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Research Article

Differential Analysis and Prediction Optimization of Ground Surface Settlement Induced by Quasi-Rectangular Shield and Pipe Jacking Tunnelling

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The shield method and pipe jacking method will impact the ground surface and surrounding settlement during tunnel construction. Due to their different tunnelling principles and their cross-section characteristics, the impact on the stratum is often different. To study the differences between the two construction methods on ground surface settlement, numerical simulations, Peck empirical formulas, and field measurement data were used for analysis and comparison in this work. Two correction coefficients α and λ are introduced for correction on the basis of the DOT Peck formula, and the analysis of sensitivity factors for the ground settlement for the two construction methods is carried out. The numerical simulation results show that the ground settlement induced by pipe jacking construction is smaller than that of the shield, and this simulation result is confirmed by the field measurement result. When λ is selected from 0.85 to 0.91 and α from 1 to 1.1 for the shield project, 1.2 to 1.4, and 1.4 to 1.6 for the pipe jacking project, the modified formula can better predict the ground surface settlement. According to the sensitivity factor analysis, grouting pressure and elastic modulus of grout material exert a more significant influence on pipe jacking construction. The retreat of the pipe section caused by the tunnelling pressure difference will lead to 0 mm ~ 1.93 mm fluctuation on the ground surface.

1. Introduction

With the acceleration of urbanization, the shield method and pipe jacking method are widely used in urban subway construction projects. Although the shield method and pipe jacking method may cause disturbances to the surrounding stratum, their respective construction characteristics can meet the needs of different projects [1, 2]. The ground disturbance caused by shield and pipe jacking tunnelling has been an important research topic. Many scholars have done a lot of research on the ground disturbance caused by the tunnelling of shield and pipe jacking.

For the ground settlement caused by shield or pipe jacking engineering, the theoretical analysis method [3, 4], empirical formula method [5–8], and numerical simulation method [9, 10] are usually used to study it. In terms of shield ground settlement, Fang et al. [11] proved the influence of tunnel depth and ground loss rate on longitudinal ground settlement caused by shield construction through a series of model tests. Accordingly, a prediction formula for the final surface longitudinal settlement of shield tunnelling is established. Zhou et al. [12] revised the prediction formula for ground settlement troughs (Peck's formula) based on the field data of a double tunnel project. Also, the prediction formula for the ground settlement caused by the construction of a double tunnel was derived and validated. Hu et al. [13] studied the effect of water content in sandy soils on the distribution and range of surface and subsurface settlement induced by shields using model experiments and numerical simulations. Based on a large number of field engineering and model test data, Lu et al. [14] proposed a formula to predict the maximum ground settlement with tunnel depth and constructed a

Gaussian function to predict the transverse ground settlement. Wang et al. [15] introduced a case of predicting ground settlement caused by a double shield tunnel in Copenhagen using analytical and numerical simulation methods. Moeinossadat and Ahangari [16] used the finite difference method (FDM) to construct a numerical intelligent model for maximum ground settlement (S_{max}) instead of numerical simulation. In the study of ground surface settlement caused by pipe jacking construction, Ma et al. [17] studied the area disturbed by pipe jacking construction. Studies have shown that surface displacement is the coupling effect of soil and forward propulsion, friction, and ground loss. There are some other factors in the tunnelling process of pipe jacking [18, 19]. For example, construction parameters, ground loss rate, and pore water pressure dissipation will affect the surface settlement. In the construction process of the pipe jacking method, the tunnel pipe section has been in a "motion" state under the thrust provided by the hydraulic cylinder in the originating well, resulting in a large disturbance of the surrounding strata. The traditional Peck formula has poor prediction accuracy for ground settlement caused by pipe jacking construction. Therefore, Yang and Li [20] proposed a modified Peck formula based on the characteristics of the repeatedly disturbed strata by the pipe jacking method and the field measurement data. But Yang et al. research results are based on small pipe jacking projects, which are not suitable for large section pipe jacking projects. Tang et al. [21] compared the settlement of practical engineering, the fitting results of the Peck formula, and the settlement predicted by random medium theory. The prediction range of pipe jacking settlement through width is clarified through research, and suggestions are put forward for the prediction method of large rectangular pipe jacking settlement. Ma et al. [22] investigated the effect of tunnel burial depth variation on the ground settlement distribution characteristics caused by pipe jacking construction via 3D numerical simulation. Researchers investigated the surface settlement induced by the shield method and pipe jacking method from various angles, but there are few research results about the differences between the shield method and pipe jacking method on surface settlement, especially in the same stratum.

Based on the project of Hangzhou Sijiqing Metro Line 9, a three-dimensional finite element model of shield method and pipe jacking method is established in this study. Combining the field measurement data and simulation results, the differences in ground surface settlement induced by shield construction and pipe jacking construction in the same stratum were studied for comparison and analysis. At the same time, the double-o-tube (DOT) Peck formulas are optimized by using the numerical simulation results and field measurement data, and sensitivity factors of surface settlement caused by two tunnelling methods are studied to guide future projects.

2. Engineering Background

2.1. Engineering and Geology. The project interval is located at the east side of the intersection of Jiefang East Road and Qiutao Road, which is arranged along Jiefang East Road in an east-west direction. The interval crosses Qiushi viaduct and Xinkai River on Jiefang East Road. The project area is divided into two intervals: from the Sijiqing Station to the middle well is the quasi-rectangular pipe jacking interval, and from the middle well to the receive well is the quasi-rectangular shield interval, as shown in Figure 1. One 11.83 m × 7.27 m earth pressure balance pipe jacking/shield dual-mode tunnelling machine is used for the construction, see Figure 2. The tunnelling machine starts from the Sijiqing Station, travels west along Jiefang East Road, crosses the Qiushi viaduct, and then arrives at the middle well. The dual-mode tunnelling machine is received from the middle well and reformed into a shield machine. From the middle well, the shield method will be used to construct the tunnel. It will be constructed along Jiefang East Road to the west, cross the Xinkai River, and then be received at the receive well.

2.2. Surface Settlement Measure Scheme. Due to the large cross section of the tunnel construction, the disturbance of the stratum generated by the construction is also large. According to the surrounding environment and geological conditions, transverse measurement sections perpendicular to the tunnel axis are installed. Transverse measurement sections are placed in the originating area, receiving area and the parts with poor geological conditions that may produce excavation surface collapse or excessive surface deformation. Ten groups of measurement sections are set for the pipe jacking interval, and twenty-one groups of measurement sections are set for the shield interval. Each group of cross sections is symmetrically arranged along the central axis of the tunnel with a total of 11 measurement points. The spacing of measurement points is 3 m, 6 m, 12 m, 24 m, and 32 m (adjusted according to the actual situation on-site) on the outside of the tunnel center axis. The measurement sections are labeled as DBC-n, where DBC is the representative measurement project code and *n* is the ring number, as shown in Figure 3.

3. Differential Analysis of Surface Settlement

3.1. Numerical Modeling and Parameters

3.1.1. Model Size and Boundary. The size of the numerical model has a certain influence on the rationality and efficiency of the calculation results. To guarantee that the analysis results are not affected by boundary effects, and considering both the accuracy and efficiency of the model, the size of the shield model is chosen to be 84 m in X direction, 172 m in Y direction, and 42 m in Z direction. The model size of the pipe jacking is selected as 84 m in X direction, 67 m in Y direction, and 42 m in Z direction. The model's nodes on the two boundary surfaces of the X and Y directions set fixed constraints on the X and Y directions. The nodes on the bottom of the model set fixed constraints on the X, Y, and Z directions are shown in Figures 4 and 5.

The length from Sijiqing Station to the middle well is 67.2 m, the interval's maximum longitudinal grade is −0.2%, and the burial depth of the tunnel is 10.2 m ~ 11.2 m. The strata traversed by the machine are mainly: ②4 sandy silt,

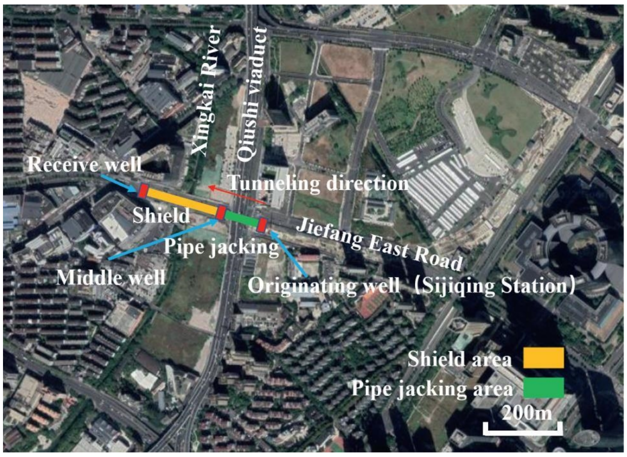


Figure 1: Tunnel location plan.

③5 sand with sandy silt, and ③7 sandy silt. The length of the middle well to the receive well is 163.9 m. The minimum plane radius of the interval is 700 m, the maximum longitudinal grade is −0.2%, and the burial depth of the tunnel is 10.9 m ~ 11.4 m. The stratum traversed by the machine is mainly: ③4 sandy silt, ③5 sand with sandy silt, and ③7 sandy silt, see Figure 3.

