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CIVIL ENGINEERING

A pre-protection method for a pipe-jacking channel over shield tunnels

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Abstract. With the improvement of the planning level of underground space, the location of the planned under-crossing tunnel can be known in advance when constructing the upper-span tunnel. Therefore, pre-protection measures can be taken in advance during the construction of the upper-span tunnel. A new pre-protection method of a pipe-jacking channel was proposed to reduce the adverse effects of under-crossing shield tunnels. Numerical simulations of different pre-protection schemes were carried out using the finite element method to analyze its deformation control effect. The simulation results show that the deformation control effect of the gantry reinforcement scheme is the most significant. It is shown that the displacement of the pipe-jacking channel is more significantly suppressed with pre-protection measures than without preventive protection measures. The vertical displacement curve of the pipe-jacking channel exhibits a "W" shape after the construction of the double-lane shield underpass. By comparing the three different working conditions, it is found that the maximum vertical displacement and surface settlement of the pipe-jacking channel greatly reduced the gantry reinforcement pre-protection. Compared with Case 3, the effect of the pre-protection measures adopted in Case 2 was less obvious, which indicated that the form of the pre-protection had an important influence on controlling the deformation of the pipe-jacking channel.

Keywords: shield; pipe jacking; numerical simulation.

1. INTRODUCTION

With the rapid development of urban transportation construction, the utilization rate of urban underground space has improved considerably, and the problems of overlapping and crossing between underground tunnels have also become prominent. With the improvement of the underground space planning level, when using pipe-jacking technology to build underground passages, it is often known in advance that subway tunnels will be built under pipe-jacking passages in the future. These planned subway tunnels are usually constructed using the shield tunnelling method. In the process of shield construction, the excavation and unloading of soil will cause the existing pipe-jacking channel above to produce different vertical displacements. When the deformation of a pipe-jacking channel exceeds the limit value, the deformation joints between pipe joints can break, and leakage and even damage to the pipe joints can occur, thus posing a great challenge to the normal operation of the adjacent pipe-jacking channel. Therefore, for protecting the pipe-jacking channel, it is very important to take corresponding protection measures in advance during construction to reduce the deformation of the pipe-jacking channel.

The deformation of strata and adjacent tunnels caused by the construction of shield tunnels and pipe-jacking tunnels has been a burning issue in recent years, and scholars worldwide have conducted extensive research. Wang *et al.* [1] conducted research based on the Mindlin displacement solution and random medium theory and proposed an analytical model of formation disturbance caused by the jacking of parallel rectangular pipes. Ma *et al.* [2] proposed a new type of rectangular pipe-jacking-soil contact model and used numerical simulations to test the model. It is believed that the prediction accuracy of the friction force in the Tokyo area is within 5.5%. Pan *et al.* [3] used Plaxis-2D finite element software to simulate and analyze the displacement deformation of the existing structure caused by the top penetration of the pipe construction and concluded that the existing tunnel deformation is dominated by bulge deformation and that the vertical deformation of the existing structure is most obvious with a reduction in the net distance between them. Mair R.J. and other researchers [4, 5] explained the mechanism of land surface settlement during tunnel excavation. Ding *et al.* [6] considered that the tunnel height-to-span ratio and soil parameters have a great influence on the stability coefficient of the soil. In addition, compared with the traditional three-dimensional damage mechanism, the improved three-dimensional damage mechanism considers the damaged area on both sides of the palm face, which is closer to actual engineering construction. Tang *et al.* [7] believed that the settlement prediction of the Peck formula is more accurate in the range of 1.5 times the diameter of the pipe jacking, and the settlement prediction of the random medium theory is more accurate outside this range. Sun *et al.* [8] believed that soil reinforcement at the end of the rectangular pipe-jacking process can better control land subsidence and used numerical simulations to calculate and verify land subsidence above the reinforcement area. Liang *et al.* [9] proposed

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a simplified semi-analytical method for evaluating the uplift of the existing lower tunnel caused by the upper span tunnel and verified it by numerical simulation. Ma *et al.* [10] conducted a comparative analysis based on actual engineering monitoring and numerical simulations and demonstrated that the lateral disturbance of the pipeline was greater than that above the pipeline, the additional stress decreased with increasing distance from the central axis of the pipeline, and the influence range was smaller. Fang [11] proposed a superposition method to describe the subsidence profile caused by a double-track tunnel; the profile is in very good agreement with the measured data. Huang *et al.* [12] considered that when isolation piles are installed on one side of the tunnel, the surface settlement will tend to develop toward the opposite side of the tunnel. Many researchers have further discussed how to address or prevent the deformation of existing tunnels in time. According to Liu [13], in the construction of multiline overlapping shield tunnels, the construction strategy of first going down and then going up can reduce the surface settlement. When the tunnel is traversed up and then down, the curvature of the existing tunnel deformation curve will be significantly increased, repeated vibrations will occur, and the method for deducing the overall spatiotemporal deformation of the tunnel can be derived from the deformation of the known points of the tunnel. Lu [14] analyzed the influence of foundation pit excavation on adjacent existing tunnels. Through finite element simulation, it was concluded that within an adjacent distance of 30 m, increasing the thickness of the segment can improve the convergence deformation of the structure, but within an adjacent distance of 50 m, additional protection measures are required to reduce longitudinal deformation. Under the condition that the proposed double-line tunnel passes through the existing tunnel, uplift deformation of the existing tunnel mainly occurs, and the vertical deformation curve has obvious "double peak" characteristics [15]. Based on the research of Gan [16], compensation grouting can significantly reduce the settlement rate of existing tunnels when large-diameter shields penetrate the existing jacking pipes. Jin [17, 18] studied the overlapping and crossing problem of shield tunnels. The method of grouting protection in the tunnel can enhance the stiffness of the tunnel lining and compensate for the stratum loss caused by the construction of the tunnel. The treatment methods of grouting and monitoring shield construction parameters can greatly decrease the settlement of existing tunnels. Lin [19] showed that timely shield tail grouting can also drastically reduce the ground loss of the shield tail. Liao [20] believed that when the shield construction passes through the existing tunnel, the settlement of the tunnel may be caused by factors such as the instability of the face and the grouting of the shield tail. As the distance between the existing tunnel and the proposed tunnel decreases, the settlement of the existing tunnel will increase, and the support force must be stable during the underpass construction of the proposed shield tunnel [21]. According to Li [22], certain measures should be taken in advance for the planning of the underpass tunnel. Zhang [23] considered that a change in the location of overlapping crossings of shield tunnels has a substantial impact on the settlement deformation of existing tunnels. Research shows the MJS method of reinforcement above the proposed twin shield tunnel can effectively reduce ground deformation. The maximum settlement of the existing tunnel is related to the cross angle between the existing tunnel and the proposed tunnel [24,25]. Some studies of shield tunneling through existing structures were also conducted by researchers outside China. Avgerinos [26] developed a 3D finite element model to study the bending moments and lining deformations in the existing tunnel due to the excavation of the new tunnel. He studied the effect between the two when double tunnels are excavated side by side in sequence and concluded that the interaction between the tunnels is almost negligible when the tunnel spacing is twice as big as the diameter. Nematollahi [27] studied the effect of parallel crossing of a two-lane underground tunnel on the pile foundations of an overpass by simulation as well as experimental tests, taking a metro project in Iran as an example. Pedro [28] studied the effect between the two double-lane tunnelling in sequence and concluded that the interaction between the tunnels was almost negligible when the tunnel spacing was greater than the doubled diameter.

