle gradation.
3	Muddy soil layer	It is layered or lenticularly distributed under the fill layer and often forms an interbedded layer with thin muddy sand.
4	Silty clay	It is green–gray and yellowish brown, mainly plastic, with smooth sections and a small amount of sand. It has good toughness and general dry strength.
5	Fully weathered argillaceous siltstone	The weathering is severe, the structure has been basically weathered and destroyed, and the local rock is strongly weathered. The core is hard soil or dense soil, and the immersion is easy to soften and disintegrate.
6	Highly weathered argillaceous siltstone	It is brownish red, grayish brown, gray, etc., and of a sandy structure, medium–thick layered structure, and argillaceous cementation. The joint fissures are more developed, and the rock mass is more broken.

2.3. Analysis of Key and Difficult Points in Construction

(1) High requirements for ground settlement control

The size of the pipe jacking section is 7 m wide and 5 m high, and the cross-section is large. During the jacking process, it is easy to drive the upper soil of the pipe jacking machine to move together. The larger the size of the pipe jacking machine, the larger the range of the upper soil affected, resulting in inevitable soil disturbance. The pipe jacking project of subway entrance No.1 passes under the G105 national highway, and the ground settlement control requirements are extremely high, which must not affect traffic operations.

(2) Water leakage at the tunnel portal may lead to ground settlements

The pipe jacking project at subway entrance No.1 mainly passes through the silty fine sand layer and silt soil layer. The soil layer has a rich water content, and sand gushing and pipe leakage may occur during the pipe jacking initiation, jacking process, and receival. In the process of jacking, the cutting and vibration of the cutter head of the pipe jacking machine are likely to cause the liquefaction of the fine sand soil so that the soil loses its shear resistance, resulting in groundwater gushing and sand gushing. This region was originally a backfilling river, and the groundwater is rich. Because there is a certain diameter difference between the tunnel door and the pipe jacking machine, it is easy for the groundwater to flow along the gap, and the outflow of groundwater forms a seepage channel, taking away the soil particles at the tunnel door, resulting in soil loss, formation loss, and ground settlement.

(3) The jacking force through the muddy silt fine sand is large.

The upper part of the pipe jacking machine passes through the muddy silt fine sand, and the lower section passes through the muddy soil. The friction resistance between the muddy silt fine sand and the segment is large.

3. Jacking Force Prediction for Large-Section Rectangular Pipe Jacking

3.1. Mechanical Model of Jacking Force Calculation

The surrounding soil hinders the process of pipe jacking. The friction coefficient between the pipe segments and the surrounding soil is determined by the friction angle δ (°) between the soil and the pipe segments, as follows [19]:

$$\mu_1 = \tan(\delta), \tag{1}$$

where μ_1 is the friction coefficient between the pipe and soil, and δ is the angle of friction between the soil and the external surface of the pipe.

The shear stress between the pipe jacking and slurry is calculated according to the parallel plate fluid model (Figure 2) [20].

$$du = \frac{v}{t}dy, \tag{2}$$

$$\tau_1 = k\gamma^m = k\left(\frac{du}{dt}\right)^m = k\left(\frac{v}{t}\right)^m, \tag{3}$$

In the formulae, du is the relative change value of flow velocity between two parallel plates; dy is the relative distance change value along the y-axis; t is the thickness of the slurry sleeve; τ_1 is the shear stress between the pipe and slurry; γ is the slurry deformation rate tensor; m is the flow parameter of thixotropic slurry, which can be tested by Fann viscometer; k is the viscosity of the slurry; and v is the jacking speed.

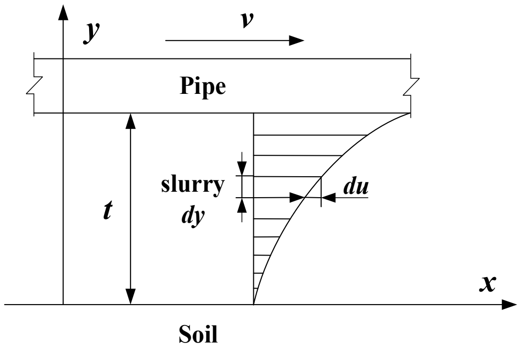


Figure 2. Schematic diagram of interaction between pipe and slurry.

The jacking force F_A is composed of tunneling face pressure F_1 and the friction force F_f. The calculation expression of the jacking force F_A is

$$F_A = F_1 + F_f, \tag{4}$$

where F_1 is the tunneling face pressure, and F_f is the friction force.

The tunneling face pressure F_1 can be estimated empirically using the standard penetration test (SPT) N-value [21,22].

$$F_1 = 10 \times 1.32A \times N \tag{5}$$

Here, A is the area of the tunneling face, and N is the SPT N-value.

According to engineering experience, the data can be simplified into the following equation [20,21]:

$$F_1 = 13.2 \times A \times N', \tag{6}$$

where A is the area of the tunneling face, and N' is the empirical factor, which equals 1.0 for clayed soil, 2.5 for sandy soil, and 3.0 for gravel soil [22].

In the process of pipe jacking, the slurry sleeve can effectively reduce the friction resistance required for jacking [23,24]. The segment is affected by its own gravity and the buoyancy of the slurry, and there may be a variety of contact states between the segment and the slurry sleeve [25,26]. This paper analyzes five different pipe–soil–slurry interaction models [27,28] and makes the following assumptions. The influence of grouting pressure on the slurry sleeve is not considered. The jacking speed is taken as the slurry flow velocity between the two parallel plates of the jacking pipe and the slurry. Due to the incompressibility of grouting slurry, the effective width of the slurry sleeve is calculated using the width of the over-excavation area to simplify the calculation.

(1) Model 1: Full pipe–soil contact (Figure 3) [27,29]

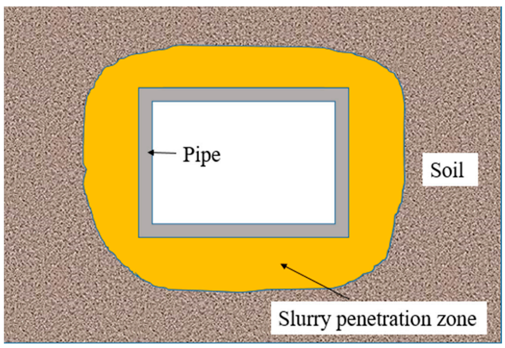


Figure 3. Full pipe–soil contact model.

The jacking force of the full contact model (no arching effect) is as follows [27]:

$$F_A = \mu_1 L[2\gamma_s H(h+b) + \gamma_s hb + \gamma_s h^2 + W] + 13.2AN', \tag{7}$$

In the formula, F_A is the jacking force; b is the external width of the pipe jacking; h is the external height of the pipe jacking; μ_1 is the friction coefficient between the pipe and soil; L is the jacking distance; γ_s is the unit weight of the soil; H is the burial depth of the pipe; W is the weight of the pipe per unit length; and A is the area of the tunneling face.

The thrust calculation parameters in Figure 4b are calculated using the following formula [27]:

$$\left.\begin{aligned} &b_0 = b + 2h\tan(45^\circ - \varphi/2), \\ &h_0 = \frac{b_0}{2\tan\varphi}, R = \frac{b_0}{2\sin 2\varphi}, \\ &\omega = \arcsin(b/2R), \\ &n = \sqrt{r^2 - (b/2)^2}, \end{aligned}\right\} \tag{8}$$

$$\left.\begin{aligned} &S_1 = \frac{\varphi\pi R^2}{180} - \frac{b_0}{4}(R - h_0), \\ &S_2 = (\frac{\varphi\pi R^2}{360} - \frac{nb}{4}) + \tfrac{b}{2}(n + h_0 - R), \\ &S_3 = S_1 - S_2, \\ &S_4 = \frac{1}{2}h_2\tan(45^\circ - \varphi/2), \end{aligned}\right\} \tag{9}$$

where b_0 is the collapse width; h_0 is the collapse height; R is the radius of arc ACB; ω is the central angle of the arc ACB; n is the calculation parameter; S_i (i = 1,2,3,4) is the area of each region in Figure 4b; and φ is the internal friction angle of the soil.