The shield machine is reformed from the pipe jacking machine in Figure 2. Both the shell thickness of the shield machine and the pipe jacking machine are 0.06 m. The shell of the machine is simulated by plate-shell elements as well as the tunnel lining. It is worth noting that the tunnel lining size of the pipe jacking and the shield are the same, but the shield tunnel has a neutral pillar see Figure 4, and the pipe section has no neutral pillar see Figure 5. In the two models, the tunnel size is 11.7 m × 7.6 m and the burial depth of the tunnel is 10.7 m. To simulate the ground volume loss caused by excavation as shown in Figure 6 the equivalent layer of pipe jacking is set to 6 cm and the shield is set to 20 cm [23].

3.1.2. Calculating Parameters. This paper assumes that the stratum material in the model is continuous isotropic elastic-plastic material. In the numerical simulation process of deep foundation pit excavation and large section excavation engineering, Mohr–Coulomb constitutive will have a large uplift, which affects the rationality of the simulation results. Therefore, this paper adopts the modified Mohr–Coulomb (MMC) constitutive model provided by the finite element software. This constitutive model is improved on the basis of the Mohr–Coulomb constitutive model, and it is especially suitable for sand materials with friction characteristics.

The shield shell and lining structure adopt a linear elastic constitutive model, and the lining thickness of the quasi-rectangular pipe jacking tunnel and shield tunnel is 650 mm. The shield's segments are assembled into rings, and the pipe jacking's lining is poured with C50 concrete. As the lining strength of the shield is lower than that of pipe jacking, the corresponding reduction is made. The initial elasticity modulus of the shield grout material is 0.9 MPa. It can reach 4 MPa after 24 hours, while the modulus of elasticity of the pipe jacking grout is 0.6 MPa since it does not harden and the grout is thinner than the shield. The specific structural parameters are given in Table 1, and the stratum material parameters are given in Table 2.

3.1.3. Simulation Process. In order to simulate the shield and pipe jacking construction process under real conditions, the stepwise method based on the lining ring width is used in the numerical simulation. The shield method assembles the segments into a ring during tunnelling, and synchronous grouting is carried out when the segment assembly is completed. The shield method and the pipe jacking method are similar during the early stages of the simulation process, the shield grout material will gradually harden over time, while the grout material of the pipe jacking will not harden. The duration of grout hardening is set to be 5 rings. When the number of excavation rings exceeds 5 rings, the short-term hardened grout material (0.9 MPa) of the *N*-5th ring (*N* means the number of rings being excavated) is replaced by the long-term hardened grout material (4 MPa).

During the jacking process, the grout material will be injected between the pipe section and the stratum, which can reduce friction and support the stratum above the pipe section. In the whole construction process, the grout material will be continuously supplemented to hold pressure. The process of numerical simulation is shown in Figure 7.

3.2. Differential Analysis of Settlement for Quasi-Rectangular Shield and Pipe Jacking

3.2.1. Analysis of Numerical Simulation Results. During the tunnelling process, the pressure applied on the excavation face is equal to the static Earth pressure of the soil ahead of the cutter head, which is 145 kPa at the uppermost of the excavated surface. Both the shield grouting pressure and the pipe jacking grouting pressure applied by the machine are set to 220 kPa, which corresponds to the Earth pressure over the tunnel.

The overall final ground surface settlements of the shield and pipe jacking model are shown in Figure 8, and the final ground surface settlements of the shield and pipe jacking model are 17 mm and 25 mm, respectively. In the shield and pipe jacking model, a ground surface transverse section above the excavation surface is selected as the measurement section. Figures 9 and 10 show the ground settlement values of shield and pipe jacking in each stage of gradual excavation. Where, "before arrival" indicates that the tunnelling machine is 7.5 m away from the excavation face, and "arrival" indicates that the machine reaches the excavation face. It can be seen from Figure 10 that the ground surface settlement curves caused by shield and pipe jacking are similar to the Peck settlement curve. The surface settlement of the two mainly occurs after the machine's tail is away from the measurement section, and the settlement caused by pipe jacking in each stage is much smaller than that caused by the shield. When crossing the measurement section, the ground settlement caused by the pipe jacking method reaches 3.6 mm, while that caused by the shield method reaches

(a) (b)

Figure 2: Quasi-rectangular earth pressure balance pipe jacking/shield dual-mode tunnelling machine: (a) The cutter head of dual-mode tunnelling machine. (b) Reformed shield segment assembly machine (pipe jacking machine mode without segment assembly machine).

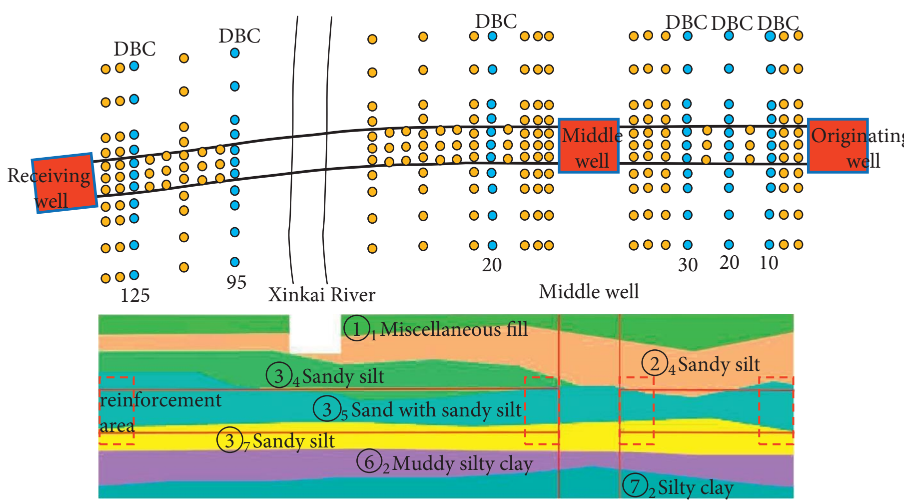
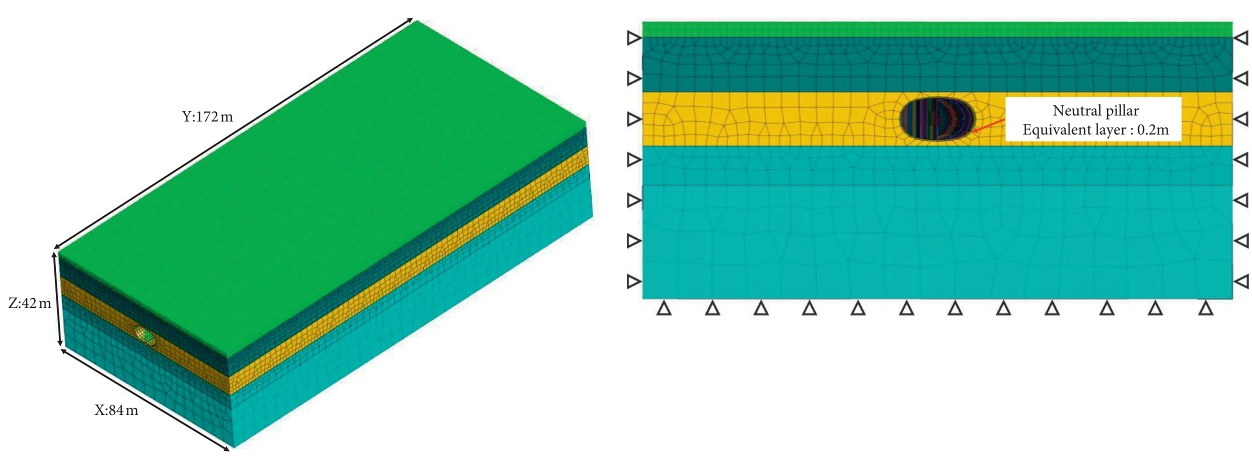


Figure 3: Stratum profile and field measurement section.



(a) (b)

Figure 4: Shield model size and boundary conditions: (a) Shield model size. (b) Shield stratum and boundary condition.

7.4 mm. It can be seen that shield construction will cause greater ground settlement than pipe jacking construction. After excavation, the final settlement generated by the pipe jacking method is 17.4 mm, and the final settlement generated by the shield method is 25.4 mm. There is little difference in the width of the settlement trough between the two, and the maximum influence range is about 3.5 times the width of the tunnel, namely, 40 m.