Previously, when the street crossing underground passages were constructed, no pre-protecting measures would be used because the plan of under-crossing of the shield tunnelling was not known. However, with the improvement of the underground space planning level, pre-protection measures can be taken in advance according to the planning of the under-crossing shield tunnels during the construction of the pipe-jacking channel of the street crossing underground passages. There are few examples and studies regarding the pre-protection engineering of the pipe-jacking channel over under-crossing shied tunnels. The authors [29] proposed a pre-protection method of an underground comprehensive pipe gallery on a planned tunnel. Due to the increasing number of such projects, the pre-protection method of the tunnel must be studied urgently. In this paper, a novel pre-protection method was proposed to protect a pipe-jacking channel over under-crossing tunnels. The numerical analysis method was used to comparatively study the pre-protection methods. Moreover, in this study, the settlement and displacement of the pipe-jacking channel were monitored when the subway shield tunnel crossed underneath the pipe-jacking tunnel, and the rationality of the adopted protection method was verified. The research results will have a certain guiding significance for the pre-protection of engineering projects and important theoretical and practical value in urban underground transportation construction.

2. THE PROPOSAL OF THE PRE-PROTECTION METHOD

2.1. Project overview

A street-crossing underground passage was constructed using pipe-jacking tunnelling method under Wenhui Road in Hangzhou, China. Before the construction of the pipe-jacking channel, it was already known that a double-line subway would cross under the pipe-jacking channel according to the Hangzhou subway plan. The location of the pipe-jacking channel and the planned subway shield tunnel is shown in Fig. 1. The total length of the pipe-jacking channel is 72.73 m; the outer dimension of the pipe-jacking channel is 6 m × 4 m; the inner dimension is

4.5 m × 2.5 m; the pipe segment is made of C50 concrete. The cross-section of the pipe-jacking channel is shown in Fig. 2.

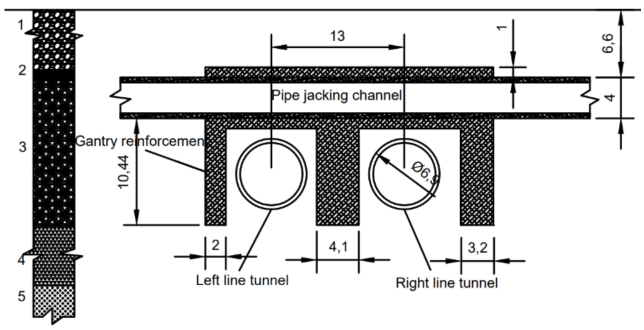


Fig. 1. Location of the pipe-jacking channel and the shield tunnel (unit: m)

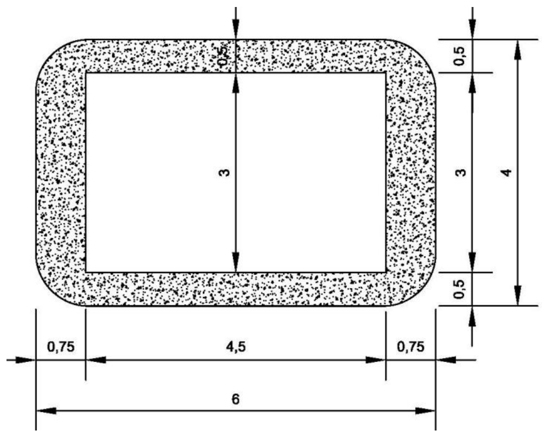


Fig. 2. Cross section of the pipe-jacking channel (unit: m)

The minimum distance from the top of the shield tunnel to the bottom of the pipe-jacking channel is 2.02 m. The proposed double-line shield tunnel is parallel with a centre spacing of 13 m and a diameter of 6.5 m, and the strength of the concrete segments is C50.

2.2. Engineering geological conditions

The project is located in a marine alluvial plain, and the natural elevation of the ground is 5.17~5.43 m. The foundation soil from top to bottom of the construction site mainly includes gravel, plain fill, marine silty clay, marine silty clay with silty sand, and grey silty clay. The physical parameters of each soil layer are shown in Table 1, where T is the layer thickness, μ is Poisson's ratio, γ is the bulk weight, Es is the compression modulus, c is the soil cohesion, and φ is the internal friction angle [30, 31].