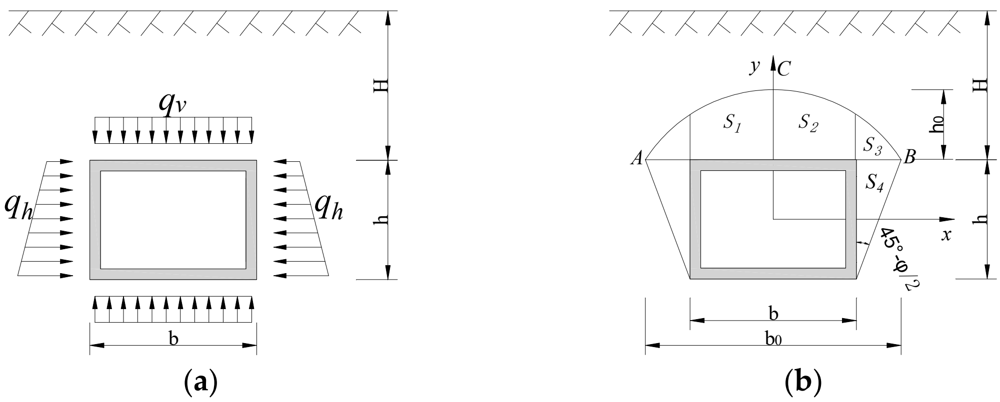


Figure 4. Stress diagram of full pipe–soil contact: (**a**) no arching effect; (**b**) arching effect.

The jacking force of the pipe–soil full contact model (arching effect) [27]:

$$F = \mu_1 L\left[(4S_2\gamma_s + W) + \frac{(S_3 + S_4)\gamma_s}{\tan(45^\circ - \varphi/2)}\right] + 13.2AN', \tag{10}$$

In the formula, F_A is the jacking force; μ_1 is the friction coefficient between the pipe and soil; γ_s is the unit weight of the soil; L is the jacking distance; A is the area of the tunneling face; and N' is the empirical factor.

(2) Model 2: Pipe–slurry interaction at the bottom (Figure 5) [27]

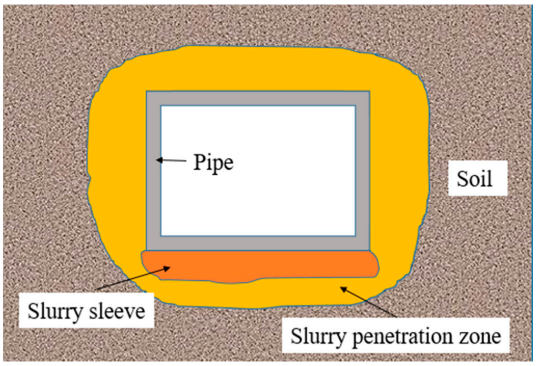


Figure 5. Pipe–slurry interaction at the bottom.

The thickness of the slurry sleeve is calculated using the following formula:

$$t = \frac{2(b+h)}{b}B, \tag{11}$$

In the formula, t is the thickness of the slurry sleeve; b is the external width of the pipe jacking; h is the external height of the pipe jacking; and B is the initial over-excavation width.

The shear stress between the pipe and slurry is calculated using the following formula:

$$\tau_1 = k[\frac{vb}{2B(b+h)}]^m, \tag{12}$$

where τ_1 is the shear stress between the pipe and slurry; b is the external width of the pipe jacking; h is the external height of the pipe jacking; k is the viscosity of the slurry; m is the flow parameter of thixotropic slurry; v is the jacking speed; and B is the initial over-excavation width.

The jacking force of the bottom slurry interaction is as follows [27]:

$$F_A = L[\tau_1 b + \mu_1(p_s b + W + \gamma_s Hh + \frac{1}{2}\gamma_s h^2)] + 13.2AN', \tag{13}$$

F_A is the jacking force in the formula; τ_1 is the shear stress between the pipe and slurry; p_s is the grouting pressure; μ_1 is the friction coefficient between the pipe and soil; h is the external height of the pipe jacking; H is the burial depth of the pipe; b is the external width of the pipe jacking; γ_s is the unit weight of the soil; A is the area of tunneling; N' is the empirical factor; and L is the jacking distance.

(3) Model 3: Pipe–slurry interaction at the bottom and 1/2 of both sides (Figure 6) [27]

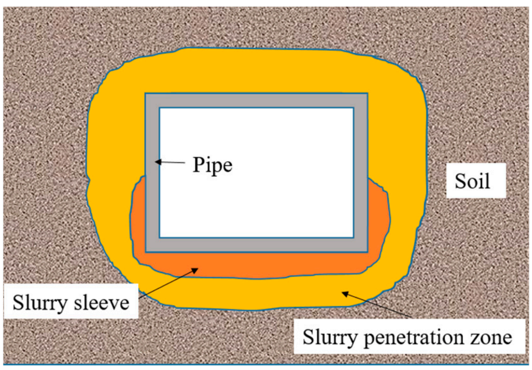


Figure 6. Pipe–slurry interaction at the bottom and 1/2 of both sides.

The thickness of the slurry sleeve is calculated using the following formula:

$$t = \frac{2(b+h)}{b+h}B = 2B, \tag{14}$$

In the formula, t is the thickness of the slurry sleeve; b is the external width of the pipe jacking; h is the external height of the pipe jacking; and B is the initial over-excavation width.

The shear stress between the pipe slurry is calculated using the following formula:

$$\tau_1 = k(\frac{v}{2B})^m, \tag{15}$$

In the formula, τ_1 is the shear stress between the pipe and slurry; b is the external width of the pipe jacking; h is the external height of the pipe jacking; k is the viscosity of the slurry; m is the flow parameter of thixotropic slurry; v is the jacking speed; and B is the initial over-excavation width.

The jacking force of the pipe–slurry interaction between the bottom and 1/2 of both sides is calculated as follows [27]:

$$F_A = L\{\tau_1(h+b) + \mu_1[p_s(b+h) + W]\} + 13.2AN', \tag{16}$$

where F_A is the jacking force; τ_1 is the shear stress between the pipe and slurry; p_s is the grouting pressure; μ_1 is the friction coefficient between the pipe and soil; b is the external width of the pipe jacking; h is the external height of the pipe jacking; A is the area of the tunneling face; N' is the empirical factor; and L is the jacking distance.

(4) Model 4: Pipe–slurry interaction at the bottom and both sides (Figure 7) [27]

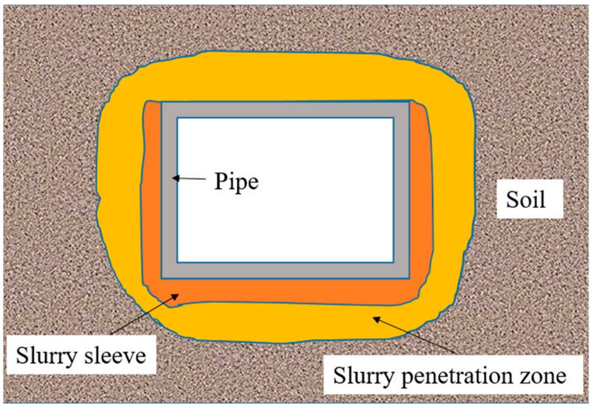


Figure 7. Pipe–slurry interaction at the bottom and both sides.