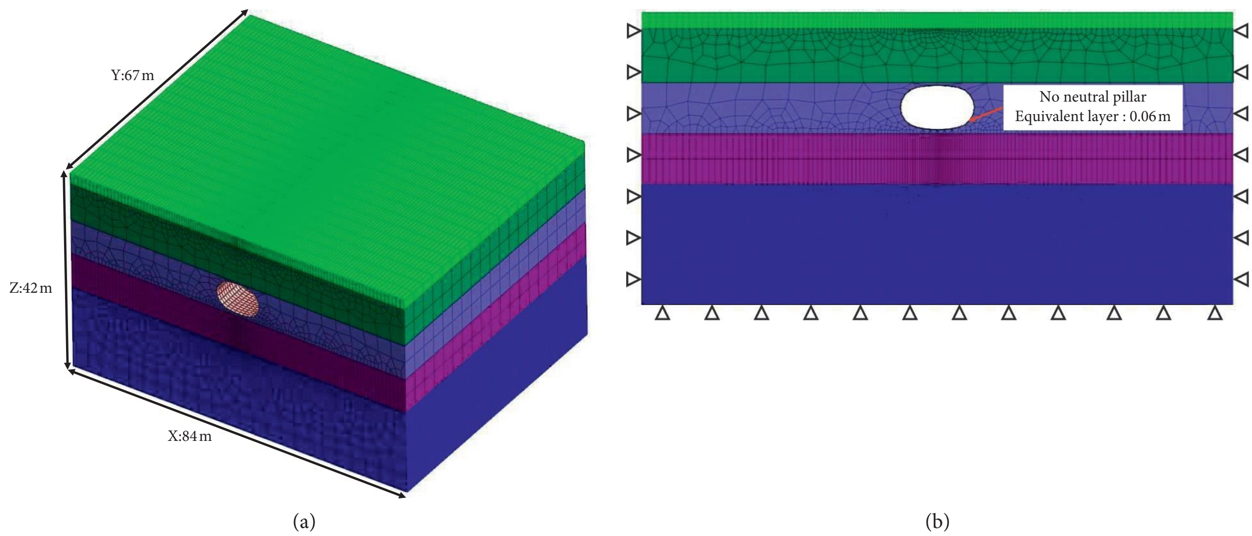


FIGURE 5: Pipe jacking model size and boundary conditions: (a) Pipe jacking model size. (b) Pipe jacking stratum and boundary condition.

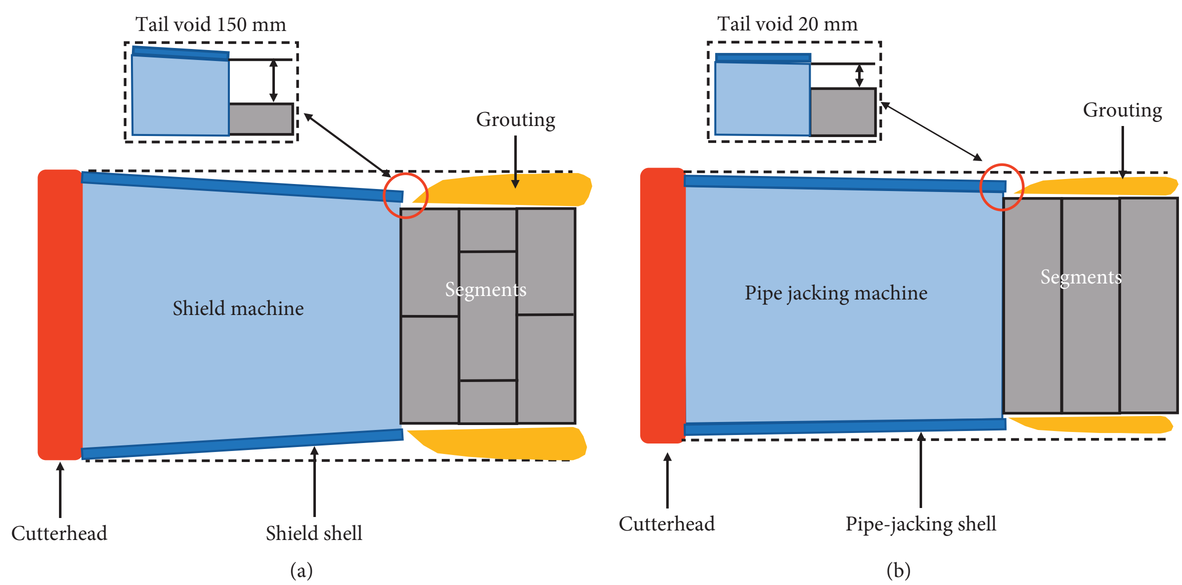


FIGURE 6: Tail void of shield and pipe jacking: (a) Shield tail void. (b) Pipe jacking tail void.

TABLE 1: Model size and structural parameters.

Name	X (m)	Y (m)	Z (m)	E (GPa)	Neutral pillar	Reduction factor	Equivalent layer (m)
Shield	172	67	42	20.7 (C50)	Yes	0.6	0.2
Pipe jacking	84	67	42	34.5 (C50)	No	1.0	0.06

3.2.2. Comparison of Numerical and Field Measurement Results. The shield machine will pass through the Xinkai River area during the tunnelling process (see Figure 3). To eliminate the influence of this area, the measurement sections of the Xinkai River and the originating area are ignored. Three measurement sections, DBC-20, DBC-95, and DBC-125, are selected for analysis. The final ground settlement of the shield is in the range of 23.1 mm–24.5 mm, and the numerical simulation value of 25.4 mm fitted the field measurement data well as shown in Figure 11. There was no significant difference between the width of the settlement trough at the field measurement points and the numerical simulation. At the same time, as shown in Figures 11 and 12, the surface settlement of the shield measured in the field is significantly larger than that of the pipe jacking, which is in agreement with the numerical simulation results.

The final surface settlement data of three measurement sections of DBC-10, DBC-20, and DBC-30 in the pipe jacking interval are selected for analysis, and the results of

Table 2: Stratum physical parameters.

Stratum	K_0	γ (kN/m^3)	E_s (MPa)	ν	C (kPa)	φ (°)
①1 miscellaneous fill	0.50	17.50	3.00	0.33	8.00	15.00
②4 sandy silt	0.52	19.20	6.00	0.34	4.00	26.00
③4 sandy silt	0.45	19.20	14.00	0.32	6.00	30.00
③5 sand with sandy silt	0.37	19.70	10.00	0.28	5.00	34.00
③7 sandy silt	0.52	19.40	15.00	0.31	7.00	24.00
⑥2 muddy silty clay	0.38	19.90	4.00	0.27	12.00	10.00
⑦2 silty clay	0.45	18.20	8.50	0.34	10.00	16.00

Here ①1 represents the first layer in the first layer of the stratum and ②4 represents the fourth layer in the second layer of the stratum, etc.

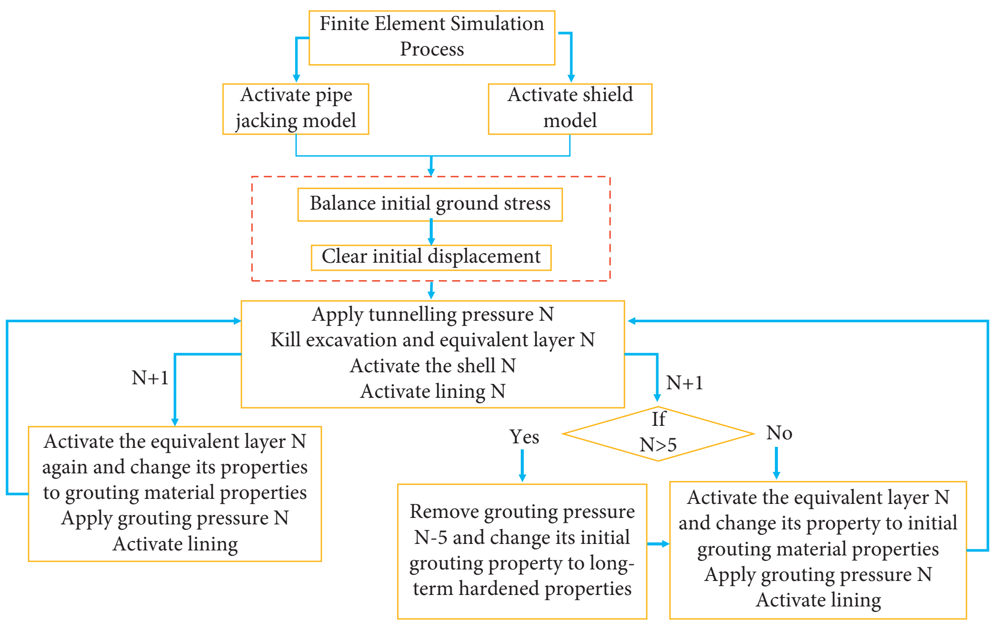


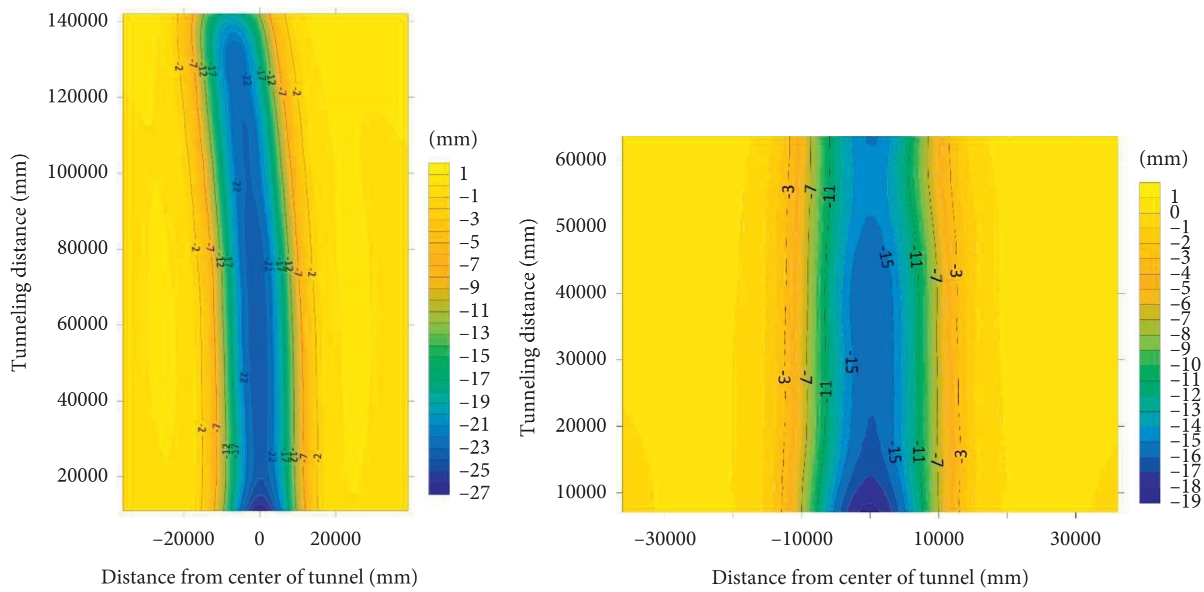
Figure 7: Simulation process.