2.3. Arrangement of monitoring

To evaluate the running status of the pipe-jacking tunnel in real time, 40 settlement monitoring points were set at 2 m intervals on the floor of the pipe-jacking channel and 30 settlement monitoring points were set at 2 m intervals on the ground surface. The arrangement of monitoring points of the floor and the ground surface is shown in Fig. 3. The warning value of the monitoring result of the pipe-jacking channel was set as follows: the cumulative settlement value of the floor was not allowed to exceed 10 mm and the change rate could not exceed 2 mm/d [32]. When the distance from the excavation surface of the new shield tunnel to the monitoring point L was less than ten times the diameter of the tunnel, the monitoring frequency was set to be 1 time/d.

Table 1
Physical parameters of each soil layer

Soil	T [m]	μ	γ [kN/m^2]	Es [MPa]	c [kPa]	φ [°]
1-Artificial fill	5.00	0.30	18.70	3.20	0	13.00
2-Plain fill	3.00	0.30	18.30	3.10	8.00	10.00
3-Marine silty clay	17.20	0.32	17.30	2.50	13.00	10.00
4-Marine silty clay with silty sand	10.00	0.31	17.60	2.60	14.00	11.00
5-Grey silty clay	3.00	0.32	18.60	2.60	24.00	13.00
6-Gantry reinforcement	/	0.30	19.00	39.97	390.00	23.00

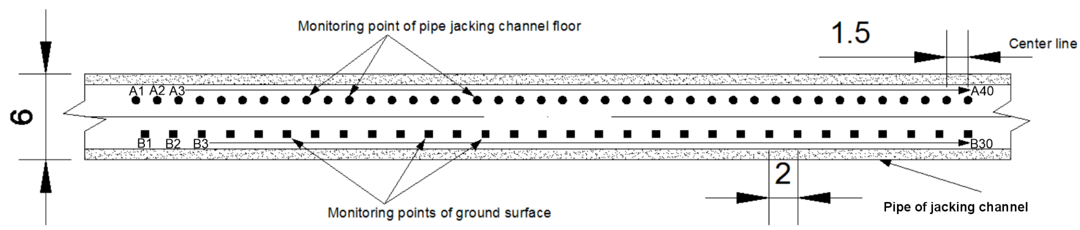
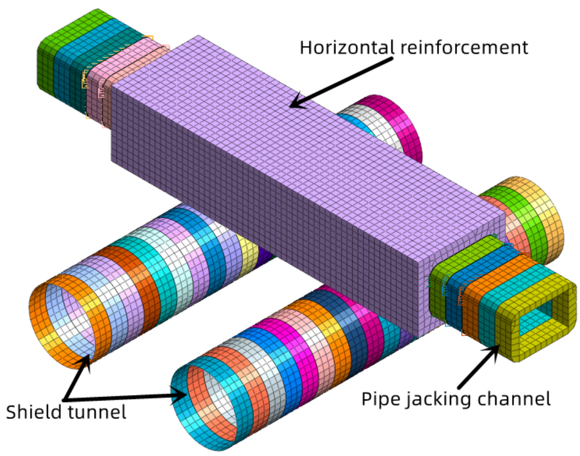


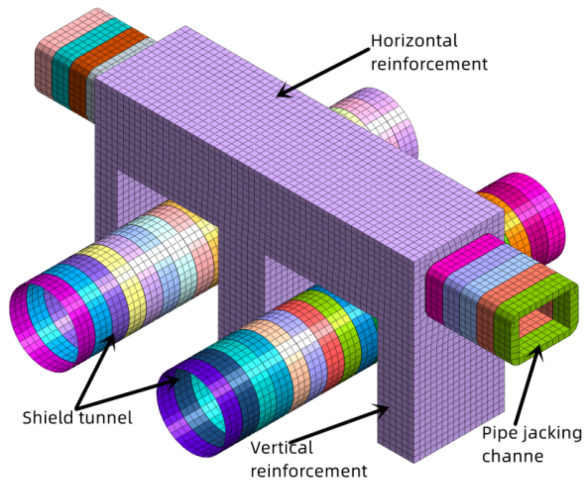
Fig. 3. Monitoring point layout diagram

2.4. Pre-protection method

For the engineering situation of this project, a new pre-protection method was proposed in this study. A gantry reinforcement body was constructed using rotary jet grouting piles before the street crossing channel was made. Then, the street-crossing channel was built in the reinforcement body using the pipe-jacking method. The gantry reinforcement includes horizontal reinforcement and vertical reinforcement, which are shown in Fig. 4b. The horizontal reinforcement can wrap around the pipe-jacking tunnel, and the vertical reinforcement is located below the horizontal reinforcement and avoids the location of the planned shield tunnel. A schematic diagram of this pre-protection scheme is shown in Figs. 1 and 4.



(a) Horizontal reinforcement (Case 2)



(b) Gantry reinforcement (Case 3)

Fig. 4. Pre-protection schemes (a) and (b)

To study the effect of this pre-protection scheme on the protection of the jacking channel, the finite element method was used to compare and analyse the following three cases: (1) Case 1: no reinforcement; (2) Case 2: only horizontal reinforcement, as shown in Fig. 4a; and (3) Case 3: both horizontal and vertical reinforcement, as shown in Fig. 4b.

The reinforcement scheme of Case 3 was taken in the project in this study. Gantry reinforcement was accomplished through the use of 800 mm diameter, 600 mm spaced high-pressure rotary jet piles. The size of the horizontal reinforcement was 28.17 m × 8 m × 6 m, and the bottom surface of the horizontal reinforcement was 1 m away from the top of the shield tunnel. There was a total of three vertical reinforcements located between and on both sides of the shield tunnels. The width of the vertical reinforcements was 8 m, and the vertical length was 9.44 m. The thickness of the three vertical reinforcements were 2.0 m, 4.1 m, and 3.2 m, respectively. The cement-mixed ratio of the reinforcement was 25%. The compressive strength standard value $Rc \geq 0.8$ MPa on the 28th day, and the permeability coefficient was less than 10^{-7}/cm/sec. The parameters of the gantry reinforcement are also given in Table 1. The bulk weight γ and the compression modulus Es of the gantry were obtained by laboratory tests. In order to obtain the cohesion c and internal friction angle φ of the gantry reinforcement, a series of parameter tests were conducted using the samples taken in the field. It was found that the obtained parameters had great dispersion, and the values of the parameters were distributed in a large range because the construction quality of soil-cement reinforcement was not uniform. In order to carry out a more accurate numerical analysis, the parameters of the gantry reinforcement within the range of parameters obtained in the test were gradually adjusted, so that the peak value of the settlement curve was more consistent with the measured results. The advantage of adjusting the parameters in this way was that it was possible to obtain a more accurate model to analyse the effects of different reinforcement schemes.