The thickness of the slurry sleeve is calculated using the following formula:

$$t = \frac{2(b+h)}{b+2h}B, \tag{17}$$

In the formula, T is the thickness of the slurry sleeve; b is the external width of the pipe jacking; h is the external height of the pipe jacking; and B is the initial over-excavation width.

The shear stress between the pipe slurry is calculated as follows:

$$\tau_1 = k[\frac{v(b+2h)}{2B(b+h)}]^m, \tag{18}$$

where τ_1 is the shear stress between the pipe slurry; b is the external width of the pipe jacking; k is the consistency coefficient; m is the flow parameter of thixotropic slurry; v is the jacking speed; and B is the initial over-excavation width.

The jacking force of the pipe–slurry interaction at the bottom and both sides is calculated as follows [27]:

$$F_A = L[\tau_1(2h + b) + \mu_1(p_s b_1 + W)] + 13.2AN', \quad (19)$$

where F_A is the jacking force; τ_1 is the shear stress between the pipe and slurry; p_s is the grouting pressure; μ_1 is the friction coefficient between the pipe and soil; b is the external width of the pipe jacking; h is the external height of the pipe jacking; A is the area of the tunneling face; N' is the empirical factor; and L is the jacking distance.

(5) Model 5: Full contact of pipe–slurry (Figure 8) [27]

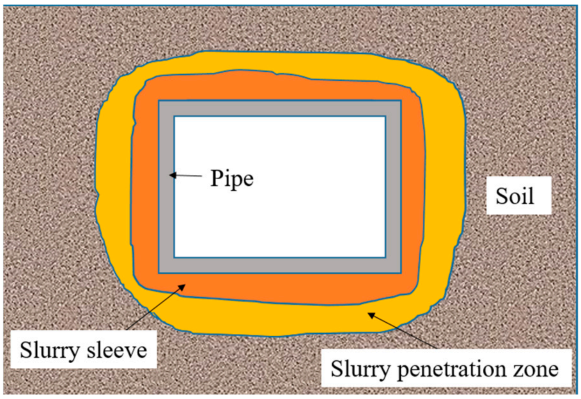


Figure 8. Full contact pipe–slurry interaction.

The shear stress between the pipe and slurry is calculated using the following formula:

$$\tau_1 = k\left(\frac{v}{B}\right)^m, \quad (20)$$

where τ_1 is the shear stress between the pipe and slurry; k is the viscosity of the slurry; m is the flow parameter of thixotropic slurry; v is the jacking speed; and B is the initial over-excavation width.

The jacking force of the full contact pipe–slurry model is calculated as follows [27]:

$$F_A = 2\tau_1 L(h + b) + 13.2AN', \quad (21)$$

where F_A is the jacking force; τ_1 is the shear stress between the pipe and slurry; b is the external width of the pipe jacking; h is the external height of the pipe jacking; A is the area of the tunneling face; N' is the empirical factor; and L is the jacking distance.

3.2. Jacking Force Prediction Analysis and Model Applicability Evaluation

To evaluate the applicability of five kinds of pipe soil slurry contact models for rectangular pipe jacking, this paper compares the jacking force of five models with the empirical jacking force prediction formula of the *Technical specification for pipe jacking engineering with rectangular cross section* (T/CECS716-2020) summarized by the actual construction situation from China's Association for Engineering Construction Standardization [29]. The jacking force formula in the *Technical specification for pipe jacking engineering with rectangular cross section* is as follows [29]:

$$F_A = \gamma_s H K_a bh + 2f(b + h)L \quad (22)$$

where F_A is the jacking force; γ_s is the unit weight of the soil; H is the burial depth of the pipe; Ka is the main dynamic earth pressure coefficient; b is the external width of the pipe jacking; h is the external height of the pipe jacking; f is the frictional resistance of the contact surface between the pipe surface and the soil per unit area. According to the pipe jacking calculation parameters in Table 2 and the *Technical specification for pipe jacking engineering* *with rectangular cross section* (T/CECS716-2020), f is taken as 10 kN/m^2, and L is the jacking distance.

Table 2. Pipe jacking calculation parameters.

Pipe Jacking Parameters	Parameter Value
External width of jacking pipe, b (m)	7
External height of jacking pipe, h (m)	5
Unit weight of soil, γ_s (kN/m^3)	17.4
Internal friction angle, φ (°)	28
Flow parameter of thixotropic slurry, m	0.5
Viscosity of slurry, k (Pa·s$^{0.5}$)	1.31
Coefficient of friction, μ_1	0.4
Weight of pipe per unit length, W (kN/m)	270
Burial depth of pipe, H (m)	6
Initial over-excavation width of pipe jacking, B (m)	0.15
Jacking speed, v (m/s)	0.0003
Grouting pressure, p_s (Pa)	0.1
Jacking distance, L (m)	63
Empirical factor, N'	2.5

The jacking force prediction results of each model are shown in Figures 9 and 10. The jacking force of rectangular pipe jacking increases linearly with the jacking distance. The jacking force of Model 1 (arching effect) is slightly smaller than that of Model 1 (no arching effect). Due to the small buried depth and large section size of the project, the arch effect is not obvious under the full contact model. Among the five models, the jacking force prediction value of Model 1 (no arching effect) is the largest, and the jacking force prediction value of Model 5 is the smallest. With the increase in the contact area between the pipe jacking and the slurry, there is an obvious decrease in the jacking force per unit jacking length.

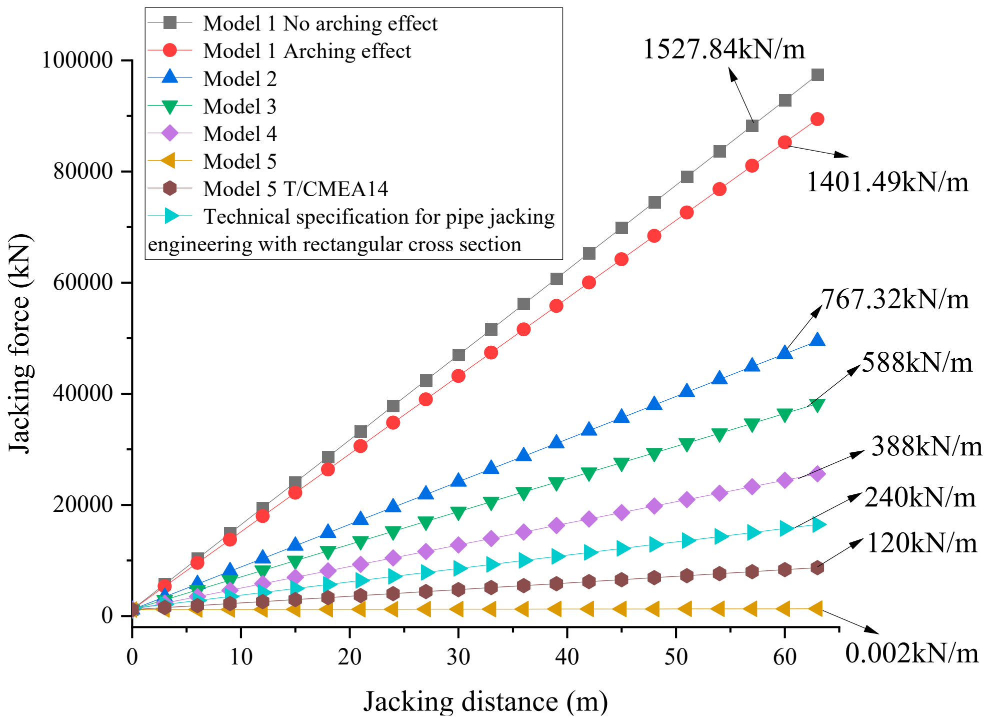


Figure 9. Jacking force prediction with distance under different models.