numerical simulation are compared with the field measured surface settlement of pipe jacking. The results are shown in Figure 12. The final settlement measured in the field is 13.6 mm ~ 17.4 mm, which is slightly smaller than the 17.43 mm of numerical simulation. The width of the settlement trough of the numerical simulation curve is nonsignificant with the field measurement point, and the prediction effect of the numerical simulation is generally good.

The ground surface settlement data of the pipe jacking DBC-20 ring, shield DBC-95 ring measurement section center point (Figure 3), and the corresponding location points in the model are selected. As we can see from Figure 13, after the tunnelling machine passes the measurement point position the pipe jacking's final settlement is about 14 mm, which is smaller than the simulation result, and the settlement speed is also slower than the simulation result. The measured final settlement result of the shield is about 22 mm, which is smaller than the simulation result, and the settlement speed of the measurement results is in general agreement with the simulation results settlement speed. This is mainly due to the fact that the pipe jacking's grouting has a pressure-holding effect, so the stabilization of the final settlement will be delayed, when there is uplift at the surface. The shield grouting has no pressure-holding effect so the settlement speed will be faster than the pipe jacking after the uplift occurs.

4. Predictive Optimization Model and Method

The total settlement profile of a quasi-rectangular tunnel is symmetrical Gaussian distribution along the tunnel axis. The classical Peck formula is no longer applicable since the difference between quasi-rectangular tunnel and circular tunnel. Zhang et al. [24] found that the settlement curve of the quasi-rectangular tunnel was between the circle Peck formula and the DOT Peck formula. By using the circle Peck formula (formula (1)) and the DOT Peck formula (formula (3)), the formulas (formulas (5) and (6)) of the surface loss rate corresponding to the maximum ground settlement are derived. The formulas (5) and (6) are used to calculate the critical ground loss rate of the circle and DOT tunnels under different buried depths, which use 30 mm as the control index of the maximum ground settlement value. The ground loss rate corresponds to the control index S^k_{max} (the maximum ground settlement), which is called the critical ground loss rate δ. The final results are shown in



(a) (b)

Figure 8: Final ground surface settlement contourline of shield and pipe jacking by numerical simulation: (a) Final settlement contourline of the shield. (b) Final settlement contourline of pipe jacking.

Table 3 and Figure 14. The critical ground loss rate δ of quasi-rectangular tunnels should be between the two, namely, $\delta_2 < \delta < \delta_1$. When the ground loss rate of quasi-rectangular tunnel is controlled below the critical value, the maximum ground settlement value can meet the control index of 30 mm.

Circular:

$$S(x) = \frac{V_s}{\sqrt{2\pi} \times i} \times \exp\left(-\frac{x^2}{2i^2}\right), \tag{1}$$

$$S_{\max} = \frac{V_s}{\sqrt{2\pi} \times i}, \tag{2}$$

DOT:

$$S(x) = \frac{V_s}{\sqrt{2\pi} \times i} \times \exp\left(-\frac{(x+2.3)^2}{2i^2}\right) + \frac{V_s}{\sqrt{2\pi} \times i} \times \exp\left(-\frac{(x-2.3)^2}{2i^2}\right), \tag{3}$$

$$S_{\max} = \frac{2V_s}{\sqrt{2\pi} \times i} \times \exp\left(-\frac{2.3^2}{2i^2}\right), \tag{4}$$

In the formulas, $S(x)$ is the ground surface settlement at the transverse distance from the center line of the DOT tunnel x, unit m. i is the width coefficient of settlement trough, unit m. VS is DOT shield tunnel unit length ground loss, unit m^3/ m.

$$\delta_1 = S^k_{\max} \times \sqrt{2\pi} \times \frac{i}{V}, \tag{5}$$

$$\delta_2 = S^k_{\max} \times \sqrt{2\pi} \times i \times \frac{\exp\left(2.3^2/2i^2\right)}{2V} \tag{6}$$

$$i = r \times \left(\frac{Z}{2r}\right)^{0.8}. \tag{7}$$

In the formulas, i is the width coefficient of settlement trough, unit m. r is the tunnel excavation radius, unit m. The noncircular tunnel can be calculated according to $r = \sqrt{W/\pi}$, W for the tunnel excavation area is shown in Figure 15. Z is the buried depth of the tunnel axis, unit m.

4.1. Peck Formula Optimization of Quasi-Rectangular Shield. The integration of the DOT Peck formula (formula (3)) leads to formula (8), and it can be concluded that the area of the settlement trough of the DOT Peck formula is twice the V_s. Thus, the relationship between V_{sf} (Back calculation of ground losses from numerical simulation results) and V_s of DOT Peck formula can be expressed by formula (9). The predicted surface settlement curve in the numerical simulation is further back-calculated to yield a ground loss rate δ_f, which is 0.7% for the shield and 0.4% for the pipe jacking.

The back-calculated shield ground loss rate ($\delta = 0.35\%$) from the numerical simulation results is brought into the DOT Peck formula, and the calculated results are shown in Figure 16. The curve fitted by the DOT Peck formula is

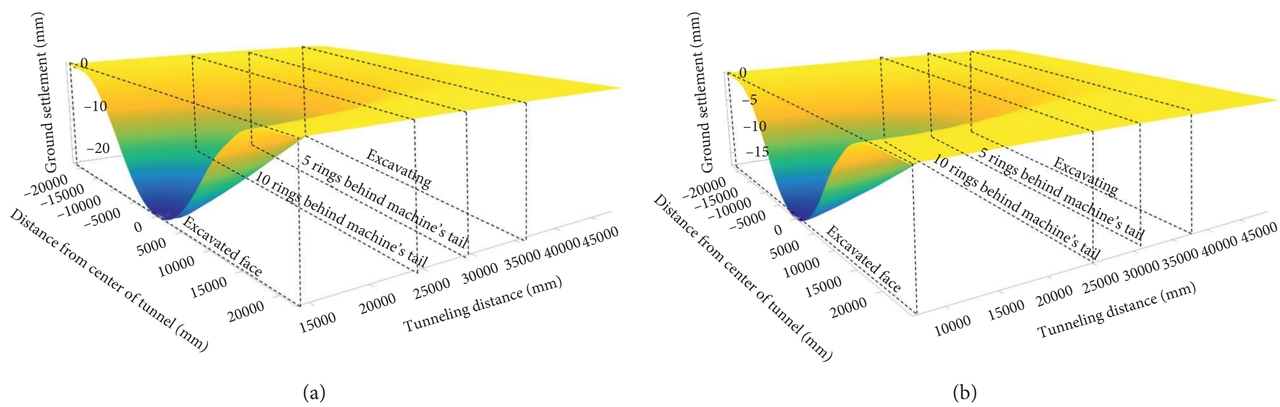


Figure 9: 3D surface settlement during excavation by shield and pipe jacking in numerical simulation: (a) 3D surface settlement during shield excavation. (b) 3D surface settlement during pipe jacking excavation.