2.5. Research methods

2.5.1. Numerical simulation

A finite element model was built to simulate the double-line shield tunnelling underpass of the pipe-jacking channel. The overall size of the model was 60 m × 30 m × 39 m. The rectangular pipe-jacking channel is simulated with 3D solid elements, with a length of 60 m in the X direction and a ring width of 1.5 m. The length of the shield tunnel is 30 m, which has 20 rings with a ring width of 1.5 m and a ring thickness of 0.4 m. Additionally, the lining segments and shield shell are simulated with 2D plate elements. The two-lane tunnel was excavated by a soil-pressure balanced shield, with a cutter speed of 0–3.15 r/min and a cutter opening rate of 33%. The lining was assembled by assembling a tube sheet, the thickness of the tube sheet was 0.4 m, and the tube sheet was made of C50 concrete, which was assembled in the form of three standard blocks + two neighbouring blocks + one capping fast. Appropriate adjustments were made according to the monitoring data of construction. The second grouting was taken, so that the stratum loss rate was within 5‰.

In this study, the modified Mohr-Coulomb constitutive model and the elastic model were chosen to simulate the soil and structure, respectively. The stratigraphic structure method was used to complete the simulation, and the single excavation of the tunnel construction was two rings of 3 m. The total length of the tunnel in the interval was 30 m. In the numerical simulation, we focused on encrypting the grids of the tunnel interior, grouting layer, and the surrounding soil, and increased the density of the network to improve the accuracy of the part, and the grids of the other parts of the soil layer were adjusted to a larger size in order to increase the speed of the computation. The construction of the proposed shield tunnel is mainly in the third layer of the marine silty clay stratum. This model used interface elements to simulate the deformation joints between the pipe segments. To simulate the friction behaviour and relative displacement between the structure and the surrounding soil, an interface element was set up between the pipe channel and the soil elements. The normal stiffness of the interface element is 100 MPa, as shown in Fig. 5. The parameters of the gantry reinforcement are shown in Table 1, and the structural parameters are shown in Table 2.

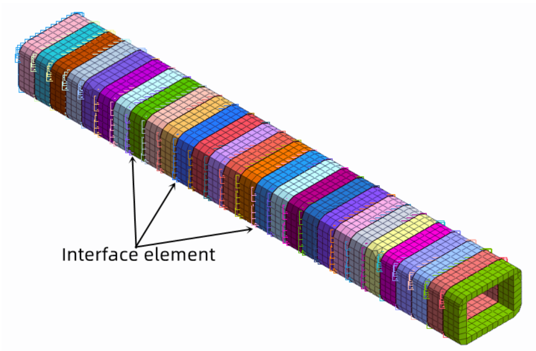


Fig. 5. Interface element model

Table 2
Structure parameters

Structure	γ [kN/m^3]	E [MPa]	μ
Pipe-jacking channel	25	36 000	0.20
Grouting layer	24	20 000	0.26
Shield Shell	78	250 000	0.20
Shield tunnel lining	25	34 500	0.20

In this model, the tunnelling thrust of the shield construction is 15 kPa, the pressure of shield tail grouting is 26 kPa, and the equivalent uniformly distributed force is used for simulation. The simulation process of shield tunnel construction under the pipe-jacking channel is as follows:

(1) Activating of the original soil elements, followed by initial field stress balance and displacement clearing.

(2) Killing the soil elements and activating the pipe-jacking channel elements and interface elements.

(3) Performing field stress balance and displacement clearing again.

(4) Start the shield construction simulation; kill the soil elements of the 1st and 2nd rings first, and then activate the shield shell elements of the 1st and 2nd rings and the excavation thrust.

(5) Continue to kill the 3rd and 4th ring soil elements and the 1st and 2nd ring shield shell elements while activating the 3rd and 4th ring shield shell elements, lining segments, and grouting layer elements and activating the corresponding loads.

The construction stages (4) and (5) above are cyclically advanced until the two-line shield tunnel is successfully built. In this paper, the left-line shield tunnel construction is carried out first, followed by the right-line shield tunnel construction, with a single excavation progress of two loops and a total of 20 construction steps for the overall shield construction.

2.5.2. Simulation results

The gantry reinforcement case (Case 3) was used as an example to study the displacement of the pipe-jacking channel and gantry reinforcement. Figure 6 shows the displacement cloud of surface settlement under the gantry reinforcing, and the maximum value of ground surface settlement is 15.65 mm.

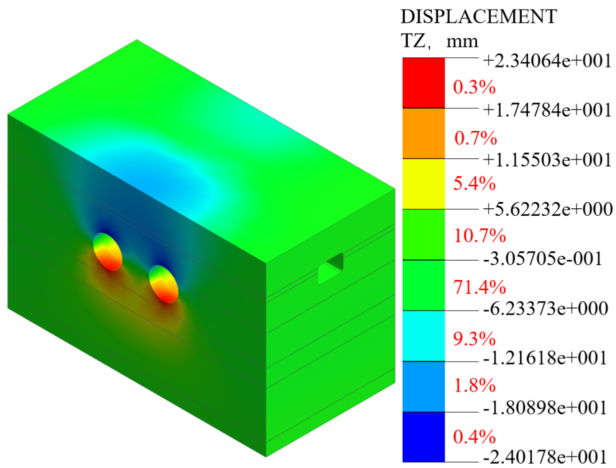


Fig. 6. Vertical displacement cloud map of the whole model

As shown in Fig. 7, the settlements of the pipe-jacking channel on the top of the two shield tunnel lines are 4.83 mm and 5.09 mm. This shows that the impact of the later shield tunnel construction on the existing horizontal pipe-jacking channel is concentrated directly above the shield tunnel and that the vertical displacements away from the shield tunnel are small enough to be neglected. This phenomenon is consistent with the predic-