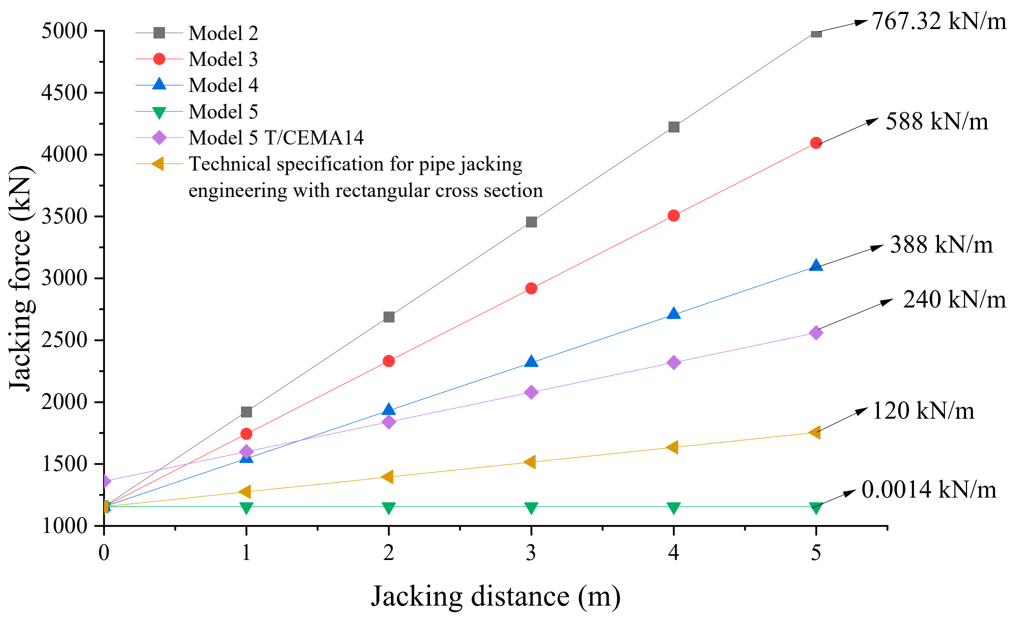


Figure 10. Partially enlarged detail of jacking force prediction with distance under different models.

When the model is in full contact with the pipe slurry, the outer surface of the pipe segment can form a continuous and complete slurry sleeve. According to the *Technical standard for rectangular pipe jacking of comprehensive pipe gallery* (T/CMEA14-2020) [30], the friction resistance per unit area of the pipe surface can be taken as 3–5 kN/m^2. Taking 5 kN/m^2 into Formula (21) to replace the shear stress between the pipe and slurry, the jacking force prediction is shown in Model 5-T/CMEA14-2020 in Figures 9 and 10.

In the initial jacking stage of the pipe jacking project, a large amount of slurry leakage occurs, the integrity of the slurry sleeve is low, and the drag reduction effect is not obvious; in the stable jacking stage, the slurry sleeve is relatively complete, and the resistance reduction effect is remarkable. In practical engineering, different jacking force calculation models can be selected to predict the jacking force according to the different jacking stages of the project. The jacking force per unit length of the full contact model is too small, which is not in line with the actual situation. According to the *Technical standard for rectangular pipe jacking of comprehensive pipe gallery* (T/CMEA14-2020) [30], the calculation formula of the full contact model of the pipe–slurry is modified. The modified calculation formula can effectively predict the jacking force of rectangular pipe jacking in full pipe–slurry contact.

Through the comparative analysis of the prediction results of the jacking force of the five models and the results obtained by the *Technical specification for pipe jacking engineering with rectangular cross section* (T/CECS716-2020) formula, it can be seen that the jacking force from Model 4 (bottom and both sides of the pipe–slurry contact) is close to that of the specification summarized according to the actual jacking construction situation. In the stable jacking stage, the contact state between the segment and the slurry is between Model 4 and Model 5 (full contact of pipe–slurry).

Under rectangular pipe jacking construction, the reaction force that the back wall could afford should be 1.2 times larger than the maximum jacking force of the rectangular pipe jacking. The calculation formula of the reaction force from the back wall is as follows [31]:

$$R = \alpha B_q[(\gamma_s H_q K_p/2 + 2cH_qK_p + \gamma_s h_q H_q K_p)], \tag{23}$$

where R is the reaction force in the back wall in the starting shaft; α is the coefficient, taken to be 2.5; B_q is the width of the back wall, which is 8 m; γ_s is the soil bulk density, which is 17.4 kN/m^3; H_q is the height of the back wall, which is 5.3 m; K_p is the passive earth pressure coefficient; c is the soil cohesion, taken to be 8.65 kPa; and h_q is the height of the soil from the ground to the top of the back wall, which is 5.4 m.

The calculated reaction force that the back wall could afford is 56945.97 kN. The jacking forces of the five models are 97408.92 kN, 89448.87 kN, 49496.16 kN, 38199.00 kN, 25599.00 kN, and 1155.10 kN, respectively. The reaction force of the back wall is 1.49 times the jacking force of Model 3 (pipe–slurry interaction at the bottom and 1/2 of both sides), which meets the design jacking force of the rectangular pipe jacking, which is between Model 4 and Model 5. In summary, the 63 m long rectangular pipe jacking project does not need to install the intermediate jacking stations using grouting to control the distribution of slurry and reduce the friction resistance.

4. Ground Settlement Law of Large-Section Rectangular Pipe Jacking of a National Highway Underpass

4.1. Numerical Modeling

The geotechnical finite element software MIDAS GTS NX was used to model the rectangular pipe jacking of the national highway underpass (Figure 11). Considering the boundary effect, the specific sizes of the model, with a total of 122,053 units and 73,399 nodes, are 60 m wide, 63 m long, and 40 m high, respectively. The top burial depth of the pipe jacking is 6 m. The distances of the pipe jacking from the left and right boundaries of the model are both 26.5 m. The distance of the pipe jacking from the bottom boundary of the model is 29 m, and the total jacking length is 63 m. The lateral boundary of the model constrains the horizontal displacement, while the bottom boundary constrains the horizontal and vertical displacements. The upper boundary is a free surface.

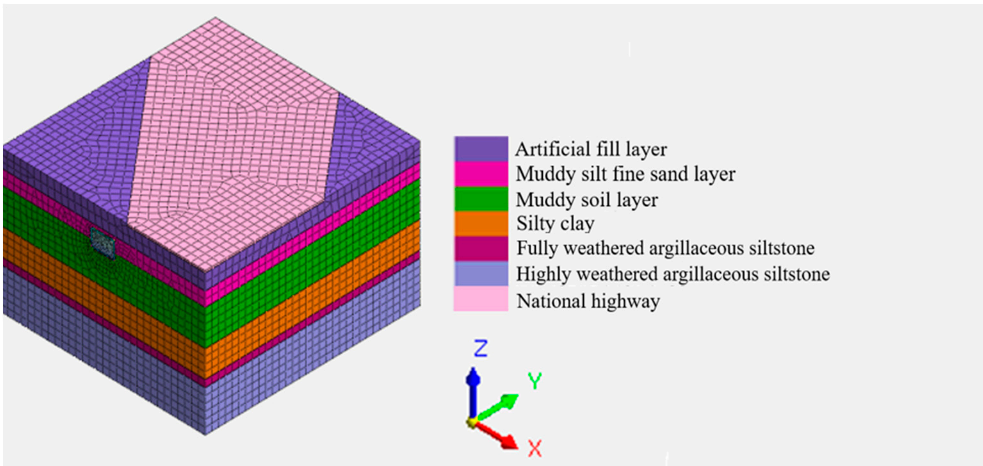


Figure 11. Numerical simulation model.