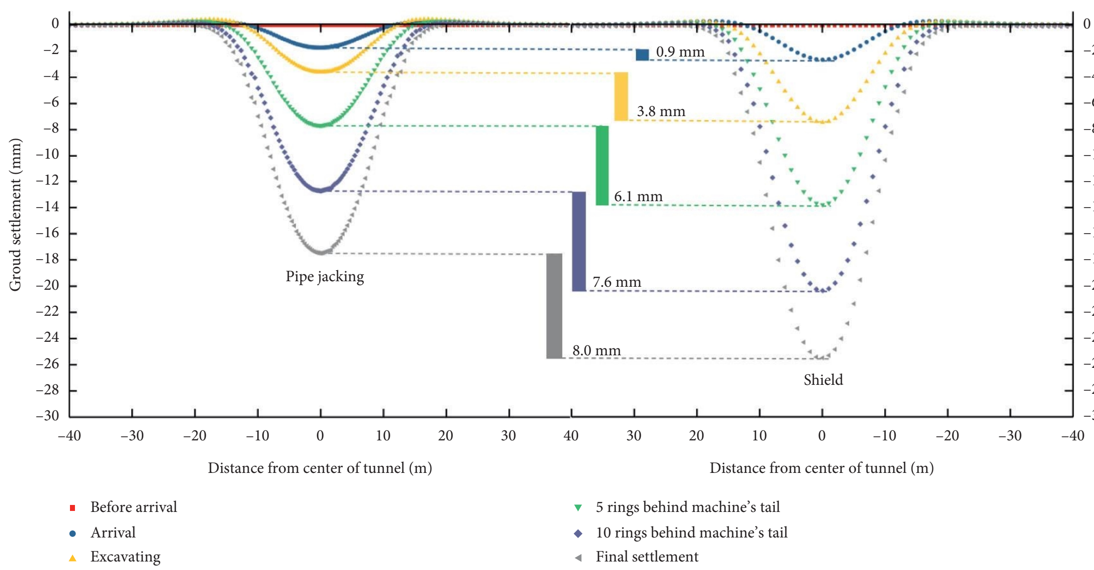


Figure 10: Transverse ground surface settlement of pipe jacking and shield in each stage.

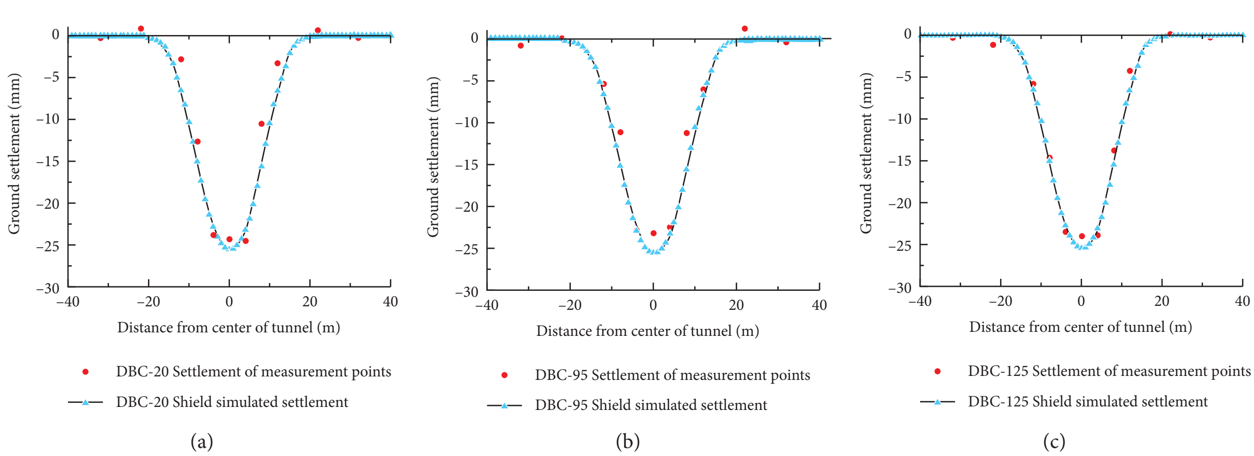


Figure 11: Final ground surface settlement of shield field measurement: (a) DBC-20. (b) DBC-95. (c) DBC-125.

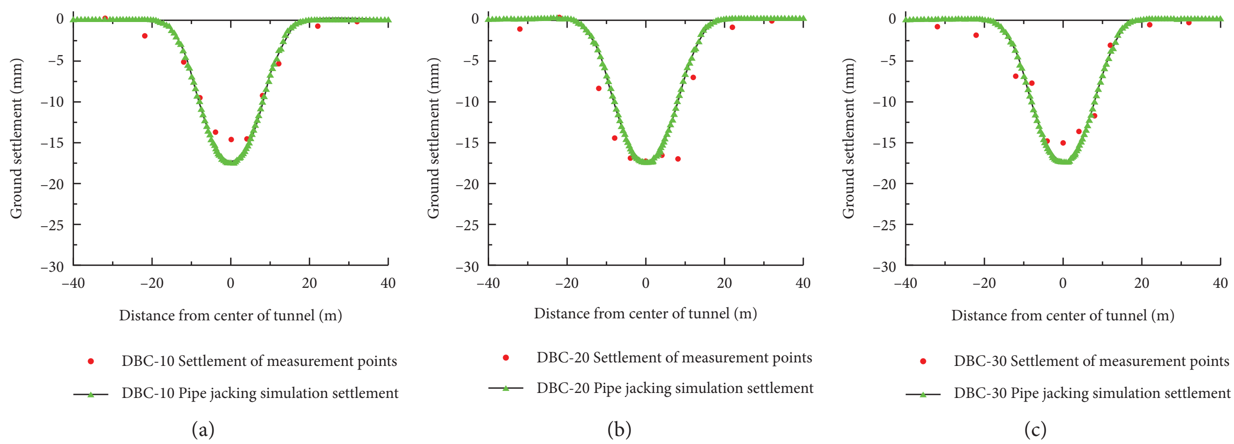


FIGURE 12: Final ground surface settlement of pipe jacking field measurement: (a) DBC-10. (b) DBC-20. (c) DBC-30.

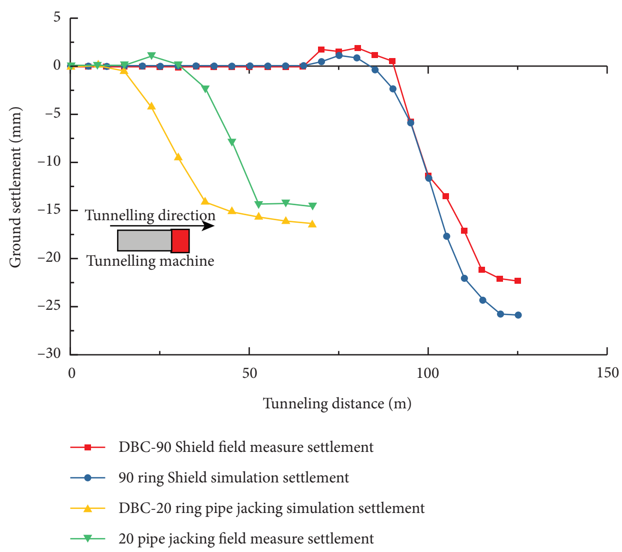


FIGURE 13: Longitudinal ground surface settlement of shield and pipe jacking.

6–8 mm larger than the measured surface maximum settlement. Therefore, the DOT Peck formula needs to be corrected to better fit the ground settlement of the shield. Because the curve shape fitted by the DOT Peck formula is related to the ground loss rate δ and the settlement trough width coefficient i. Therefore, based on the existing DOT Peck formula, two correction coefficients λ (correction coefficient of ground loss rate) and α (correction coefficient of settlement trough width) are proposed to optimize the formula (formula (10)–(13)). It can be seen from Figure 16 that when λ is 0.85 ~ 0.91 and α is 1 ~ 1.1, the correlation coefficient R of the fitting curve is 0.97 ~ 0.98. This shows that the modified formula can more accurately predict the surface settlement induced by quasi-rectangular shield tunnelling. Therefore, to achieve a better prediction effect, it is recommended to use the corresponding correction coefficient when using the range of ground loss rate δ recommended in Table 3.

$$\int_{-\infty}^{+\infty} S(x)\mathrm{d}x = \int_{-\infty}^{+\infty} \frac{V_s}{\sqrt{2\pi}\times i}\times \exp\left(-\frac{(x+2.3)^2}{2i^2}\right) + \frac{V_s}{\sqrt{2\pi}\times i}\times \exp\left(-\frac{(x-2.3)^2}{2i^2}\right)\mathrm{d}x = 2V_s, \tag{8}$$

$$V_{sf} = \pi r^2\delta_f = 2V_s = 2\pi r^2\delta. \tag{9}$$

Optimised DOT Peck formula for quasi-rectangular tunnel:

$$S(x) = \frac{V_{sx}}{\sqrt{2\pi}\times i_x}\times \exp\left(-\frac{(x+2.3)^2}{2i_x^2}\right) + \frac{V_{sx}}{\sqrt{2\pi}\times i_x}\times \exp\left(-\frac{(x-2.3)^2}{2i_x^2}\right), \tag{10}$$

$$V_{sx} = \lambda\cdot\delta\cdot\pi\cdot r^2 = \delta_x\cdot\pi\cdot r^2, \tag{11}$$

$$\delta_x = \lambda\cdot\delta, \tag{12}$$

$$i_x = \alpha\cdot i. \tag{13}$$

Here, δ_f is the ground loss rate back-calculated from the numerical simulation results, and δ is the ground loss rate in the DOT Peck formula. δ_x is the corrected ground loss rate, i_x is the corrected settlement trough width coefficient, unit m.