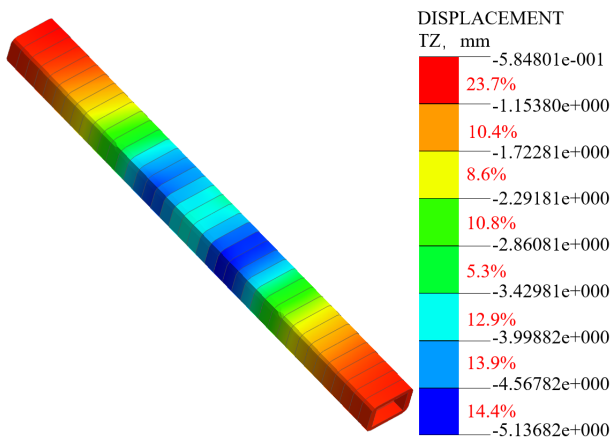


Fig. 7. Vertical displacement cloud map of the pipe-jacking tunnel

tions of previous numerical simulations and actual engineering monitoring results [5].

As shown in Fig. 8, the maximum settlement of the gantry reinforcement is also concentrated above the shield tunnel. The maximum settlement of the gantry reinforcement reaches 6.33 mm, and the gantry reinforcement presents a bulging deformation toward the centre of the shield tunnel. The deformation is caused by the soil loss during shield construction. However, the value of vertical displacement after the successful crossing of the double-line shield tunnel is small. According to the warning value of 10 mm for the settlement of the pipe-jacking channel requested by the design, the settlement of the pipe-jacking channel caused by the subsequent shield underpass construction meets the design standard. This indicates that the pre-protection method adopted in the actual project has a significant effect on the deformation control of the pipe-jacking channel.

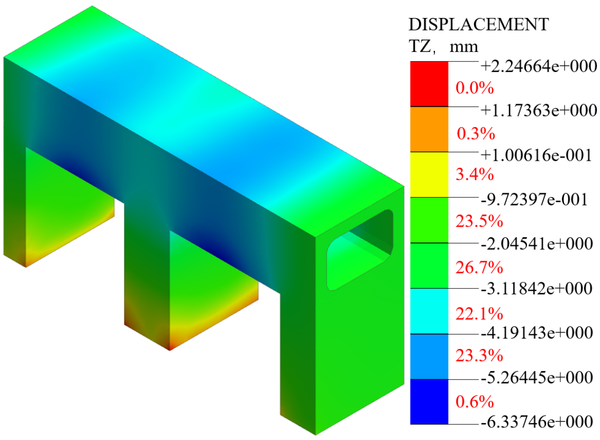


Fig. 8. Vertical displacement cloud map of gantry reinforcement

3. ANALYSIS OF RESULTS

3.1. Comparative analysis of pre-protection effects

3.1.1. The pipe-jacking tunnel settlement control effect

To study the control effect of different pre-protection schemes, the maximum vertical displacement variation of the pipe-jacking channel during shield construction under different pre-protection schemes is compared and analysed. The 20 construction stages of shield construction are taken for analysis in accordance with the construction steps of the left line first and then the right line for double-lane shield construction. Figure 9 shows the maximum vertical displacement change curve of the pipe-jacking channel during shield construction. The left line shield goes to the bottom of the pipe-jacking channel in the 5th stage, the vertical displacements of Case 1, Case 2, and Case 3 are −11.34 mm, −8.36 mm, and −3.05 mm, respectively. The vertical displacement of Case 1 exceeds the warning value of 10 mm, and Case 2 and Case 3 reach 83.60% and 30.5% of the warning value, respectively. When the left shield tunnel crossing is finished, the vertical displacement of the pipe-jacking channel is −10.24 mm, −9.32 mm, and −3.90 mm. The vertical displacement of Case 1 and Case 2 exhibit a small increase when the shield leaves the pipe-jacking channel, whereas the vertical displacement of Case 3 shows a 27.87% increase but still meets the design requirements. The maximum vertical displacements of Case 1 and Case 2 reach −12.21 mm and −11.61 mm, respectively. They both exceed the warning value of a 10 mm settlement while the maximum vertical displacement of Case 3 is only −5.63 mm. A comparison of the results shows that the pre-protection measures of Case 2 improve the control effect of the vertical displacement of the pipe-jacking tunnel, and the final settlement is only reduced by 4.91% compared with Case 1. However, it still breaks the warning value of a 10 mm settlement, which does not meet the design requirements. In addition, in Case 3 in the pipe-jacking channel with the gantry reinforcement pre-protection, the maximum vertical displacement is only 46.11% of Case 1, which can meet the engineering needs.

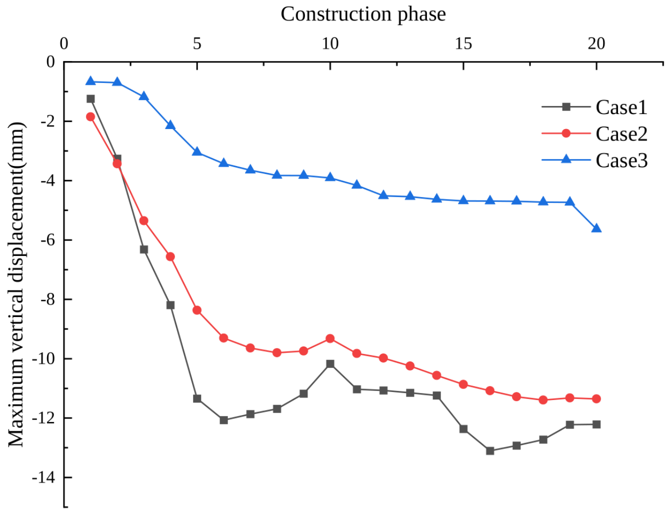


Fig. 9. Comparison of the maximum vertical displacement change

Figure 10 shows the settlement comparison of the pipe-jacking channel in three cases after the left line shield passes the pipe-jacking channel. The vertical displacement of the pipe-jacking channel at the cross interval of the left line tunnel is the largest. Compared with Case 1, the maximum vertical dis-