The modified Mohr–Coulomb constitutive model was used to simulate the soil of each stratum in this project. The elastic model was used to simulate the national highway, segment, grouting layer, and pipe jacking casing. The physical and mechanical parameters of the surrounding soil layer and the pipe jacking construction parameters are shown in Tables 3 and 4 according to the engineering geology investigation reports.

Table 3. Physical and mechanical parameters of soil layers.

Soil Horizon	Thickness (m)	Natural Weight-Specific Density (kN/m^3)	Poisson Ratio	Cohesion (kPa)	Angle of Internal Friction (°)	Secant Modulus (MPa)	Tangent Modulus (MPa)	Unloading Modulus (MPa)
Artificial filling soil layer	5	17.5	0.34	14	30	8	8	24
Muddy silt fine sand layer	4	17.2	0.3	2	28	10	10	60
Muddy soil layer	10	17.2	0.3	8	4	2	2	20

Table 3. *Cont.*

Soil Horizon	Thickness (m)	Natural Weight-Specific Density (kN/m^3)	Poisson Ratio	Cohesion (kPa)	Angle of Internal Friction (°)	Secant Modulus (MPa)	Tangent Modulus (MPa)	Unloading Modulus (MPa)
Silty clay	7.5	19.6	0.3	16	12	13	13	52
Fully weathered argillaceous siltstone	2	21.1	0.3	20	12	34	34	130
Highly weathered argillaceous siltstone	11.5	20.1	0.3	21	27	50	50	200

Table 4. Pipe jacking construction parameters.

Name	Unit Type	Constitutive Model	Elastic Modulus (kPa)	Poisson Ratio	Unit Weight (kN/m^3)
Pipe jacking casing	2D plate element	elasticity	200,000,000	0.25	78.5
Grouting layer	entity units	elasticity	100,000	0.3	20
Pipe segment	entity units	elasticity	35,000,000	0.2	25

4.2. Simulation of Construction Process of Rectangular Pipe Jacking

Due to the complex and changeable geological conditions and construction parameters during the rectangular pipe jacking construction, the following simplifications and assumptions were made in the process of establishing the numerical simulation model.

- Each soil layer is regarded as a continuous, homogeneous, and isotropic elastic–plastic solid, and the soil layer with ups and downs and staggered changes is simplified into a flat soil layer.
- The pipe jacking segment and the head are regarded as elastomers.
- The earth chamber pressure, grouting pressure, friction force, and jacking force applied on the segments are regarded as a uniform load.
- The influence of groundwater is not considered.
- The instantaneous settlement during jacking is studied without considering the consolidation settlement of the soil.

Pipe jacking construction is a continuous and dynamic process. At present, the numerical simulation software generally simulates the advancement of pipe jacking using passivation of the excavation strata, activating the pipe jacking machine shell, segments, and grouting layer to achieve segmented excavation and jacking. The earth chamber pressure is applied on the front tunneling face in each excavation section. The friction and grouting pressure are applied on the outside of the pipe segments, and the jacking force is applied behind the new jacking pipe segment. The excavation of the rectangular pipe jacking project is simulated by jacking 3 m (two pipe segments' length) each time.

4.3. Ground Settlement Law during Large-Section Rectangular Pipe Jacking

According to the engineering geological conditions of subway entrance No.1 of Lintou Station, Guangzhou Metro Line 7, the calculation model of the large-section rectangular pipe jacking of the national highway underpass is established, and the surface settlement law of the pipe jacking process under the main influencing factors, such as slurry sleeve thickness, grouting pressure, and earth chamber pressure, is analyzed.

The earth chamber pressure F_2 can be calculated according to Formula (24):

$$F_2 = K_0\gamma_s(H + 2\,h/3) + \gamma_w(H_w + 2\,h/3), \tag{24}$$

where F_2 is the earth chamber pressure; γ_s is the soil bulk density, which is 17.4 kN/m^3; K_0 is the static earth pressure coefficient, taken to be 0.55; H is the top burial depth of the pipe jacking, taken to be 6 m; h is the external height of the pipe jacking, taken to be 5 m; γ_w is the bulk density of water, taken to be 10 kN/m^3; and H_w is the distance from the top of the pipe to the groundwater level, taken to be 3 m. The calculated chamber pressure is 153 KPa.

The simulation schemes are as follows.

- The vertical displacements of the ground surface during large-section rectangular pipe jacking of the national highway underpass under different slurry sleeve thicknesses of 50 mm, 150 mm, and 300 mm are analyzed when the grouting pressure is 200 kPa, and the earth chamber pressure is 153 kPa.
- The vertical displacements of the ground surface during jacking under grouting pressures of 100 kPa, 200 kPa, 300 kPa, 400 kPa, 500 kPa, 600 kPa, 700 kPa, and 800 kPa are analyzed when the slurry sleeve thickness surrounding the rectangular pipe jacking is 150 mm, and the earth chamber pressure is 153 kPa.
- The surface displacements of the ground surface during jacking under different earth chamber pressures of 100 kPa, 153 kPa, 200 kPa, and 250 kPa are analyzed when the slurry sleeve thickness surrounding the rectangular pipe jacking is 150 mm, and the grouting pressure is 200 kPa.

4.3.1. Ground Settlement Law during Jacking under Different Slurry Sleeve Thicknesses

The maximum ground settlements at the jacking distance of 30 m (the cross-section y = 30 m) after finishing jacking are 6.40 mm, 7.38 mm, and 9.62 mm, respectively, when the thicknesses of the slurry sleeve are 50 mm, 150 mm, and 300 mm (Figure 12).

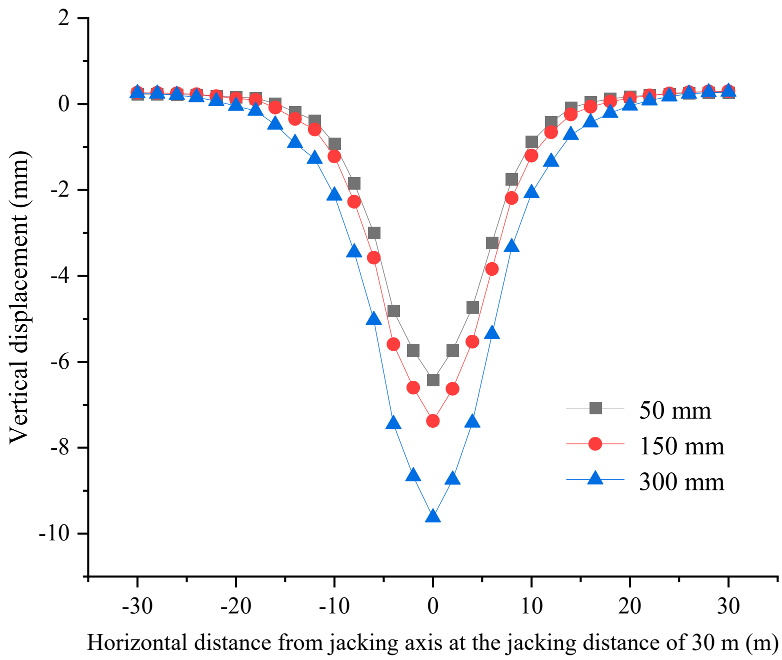


Figure 12. Vertical displacements of ground surface at the jacking distance of 30 m (the cross-section y = 30 m) under different slurry sleeve thicknesses after finishing jacking.