4.2. Peck Formula Optimization of Quasi-Rectangular Pipe Jacking. The ground loss rate ($\delta = 0.2\%$) is back-calculated based on the numerical simulation results of pipe jacking, and it can be found that the settlement trough fitted by the measured data of pipe jacking is wider than that fitted by the DOT Peck formula (Figure 17). Similarly, in order to better let the DOT Peck formula predict the ground settlement of the pipe jacking. Two correction coefficients λ and α are used to optimize the existing DOT Peck formula (formula (10)–(13)). As shown in Figure 17, when λ is in the range of 1.2 ~ 1.4 and α is in the range of 1.4 ~ 1.6, the modified

Table 3: The critical ground loss ratio of different tunnel depths [24].

Axis buried depth Z (m)	Width coefficient of settlement trough i (m)	Critical ground loss rate δ_1 (%)	Critical ground loss rate δ_2 (%)
6	3.29	0.344	0.194
7	3.73	0.389	0.214
8	4.15	0.433	0.233
9	4.56	0.476	0.253
10	4.96	0.518	0.273
11	5.35	0.559	0.292
12	5.73	0.599	0.311
13	6.11	0.639	0.330
14	6.49	0.678	0.349
15	6.86	0.716	0.367

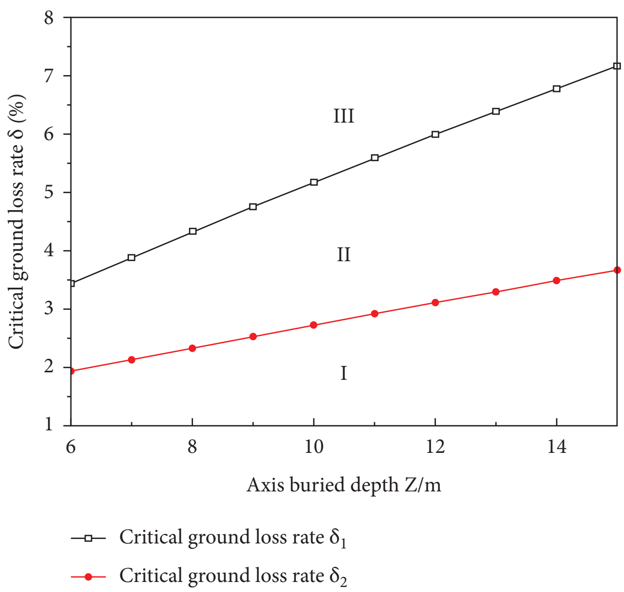


Figure 14: The critical ground loss ratio versus tunnel depth [24].

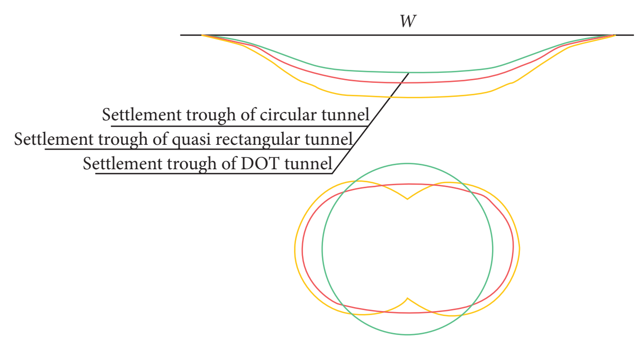


Figure 15: The rough sketch of surface settlement induced by circular, DOT, and quasi-rectangular shield construction. [24].

formula can better fit the characteristics of wide pipe jacking settlement trough. The correlation coefficient R of the improved Peck formula is in the range of 0.92 ~ 0.99. The correlation coefficient R of the uncorrected Peck formula is 0.62 ~ 0.89, as shown in Figure 17. This shows that the improved formula has a good prediction effect on surface settlement caused by quasi-rectangular pipe jacking construction.

5. Analysis of Sensitivity Factors of Ground Settlement

5.1. Analysis of Grouting Pressure. In the construction of shield and pipe jacking, the ground settlement can be controlled by adjusting the grouting pressure during the grout. Due to the difference between shield grout and pipe jacking grout, changes in grouting pressure have different effects on ground surface settlement. In this study, the sensitivity of grouting pressure to the ground settlement is studied by adjusting the variation of grouting pressure parameters.

The ground settlement of shield and pipe jacking is shown in Figure 18 under the conditions of 176 kPa (under balance pressure 20%), 220 kPa (balance pressure), and 264 kPa (surplus balance pressure 20%). The ground settlement of the shield increased by 1.26 mm under 176 kPa and decreased by 0.68 mm under 264 kPa. The ground settlement of pipe jacking increases 8.19 mm when grouting pressure is under 176 kPa and decreases 5 mm when grouting pressure is under 264 kPa. Under the same grouting pressure change, the ground settlement of the shield is much smaller than that of pipe jacking. Since the grouting of pipe jacking has a certain pressure-holding effect, the continuous grouting pressure has a supporting effect on the stratum, which effectively reduces the surface settlement. Therefore, the control of pipe jacking grouting pressure on surface settlement is much more obvious compared with shield grouting pressure.

5.2. Analysis of Grout Materials. The change of elastic modulus of grout material will affect ground settlement [25]. In order to study the influence of grout material strength change (mainly for the elastic modulus of grout material) on shield and pipe jacking. In this study, the long-term hardening elastic modulus of shield grout material was increased by 200% (8 MPa), 250% (10 MPa), and 300% (12 MPa), respectively. The pipe jacking grout material does not harden, its elastic modulus is similar to the shield grout material's initial elastic modulus. Therefore, the pipe jacking grout material is enhanced with 0.6 MPa as the benchmark, which is increased by 150% (0.9 MPa) and 200% (1.2 MPa), respectively.

As shown in Figure 19(a), when the long-term harden elastic modulus of shield grout material increases by 200%, the

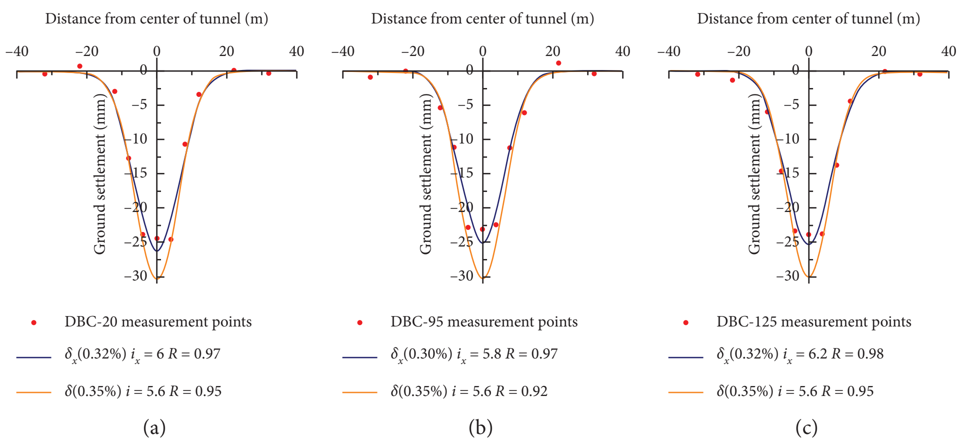


Figure 16: Field measurement and Peck formula optimization of shield ground surface settlement: (a) DBC-20. (b) DBC-95. (c) DBC-125.

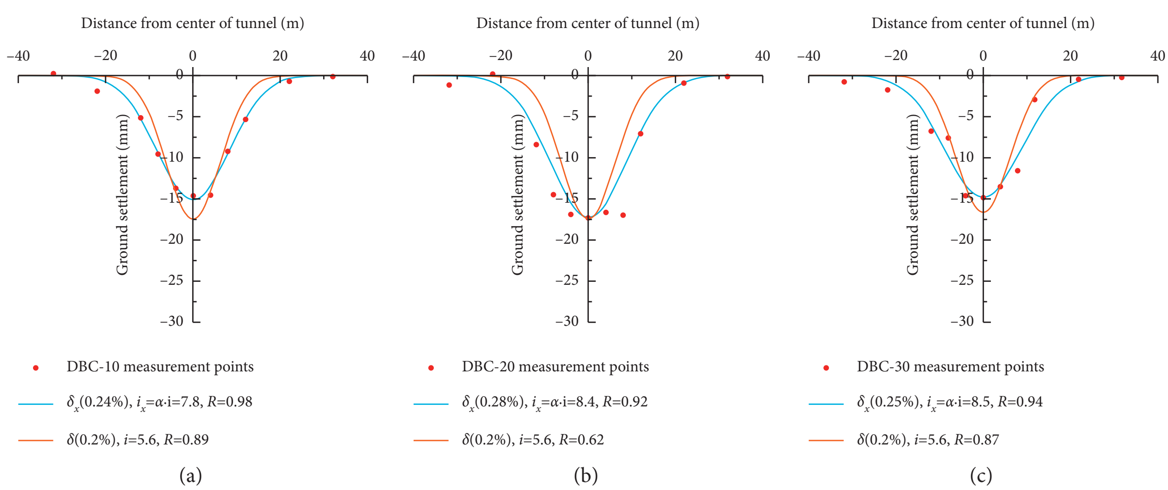


Figure 17: Field measurement and Peck formula optimization of pipe jacking ground surface settlement: (a) DBC-10. (b) DBC-20. (c) DBC-30.