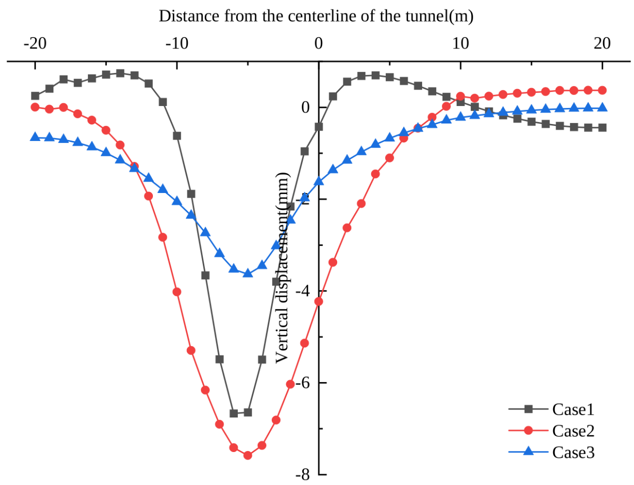


Fig. 10. Vertical displacement of the pipe-jacking channel after the left line shield crossed

placement control effect of Cases 2 and 3 is significant. All the maximum vertical displacements do not exceed the warning value. There is an obvious bulge phenomenon on both sides of the pipe-jacking channel directly above the left line tunnel in Case 1. The misplaced platform phenomenon of the corresponding pipe section of Case 1 may be significant due to the uplift of the pipe section.

The comparison of the vertical displacement of the pipe-jacking channel after the double-line shield crossed is shown in Fig. 11. The settlement of the pipe-jacking channel under the three different cases is large in the middle, the maximum vertical displacement of the pipe-jacking channel is concentrated at the top of the left and right line shield tunnel, and the vertical displacement between the double lines is relatively small. Thus, the overall vertical displacement curve of the pipe-jacking channel shows a "W" shape after the double shield tunnel crossed, which is consistent with the monitoring law of similar projects [13,18]. The problem of uneven settlement of the pipe-jacking channel in the double-line shield crossing area in Case 1 and Case 2 is prominent, which easily causes damage to the joints of the pipe-jacking channel. In Case 2, the deformation control of the pipe-jacking channel by the reinforcement is better than that in Case 1, but the effect is not as satisfactory. In Case 3, the slope of the settlement curve of the pipe-jacking channel under the effect of the gantry reinforcement is smaller than that in Case 1 and Case 2, and the uneven settlement is controlled very effectively. Therefore, the use of gantry reinforcement in the double-line shield crossing area plays a very important role in the pre-protection of the pipe-jacking channel.

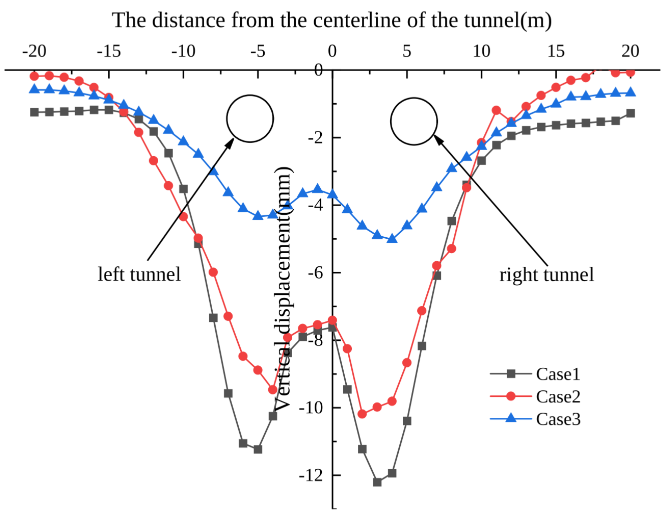


Fig. 11. Vertical displacement of the pipe-jacking channel after the double line shield crossed

The surface vertical displacement after the double-line shield is crossed is shown in Fig. 12. The monitoring points of the surface vertical displacement are distributed on the ground surface in the centre line of the pipe-jacking tunnel as shown in Fig. 3. The maximum vertical displacement of the ground surface under the Cases 1, 2 and 3 are −26.73 mm, −21.6 mm, and −15.64 mm, respectively. The maximum vertical displacement of Case 3 is reduced by 41.48% compared with Case 1 and is only 58.52% of that of Case 2. It can be seen that the gantry reinforcement can effectively reduce the ground disturbance caused by the construction of a shield tunnel. At the same time, the vertical displacement of the ground surface is decreasing on both sides away from the shield crossing area, and the overall vertical displacement curve is a "V"-shaped curve, which is in line with the prediction of the "Peck" formula and the law of tunnel overlapping crossing construction [18,21,33]. This indicates that the finite element numerical simulation is consistent with the actual engineering construction. Therefore, pre-protection of the pipe-jacking tunnel to control surface settlement is necessary, and the proposed method of gantry reinforcement is appropriate.