The corresponding maximum ground settlements above the jacking axis after finishing jacking are 13.10 mm, 14.40 mm, and 18.10 mm, respectively, when the thicknesses of the slurry sleeve are 50 mm, 150 mm, and 300 mm (Figure 13).

According to the maximum ground settlement results under the three kinds of slurry sleeve thicknesses, the greater the thickness of the slurry sleeve, the greater the ground settlement. As the thickness of the slurry sleeve increases, the larger the over-excavation area, the greater the disturbance to the soil, and the greater the ground settlement. However, the effect of reducing friction resistance is not obvious when the thickness of the slurry sleeve is too small. In the actual project, the thickness of the slurry sleeve is determined to be 150 mm, considering the two factors of ground settlement and friction resistance.

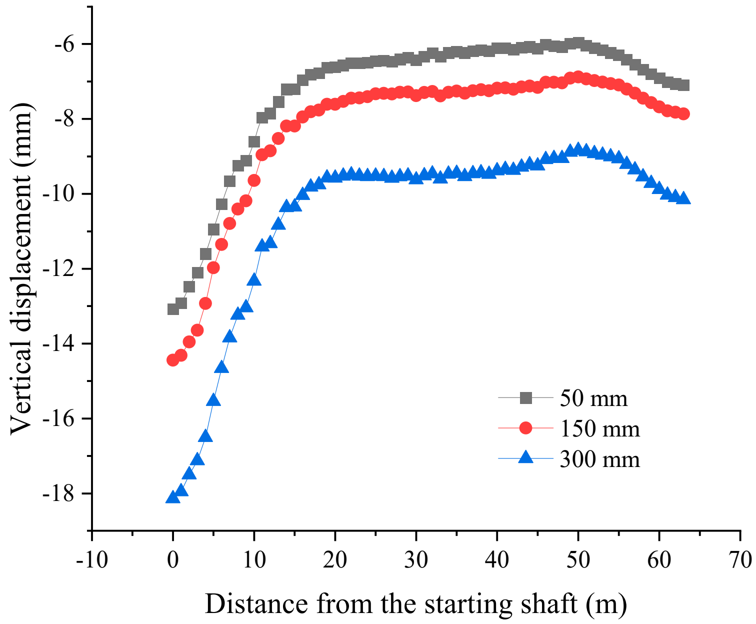


Figure 13. Vertical displacements of ground surface above the jacking axis under different slurry sleeve thicknesses after finishing jacking.

4.3.2. Ground Settlement Law during Jacking under Different Grouting Pressures

Within the range of grouting pressure from 100 kPa to 600 kPa, the maximum ground settlement caused by pipe jacking construction decreases with the increase in the grouting pressure (Figure 14). The decreasing rate of the maximum surface settlement becomes smaller and smaller; however, there is grouting-induced ground heave when the grouting pressure is 700–800 kPa. The surface disturbance range changes slightly under the eight grouting pressures.

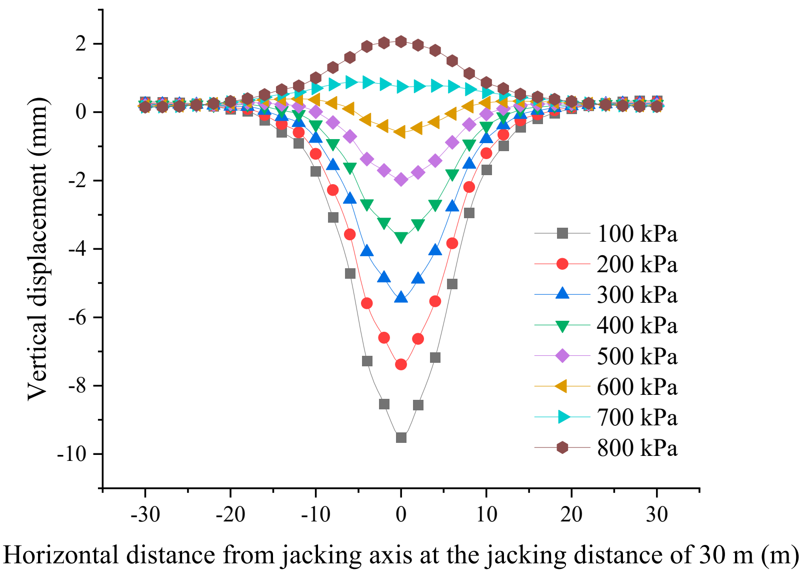


Figure 14. Vertical displacements of ground surface at the jacking distance of 30 m (the cross-section y = 30 m) with the horizontal distance from jacking axis varying under different grouting pressures after finishing jacking.

A reasonable grouting pressure and grouting amount have a great effect on the controlling ground settlement during the construction of large-section rectangular pipe jacking of the national highway underpass. Grouting can make up for the loss of strata and has a certain supporting effect on the surrounding soil. Within a certain range, the greater the grouting pressure, the smaller the ground settlement. However, a grouting pressure that is too high may lead to ground heave.

When the grouting pressure is 100 kPa, 200 kPa, 300 kPa, 400 kPa, 500 kPa, 600 kPa, 700 kPa, and 800 kPa, respectively, the corresponding maximum ground settlements behind the tunneling face are 16.80 mm, 14.50 mm, 12.50 mm, 10.57 mm, 8.65 mm, 6.90 mm, 5.30 mm, and 3.50 mm, respectively (Figure 15). The larger the grouting pressure, the smaller the ground settlement behind the tunneling face. When the grouting pressure is 800 kPa, the local ground surface behind the tunneling face heaved. Therefore, a grouting pressure control between 600 and 700 kPa is appropriate based on the comprehensive analysis of ground settlements.

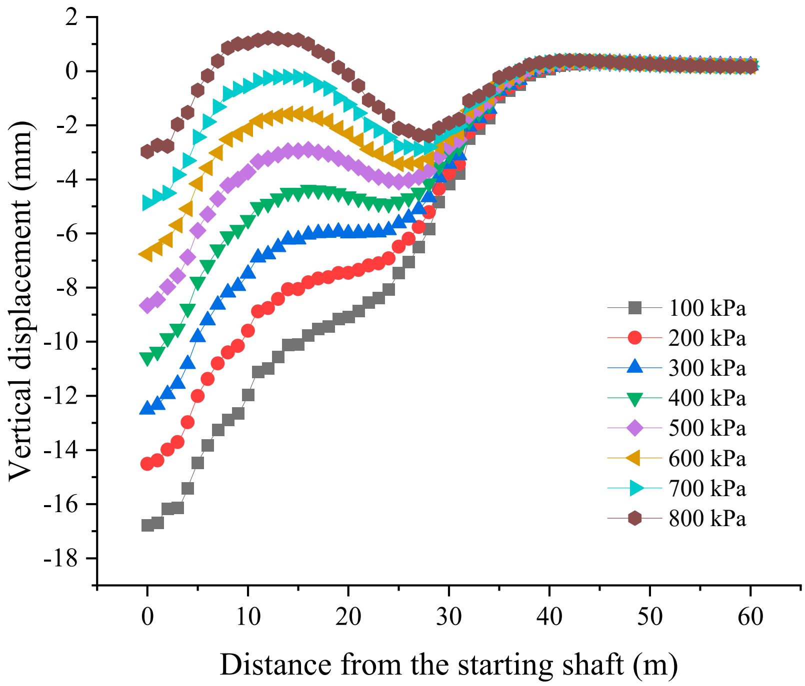


Figure 15. Vertical displacements of ground surface above the jacking axis under different grouting pressures when the tunneling distance is 30 m.