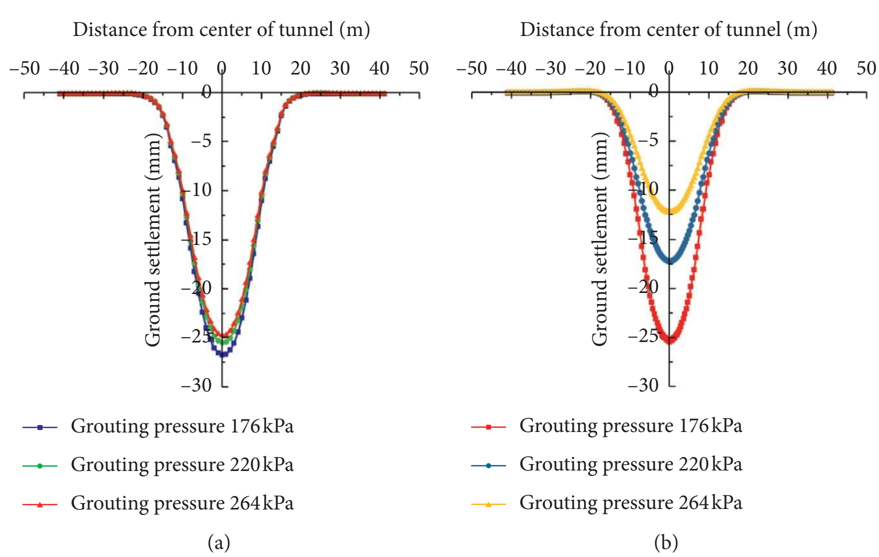
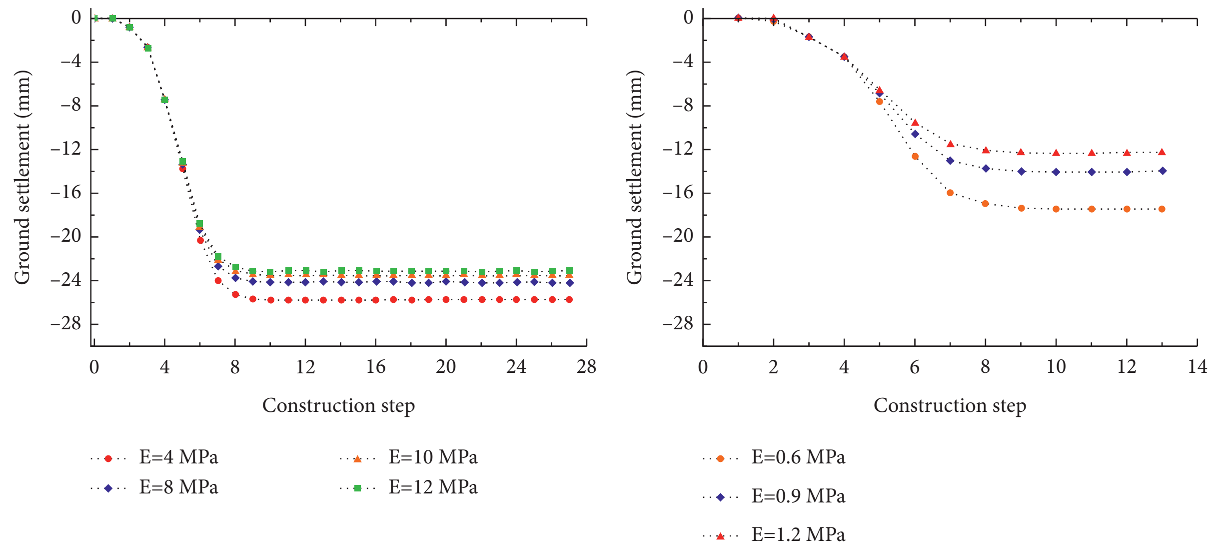
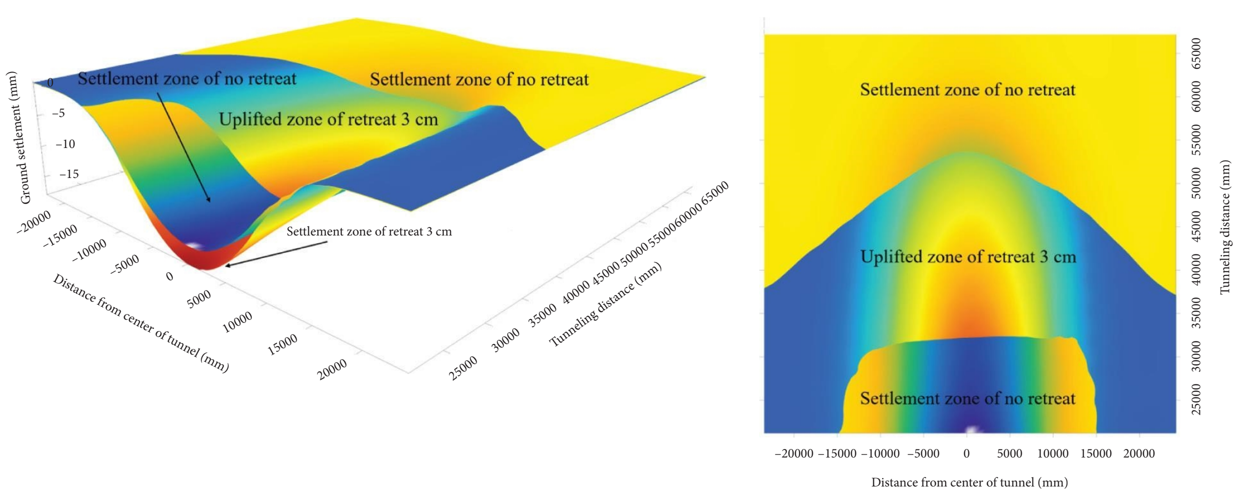


Figure 18: Ground surface settlement of shield and pipe jacking under different grouting pressures: (a) Ground surface settlement of shield. (b) Ground surface settlement of pipe jacking.



(a) (b)

Figure 19: Longitudinal ground settlement of shield and pipe jacking under different elastic modulus: (a) Longitudinal settlement of shield. (b) Longitudinal settlement of pipe jacking.



(a) (b)

Figure 20: 3D map and plane map of settlement superposition when no retreat and 3 cm retreat of pipe section: (a) No retreat and retreat 3 cm settlement superimposed 3D map. (b) No retreat and retreat 3 cm settlement superposition plane map.

settlement decreases by 1.6 mm compared with that of 4 MPa. The settlement decreases by 2.2 mm when the reinforcement is 250% and 2.63 mm when the reinforcement is 300%. It can be seen from Figure 19(b) that when the elastic modulus of pipe jacking grout material increases from 0.6 MPa to 0.9 MPa, the settlement decreases by 3.4 mm, and when the elastic modulus increases to 1.2 MPa, the settlement decreases by 5 mm. By comparison, it can be found that with the enhancement of the pipe jacking grout material elastic modulus the influence on the ground settlement is more obvious than that of the shield.

5.3. Analysis of Tunnelling Pressure Difference. In the process of pipe jacking tunnel construction, due to the differential pressure between the soil pressure in front of the excavation surface and the cutter head, the head of the machine will retreat. Compared with the grout material used in the shield method, the grout material used in pipe jacking will aggravate the overall retreat of the pipe section. In this project, it is measured that the overall retreat of the pipe jacking section is about 2 cm ~ 3 cm, and the overall retreat of the lining ring of the shield method is about 1 cm. Considering that the distance of pipe jacking interval is shorter than that of shield interval and the retreat is larger than that of shield, this study mainly focuses on the influence of pipe jacking interval retreat on ground settlement. By applying the forced displacement in the range of 1 cm ~ 3 cm in the three-dimensional model, the influence of ground settlement caused by the overall displacement of the pipe section is shown in Figure 20.

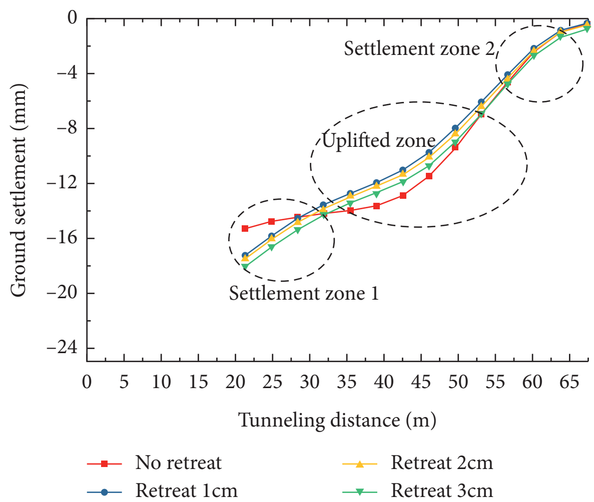


Figure 21: The longitudinal ground surface settlement is caused by pipe section retreat.