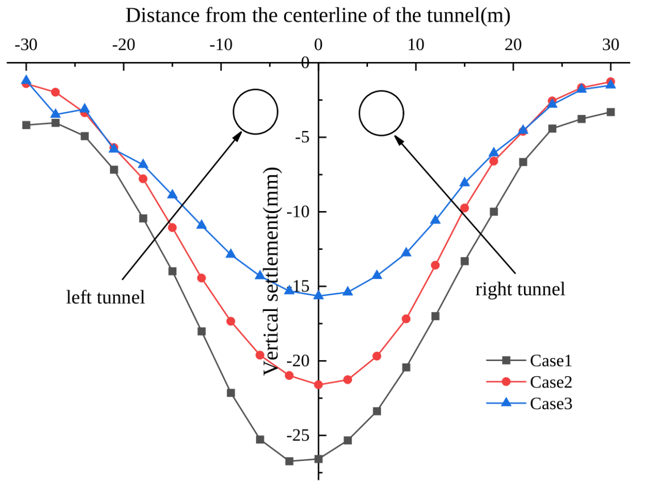


Fig. 12. Ground surface settlement after shield tunnelling

The "F" type socket joint was a weak part of the pipe-jacking channel. Obvious misalignment deformation between pipe joints in pipe-jacking tunnels is often found in projects. The relative settlements of two adjacent pipes are shown in Fig. 13, and the horizontal axis is the serial number of the pipe joint. Because the

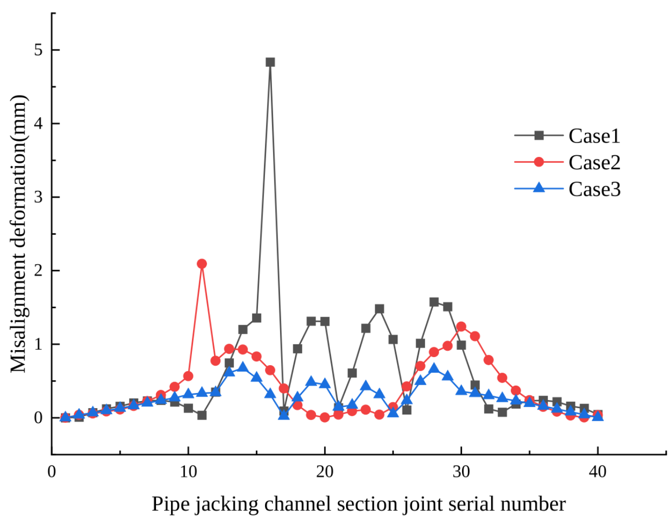
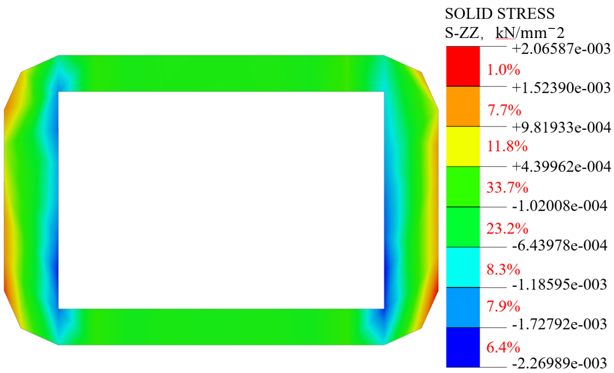


Fig. 13. Misalignment deformation of pipe jacking channel section joints

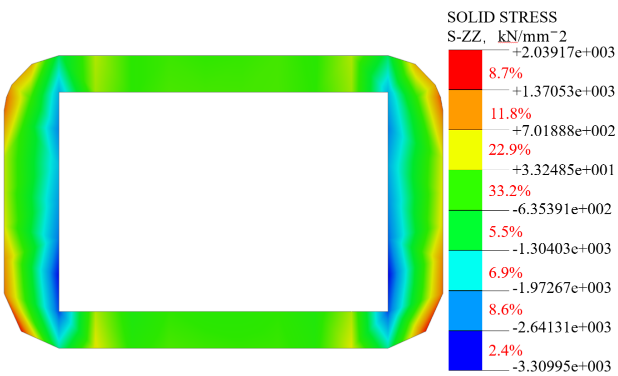
two shield tunnels pass through the underground street passage at a certain angle, the misalignment deformation along the pipe-jacking tunnel is not the same. The maximum misalignment deformation occurs right on the top of the shield tunnel. The maximum values of the misalignment deformation of working conditions 1, 2, and 3 are 4.83 mm, 2.09 mm, and 0.66 mm, respectively. It was found that the reinforcement method in working condition 3 had an obvious effect on controlling the misalignment deformation of pipe joints.

3.2. Stress analysis

To analyse the influence of the double-line shield tunnelling on the stress state of the pipe-jacking channel, the stress of the pipe segment at the intersection of the pipe-jacking channel and the shield tunnel is presented in Fig. 14 and Fig. 15. As seen in Fig. 14a–14b, the vertical stress of the lateral wall of the pipe segment is tensile on the outer and compressive on the inner. Under the pre-protection measures of gantry reinforcement, the maximum compressive stresses of the pipe segment of Case 1 and Case 3 are 3309.95 kPa and 2269.89 kPa, respectively. The maximum compressive stress is reduced by 45.82%, but the maximum tensile stress only differs by 1.3%. The horizontal stress of the pipe segment is shown in Fig. 15a–15b. The pipe segment has a compressive stress on the outer and a tensile stress on the inner part. Compared with Case 1, the maximum compressive stress is reduced by 29.01% and the maximum tensile stress is reduced by 57.52% in Case 3. It is indicated that gantry reinforcement can effectively control the stress variation of the pipe-jacking channel during shield tunnelling.