4.3.3. Ground Settlement Law during Jacking under Different Earth Chamber Pressures

The corresponding vertical displacements of ground surface at the jacking distance of 30 m (the cross-section y = 30 m) are 8.61 mm, 7.38 mm, 7.50 mm, and 8.08 mm when the earth chamber pressures are 100 kPa, 153 kPa, 200 kPa, and 250 kPa, respectively (Figure 16).

The maximum ground settlements under the four kinds of earth chamber pressure occur at the center of the axis. The closer the horizontal distance from the jacking axis, the greater the ground settlements. Moreover, the ground settlements are more obvious in the areas of 18 m beside the jacking axis (from x = –18 m to x = 18 m). The ground settlement is the smallest when the earth chamber pressure is 153 kPa, whilst the ground settlement is the largest when the earth chamber pressure is 100 kPa. At this time, the earth chamber pressure is less than the sum of the water and earth pressure in front of it, which cannot maintain the stability of the tunneling face, resulting in a large surface settlement. However, the greater the earth chamber pressure, the greater the ground heave.

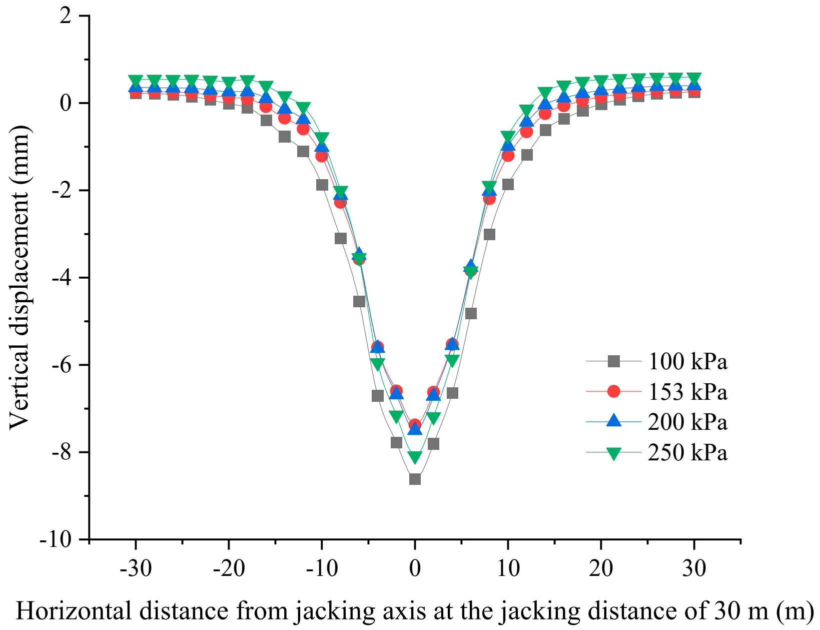


Figure 16. Vertical displacements of ground surface at the jacking distance of 30 m (the cross-section y = 30 m) with the horizontal distance from jacking axis under different earth chamber pressures.

The corresponding maximum ground settlements behind the tunneling face are 16.40 mm, 14.50 mm, 16.40 mm, and 19.00 mm, respectively, when the earth chamber pressure is 100 kPa, 153 kPa, 200 kPa, and 250 kPa, respectively (Figure 17). The disturbance to the surface is the largest when the pressure of the soil chamber pressure is 250 kPa. The disturbance to the ground is the smallest when the earth chamber pressure is 153 kPa. In summary, it is more appropriate to control the earth chamber pressure at about 153 kPa.

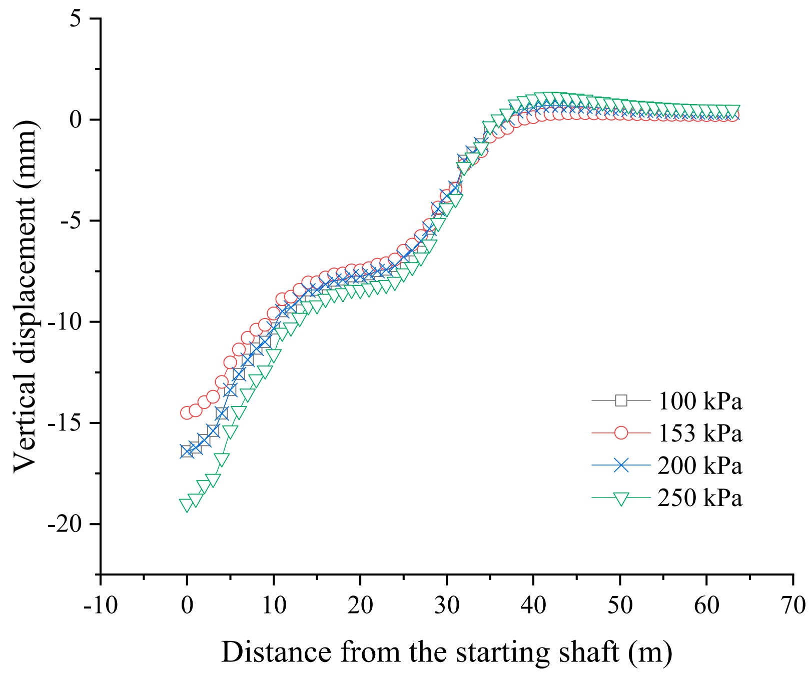


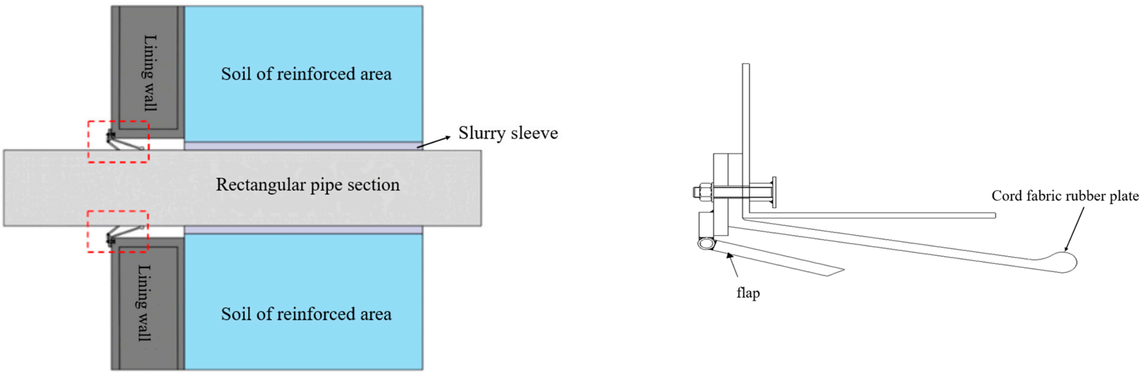
Figure 17. Vertical displacement of ground surface above the jacking axis under different earth chamber pressures when the tunneling distance is 30 m.