After the overall displacement is applied to the pipe section, it can be seen in Figure 21 that it can be divided into three impact zones: settlement zone 1 (20 m ~ 30 m), uplift zone (35 m ~ 52 m), and settlement zone 2 (55 m ~ 65 m). When the displacement of 1 cm is applied, the maximum settlement of 1.93 mm appeared on settlement zone 1. The uplift zone shows a maximum uplift of 1.9 mm. When the retreat displacement increases, the settlement in settlement zone 1 will also increase. When the retreat increases by 2 cm, the settlement of settlement zone 1 increases by 0.7 mm at most, and the uplift zone's uplift will gradually decrease, and the maximum will decrease by 0.77 mm. At the same time, with the increase of retreat, settlement zone 2 gradually appears, the maximum settlement in settlement zone 2 is 0.31 mm. The main reason for the above phenomenon is that the cutter head's retreating formed a certain gap, leading to the front soil settlement. Due to the early construction of the tunnel in the direction of the originating well, the settlement is larger than that of other areas, and the retreat of the pipe section will aggravate the settlement in the direction of the originating well, resulting in the overall rotation of the pipe section. This also reduces the settlement of the middle area.

6. Conclusions

In this study, the differences in ground settlement caused by the pipe jacking method and the shield method in the same stratum are investigated by numerical analysis. The ground surface settlement caused by the two construction methods is compared and verified with the measured settlement data. At the same time, the DOT Peck formula is modified, and the sensitive factors that have the greatest impact on ground surface settlement in the tunnelling process are given through parameter analysis.

The numerical simulation results show that the ground settlement caused by the shield is larger than that caused by pipe jacking in each stage of tunnelling process. The final ground surface settlement of pipe jacking is about 17.4 mm, and the final ground surface settlement of shield is about 25.4 mm.

Field measurement shows that the ground surface settlement range of the pipe jacking is 13.59 mm ~ 17.4 mm, and that of the shield is 23.11 mm ~ 24.5 mm, which verifies that the shield has a larger settlement than the pipe jacking. Two correction coefficients λ and α are proposed to correct the DOT Peck formula. When shield engineering λ is 0.85 ~ 0.91 and α is 1 ~ 1.1, the formula is more accurate for settlement prediction. For the pipe jacking λ in 1.2 ~ 1.4, α in 1.4 ~ 1.6. The correlation coefficient R reaches 0.92 ~ 0.99, which has a good prediction effect on quasi-rectangular pipe jacking.

By comparing the grout pressure of shield and pipe jacking under the condition of under balance pressure and surplus balance pressure, it can be concluded that the change of pipe jacking grouting pressure has a more significant influence on surface settlement. Under 176 kPa, the pipe jacking settlement increases by 8.19 mm, and the shield is 1.26 mm. The ground settlement of the pipe jacking is reduced by 5 mm and the shield is 0.68 mm under 264 kPa.

It can be found from the elastic modulus enhancement of shield and pipe jacking grout materials that pipe jacking is more conducive to reducing ground surface settlement than shield after increasing the elastic modulus of grout materials. When the long-term hardened elastic modulus of shield grout materials increases by 300%, the settlement decreases by about 2.63 mm compared with 4 MPa. When the elastic modulus of pipe jacking grout materials increases by 200%, the settlement decreases by 5 mm.

In the numerical simulation, the pipe section applied 1 cm ~ 3 cm overall retreat, and the surface settlement value increased by 1.93 mm in settlement zone 1. The surface settlement in the uplift zone will decrease by about 1.9 mm, and the surface settlement in settlement zone 2 will gradually increase with the increase of the retreat.

Data Availability

The data are available on request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References

[1] Li Pei, T. Wang, and X. Zhang, "Composite Technology application study on pipe jacking and shield engineering," *Special Structures*, vol. 36, no. 1, 2019, in Chinese.

[2] Editorial Department of China Journal of Highway and Transport, "Review on China's traffic tunnel engineering

Research," *China Journal of Highway and Transport*, vol. 35, no. 4, pp. 1–40, 2022, in Chinese.

[3] J. Dalong, S. Xiang, and Y. Dajun, "Theoretical analysis of three-dimensional ground displacements induced by shield tunneling," *Applied Mathematical Modelling*, vol. 79, pp. 85–105, 2020.

[4] G. Wei, X. Zhang, Y. Xu, and Z. Wang, "Prediction of ground settlement due to excavation of a quasi-rectangular shield tunnel based on stochastic medium theory," *Geotechnical & Geological Engineering*, vol. 37, no. 5, pp. 3605–3618, 2019.

[5] J. Wang, P. Zhou, Z. Song, S. Li, and Q. Zhang, "A new calculation method for tunneling-caused stratum settlement," *KSCE Journal of Civil Engineering*, vol. 26, pp. 1–17, 2022.

[6] R. B. Peck, "Deep excavations and tunneling in soft ground," in *Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering (Mexico)*, pp. 225–290, Mexico, MX, USA, August1969.

[7] P. B. Attewell, "Predicting the dynamics of ground settlement and its derivatives caused by tunnelling in soil," *Ground Engineering*, vol. 15, no. 8, pp. 13–22, 1982.

[8] I. Ocak, "A new approach for estimating the transverse surface settlement curve for twin tunnels in shallow and soft soils," *Environmental Earth Sciences*, vol. 72, no. 7, pp. 2357–2367, 2014.

[9] S. L. Chen, C. Ho, and Y. C. Kuo, "Three-dimensional numerical analysis of ground surface settlement induced by the excavation of shield tunnels," *Tunnel Management, Emerging Technologies, and Innovation*, pp. 80–87, 2011.

[10] L. X. Gao, X. J. Yang, and L. K. Qin, "Finite element analysis of the surface settlement induced by the shield tunnel construction," *Applied Mechanics and Materials*, Trans Tech Publications Ltd, vol. 501-504, , pp. 111–114, 2014.

[11] Y. Fang, Z. Chen, L. Tao, J. Cui, and Q Yan, "Model tests on longitudinal surface settlement caused by shield tunnelling in sandy soil," *Sustainable Cities and Society*, vol. 47, Article ID 101504, 2019.

[12] Z. Zhou, H. Ding, L. Miao, and C. Gong, "Predictive model for the surface settlement caused by the excavation of twin tunnels," *Tunnelling and Underground Space Technology*, vol. 114, Article ID 104014, 2021.

[13] X. Hu, C. He, Z. Peng, and W. Yang, "Analysis of ground settlement induced by Earth pressure balance shield tunneling in sandy soils with different water contents," *Sustainable Cities and Society*, vol. 45, pp. 296–306, 2019.

[14] D. Lu, Q. Lin, Y. Tian, X. Du, and Q. Gong, "Formula for predicting ground settlement induced by tunnelling based on Gaussian function," *Tunnelling and Underground Space Technology*, vol. 103, Article ID 103443, 2020.

[15] X. Wang, T. von Schmettow, X. Chen, and C.-Q. Xia, "Prediction of ground settlements induced by twin shield tunnelling in rock and soil-a case study," *Underground Space*, vol. 7, 2022.

[16] S. R. Moeinossadat and K. Ahangari, "Estimating maximum surface settlement due to EPBM tunneling by Numerical-Intelligent approach - a case study: tehran subway line 7," *Transportation Geotechnics*, vol. 18, pp. 92–102, 2019.

[17] W. Ma, B. Wang, X. Wang, S. Zhou, and B. Wang, "Soil layer disturbance caused by pipe jacking: measurement and simulation of a case study," *KSCE Journal of Civil Engineering*, vol. 25, no. 4, pp. 1467–1478, 2021.

[18] Y. Xu, Y. Wang, and F. Chao, "Research on ground deformation caused by rectangular pipe jacking construction," *Chinese Journal of Underground Space and Engineering*, vol. 14, no. 1, pp. 192–199, 2018, in Chinese.

[19] D. J. Ren, Y. S. Xu, J. S. Shen, A. Zhou, and A Arulrajah, "Prediction of ground deformation during pipe-jacking considering multiple factors," *Applied Sciences*, vol. 8, no. 7, 2018.

[20] X. Yang and Y. Li, "Research of surface settlement for a single arch long-span subway station using the Pipe-roof Pre-construction Method," *Tunnelling and Underground Space Technology*, vol. 72, pp. 210–217, 2018.

[21] J. Tang, S. Li, and Y. Zhu, "Measurement and analysis of settlement induced by rectangular pipe jacking in silt stratum," *Advances in Materials Science and Engineering*, vol. 2021, Article ID 8347227, 17 pages, 2021.

[22] S. Ma, M. Li, J. Jin, and K. Bai, "The influence of shallow buried double-line parallel rectangular pipe jacking construction on ground settlement deformation," *Alexandria Engineering Journal*, vol. 60, no. 1, pp. 1911–1916, 2021.

[23] Q. Li, *Comparison of Equivalent Circle Zone Method and Displacement Convergence Method in Analyzing Construction Effects of Shield Tunneling*, Suzhou University, Suzhou, China, 2018, in Chinese.

[24] F. Zhang, X. Kou, and J. Huang, "Application of Peck formula and its modified versions in ground settlement prediction during quasi-rectangular tunnelling," *Modern Tunnelling Technology*, vol. 53, no. S1, pp. 189–194, 2016, in Chinese.

[25] X. Yang, R. Zhang, K. Fang, S. Liu, and Z. Yang, "Study on the Influence of shield synchronous grouting slurry performance and the optimization of its proportion," *Geotechnical Engineering Technique*, vol. 35, no. 5, pp. 336–340, 2021.