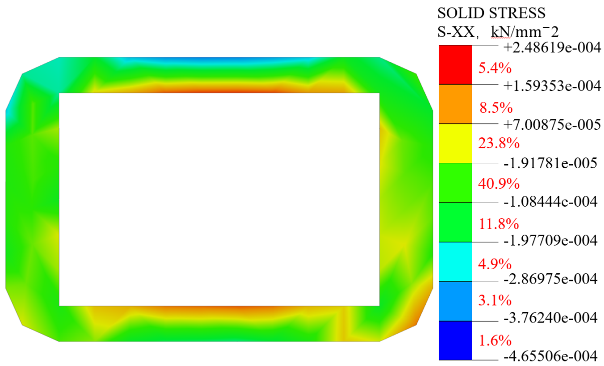


(a) Vertical stress cloud of Case 3

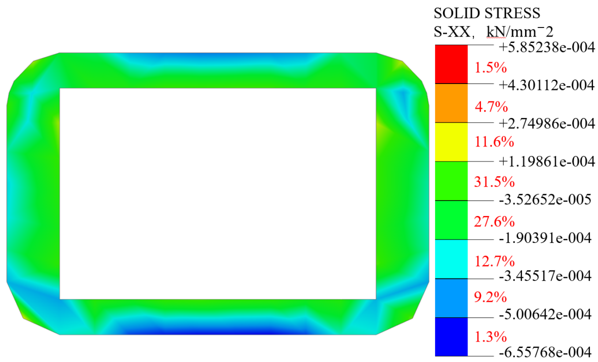


(b) Vertical stress cloud of Case 1

Fig. 14. Vertical stress of the pipe segment of the pipe-jacking channel at the intersection



(a) Horizontal stress cloud of Case 3



(b) Horizontal stress cloud of Case 1

Fig. 15. Horizontal stress of the pipe segment of the pipe-jacking channel at the intersection

3.3. Verification of the proposed pre-protection method

To verify the effect of the proposed pre-protection method, the displacement of the ground surface and floor of the pipe-jacking channel was monitored during the shield tunnelling in the actual project. The pipe-jacking channel was built in September 2021, and the shield tunnelling was conducted in October 2021. The location of the monitoring points is shown in Fig. 3. Figure 16 presents the comparison of the surface settlement of the monitoring and the simulation of Case 3. Figure 17 shows the comparison of the vertical displacement of the pipe-jacking channel of the monitoring and the simulation of Case 3.

It is found that the simulation of the vertical displacements of the ground surface and the pipe-jacking channel match well with the monitoring results. It indicates that the numerical model is correct, and the pre-protection method of Case 3 is verified by the actual engineering construction. The measured vertical displacements of the ground surface and the pipe-jacking channel meet the design requirements, indicating that the gantry reinforcement is effective in protecting the pipe-jacking channel during shield tunnelling. However, it should be noted that the

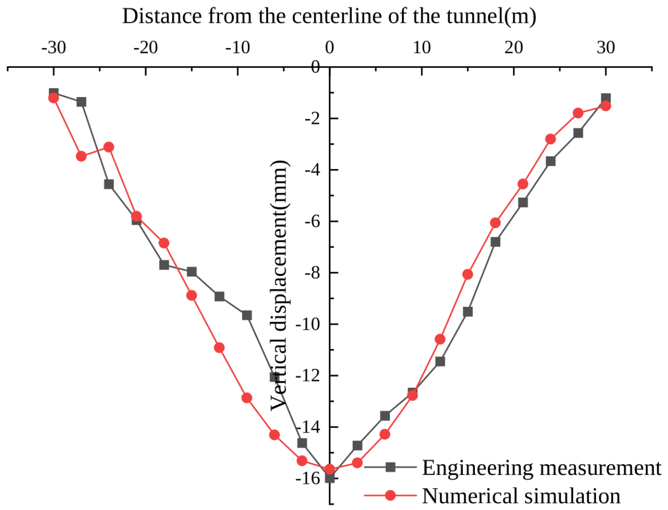


Fig. 16. Comparison of vertical displacement of the ground surface of simulation and measurements

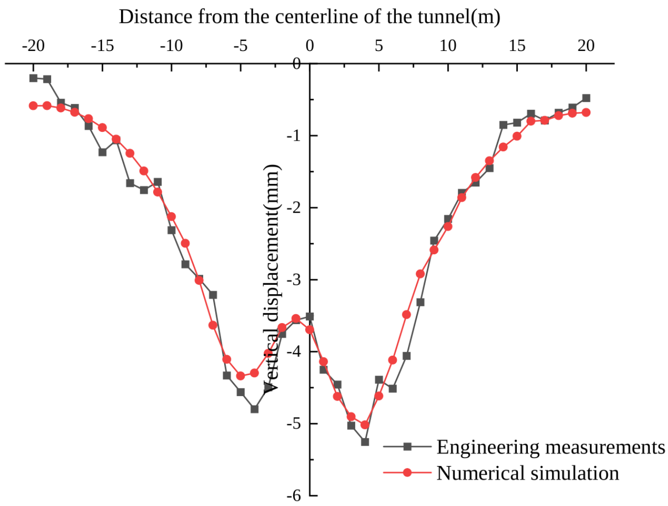


Fig. 17. Comparison of vertical displacement of the pipe-jacking channel of simulation and measurements

proposed pre-protection scheme was recommended for the underground pipe-jacking channel in soft clay or silt. The gantry reinforcement was not suitable for miscellaneous fill soil and gravel soil because of difficulties in construction.

4. CONCLUSIONS

A new pre-protection method of the pipe-jacking channel over shield tunnels was proposed, and numerical analysis was carried out to simulate the displacement control effect of different pre-protection schemes on the existing pipe-jacking channel. The monitoring results in the actual project were compared with numerical simulation results, and the following conclusions were obtained.

1. The change of the vertical displacement of the existing pipe-jacking channel caused by double-line shield construction could be effectively controlled by the pre-protection of the gantry reinforcement. After the shield crossing, the maximum settlement of the floor of the channel was only −5.63 mm, which was only 56.32% of the 10 mm warning value. The reinforcement form of Case 3 was more effective in controlling the overall settlement and uneven settlement of the pipe-jacking channel at the crossing interval than other solutions.
2. Horizontal reinforcement in Case 2 could not control the displacement of the pipe-jacking channel, and the maximum settlement of the channel exceeded the warning value. The gantry reinforcement of Case 3 was more effective in controlling the deformation than that of Case 2, and the maximum settlement of Case 3 was only 48.49% of that of Case 2.
3. The maximum settlement of the ground surface caused by the construction of the double-line shield tunnel occurred at the centreline of the double-line shield crossing. After the double line shield tunnelling crossed, the ground surface settlement curve was "V" shaped. The vertical displacement curve of the pipe-jacking channel exhibited a "W" shape after the construction of the double-line shield underpass.

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