5. Ground Settlement Control Countermeasures for Large-Section Rectangular Pipe Jacking of the National Highway Underpass

The large-section rectangular pipe jacking project at subway entrance No.1 of Lintou Station, Guangzhou Metro Line 7, mainly passes through muddy silty fine sandstone and muddy soil. There are problems such as large jacking resistance, controlling the soil stability of the tunneling face, and ground settlement. National highway G105 is busy and requires restricted settlement control. Reasonable construction parameters are determined, and necessary control measures are taken to ensure construction safety and normal passage along the national highway during the jacking.

5.1. Installation of Waterproof Rubber Curtain for the Tunnel Portal

There is a gap of 150–200 mm between the tunnel portal and the pipe section. If it is not treated, groundwater, soil, and thixotropic slurry are likely to leak into the starting shaft during the pipe jacking construction process, resulting in soil loss and ground settlements. To prevent external water and soil from entering the portal, a steel ring is embedded in the portal, and a waterproof rubber curtain (Figure 18) is installed on the steel ring [32]. Due to the effect of bolts, the cord fabric rubber plate is always close to the pipe jacking machine and the segment during the jacking, which plays a role in stopping water. The rear flip plate behind the rubber plate plays the role of holding the rubber plate to prevent it from reverse deflection under impact.



(**a**) (**b**)

Figure 18. Installing waterproof rubber curtain for the tunnel portal: (**a**) longitudinal section of the waterproof device; (**b**) details of the waterproof device.

5.2. Pipe Jacking Machine Receiving Techniques in Receiving Shaft

Because there is a gap of 150–200 mm between the tunnel reserved hole and the pipe section in the receiving shaft, the pipe jacking machine can easily cause the soil and groundwater in the portal to flow out along the gap when receiving. The serious loss of soil and water will lead to ground settlements, and corresponding control countermeasures must be taken. Grouting is gradually stopped surrounding the front pipe segments when the last four pipe segments are jacked so that the receiving shaft door maintains a soil plug of about 6 m, preventing the pipe jacking machine from taking out a large amount of water and soil from the receiving shaft door.

5.3. Thixotropic Slurry for Reducing Friction Resistance

During the pipe jacking construction, the thixotropic slurry is transformed into a flow state through the disturbance of the machine and the mud pump, and the flow between the pipe jacking and the soil can reduce friction resistance. When the pipe jacking is stationary, the thixotropic slurry is transformed into a gel state, which can support the surrounding soil, fill the gap between the pipe jacking and the soil, and reduce ground settlements. When the grouting pressure is between 600 kPa and 700 kPa and the thickness of the slurry sleeve is 150 mm, the numerical calculation shows that the ground settlement is the smallest—between 6.90 mm and 8.65 mm, and the rectangular pipe jacking construction will not cause ground heave.

5.4. Countermeasures for Soil Stability at the Tunneling Face

The rectangular pipe jacking project at subway entrance No.1 adopts the earth pressure balance pipe jacking machine, and the earth pressure on the tunneling face is kept stable by controlling the earth chamber pressure inside the pipe jacking machine. The earth chamber pressure dynamically changes during jacking. It is necessary to continuously adjust the earth chamber pressure according to the soil condition, jacking speed, soil discharge, and other factors. Even at the same time, the earth pressure on each cutter head is also different. In some special cases, such as the restart after the pipe jacking machine stops, the unknown advanced soil condition or the existence of underground obstacles will also cause the instability of the earth chamber pressure. Through the previous analysis, the suitable earth chamber pressure of this project is about 153 kPa. Because there may be a certain deviation between the theoretical value and the actual value, in the actual project, the earth chamber pressure is generally set to be slightly larger than the sum of the water and earth pressure in front of the tunneling face to reduce the disturbance to the soil and maintain the stability of the front tunneling face and control the ground settlements.

When the jacking speed is too fast, the amount of mud produced by the screw excavator is smaller than that of the cutter head of the pipe jacking machine, which causes the earth chamber pressure on the excavation surface to increase and the ground to heave. When the jacking speed is too slow, the amount of mud produced by the screw excavator is larger than that of the cutter head of the pipe jacking machine, which causes the earth pressure on the tunneling face to decrease and leads to ground settlements. When the jacking is stopped, the screw excavator must stop the excavation to prevent the collapse of the tunneling face, again leading to ground settlements. The jacking speed should not be too fast in the initial stage of pipe jacking and should be controlled at 5–10 mm/min. As the pipe jacking machine is far away from the starting shaft, the normal jacking should be controlled at 10–20 mm/min, and four pipe segments should be jacked daily.

The field practice shows that the maximum ground settlement during the jacking of the large-section rectangular pipe constructing subway entrance No.1 is 10 mm, and there is no obvious uplift phenomenon, which is close to the predicted results of the numerical calculation. The maintenance effect of the national highway is excellent, and the traffic operates normally during jacking. The site pipe jacking of subway entrance No.1 is shown in Figure 19.

Figure 19. Field photos of pipe jacking construction.

6. Conclusions

(1) An evaluation of the jacking force prediction of different models of pipe–soil–slurry interactions during rectangular pipe jacking was conducted. The results show that the distribution of slurry plays an important role in reducing the jacking force. By comparing and analyzing the results of the jacking force prediction of the five models and the empirical formula of the *Technical specification for pipe jacking engineering with rectangular cross section* (T/CECS716-2020), Model 4 (pipe–slurry interaction at the bottom and both sides) is close to the specification summarized by the actual construction situation. In the stable jacking stage of the rectangular pipe jacking, the contact state between the segments and the slurry is between Model 4 and Model 5 (full contact of pipe–slurry).

(2) The jacking force of rectangular pipe jacking increases linearly with the jacking distance. As the contact area between the pipe and slurry increases, the thrust per unit length decreases. In the 63 m long large-section rectangular pipe jacking project, it was not necessary to install the intermediate jacking stations after reducing the friction resistance by strengthening the grouting resistance reduction.

(3) The numerical calculation showed that the increase in the thickness of the slurry sleeve leads to an increase in the over-excavation range and the surface settlement. The most reasonable slurry sleeve thickness is about 150 mm. The ground settlement caused by different earth chamber pressures is different. The most appropriate earth chamber pressure is 153 kPa, and the corresponding ground settlement is the smallest. A grouting pressure that is too low leads to large ground settlement; conversely, excessive grouting pressure leads to obvious ground heave. The most reasonable grouting pressure is 600–700 kPa, and the maximum corresponding ground settlement is between 6.90 and 8.65 mm.

(4) The control countermeasures of the ground settlements, such as installing a waterproof rubber curtain for the tunnel portal, pipe jacking machine receiving techniques, thixotropic slurry for reducing friction resistance, and the soil stability at the tunneling face, were carried out during pipe jacking of subway entrance No.1 of Lintou Station, Guangzhou Metro Line 7, underpass of the national highway G105. At the same time, the earth pressure and jacking speed of the tunneling face were strictly controlled. An excellent control effect for ground settlements of the national highway was achieved, which ensured normal traffic operations.

Author Contributions: Data curation: D.Q. and Z.L.; formal analysis: H.J. and Z.L.; funding acquisition: D.Q.; investigation: Z.L.; project administration: D.Q.; writing—original draft: D.Q.; Z.L., and H.J.; writing—editing: D.Q., H.J., and Y.Z.; writing—review: D.Q., H.J., Z.L., Y.Z., J.L., Z.C., X.G., H.L., B.T., and Z.X. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the Fundamental Research Funds for the Central Universities (grant no. 2018QNA27).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors would like to express their appreciation to the staff at Guangzhou Jintu Geotechnical Engineering Co., Ltd. for technical support during the field pipe jacking.

Conflicts of Interest: The authors declare no conflict of interest.

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