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Research on optimization of frozen wall thickness of underwater tunnel based on fluid-solid coupling theory

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Abstract: The design of underwater tunnel has special requirements for the thickness of the frozen wall. To improve the frozen wall design of the cross-passage in the Maliuzhou waterway section of the Zhuji Intercity Rail Transit Project, based on the fluid-solid coupling theory, the finite difference method is adopted to analyse the stability of the underwater tunnel numerically. By simulating underwater tunnel with different frozen wall thickness, the responses of underwater tunnel stability to the thickness of frozen wall are discussed and the optimizaitons of frozen wall thickness are done. Some findings are as follows. Compared with the non-permeability model, the fluid-solid coupling model has the same distribution of stress on the frozen wall, but the overall values are obvious larger, which means the effect of water cannot be ignored. Due to the existence of water, the frozen wall tends to be “homogeneous”, and the stress concentration phenomenon is alleviated, but the distribution range of high shear stress is expanded, which increases the risk of shear damage; the frozen wall is changed to be under the tension from the pressure, which decrease structural stability. The deformation of the frozen wall is intensified under influence of the fluid-solid coupling and increase with the decreases of the thickness until the thickness of the model reaches 2.0 m or more, where the deformation of the frozen wall is basically stable. The plastic zones of the fluid-solid coupling models mostly exist at the arched areas on both sides, no plastic zone is formed in the models with 3.0 m and 2.5 m thickness, the plastics are formed in the opposite sides of the model with 2.0 m thickness, the plastic zone is almost going through in the models with 1.5m thickness, the damage zone is formed obviously at frozen wall arch of the model with 1.0 m thickness. The thickness of 2.5 m is selected as the optimized thickness of the frozen wall. This optimized thickness is directly applied to the design of the No.4 cross-passage, which is constructed by a freezing method. Through the on-site monitoring test, the validity and the effectiveness of the optimization scheme are verified, which means this optimization scheme has essential promotion and application value for the design of frozen wall thickness in similar projects.

Keywords: underwater tunnel; fluid-solid coupling theory; frozen wall; thickness optimization

1 Introduction

In recent years, with the increasing number of sub-sea and cross-river tunnels, relative engineering problems in the construction of underwater tunnels have gradually become a hot spot in the research field[1]. There are two main problems during the underwater tunnel construction. First, the existence of overlying water always leads to the occurrence of sand and water disasters in tunnels. Second, different from the tunnel construction in general water-rich stratum, once the inrush event occurs, the destruction to the entire project could be catastrophic due to the endless water supply. What’s more, the strata under the seabed and riverbed are composed of soft soils such as mucky soil and silty clay. Tunnel deformation and collapse disasters are prone to occur during the construction because of their low bearing capacity. In addition, the high water content makes an even higher demand to the bearing capacity of tunnel supporting structure. The artificial ground freezing (AGF) method can solve the problems encountering in the construction of underwater tunnels because of its waterproof and reinforced characteristics, and it has been widely used in the engineering practice nowadays[2]. As one of the core techniques of the AGF method, freezing wall design theory has also become a key research issue for scholars in this field.

Horizontal freezing method refers to drilling and laying freezing pipes in water-rich formations and using low-temperature brine or liquid nitrogen circulation to reduce the stratum temperature, turning natural rock and soil into frozen ones, which are with good integrity, high strength and good sealing effect. And this temporary horizontal freezing and solidification with strong overall support performance ensures the following excavation and lining construction can be carried out safely[3−6]. In 1997, China successfully applied the AGF method to the construction of Beijing subway tunnels for the first time[7]. After that, the horizontal freezing method gradually showed its superiority and achieved good results in subway

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constructions in Shanghai, Guangzhou, Nanjing and many other places[8–10]. At present, the researches carried out around this method are mainly focused on the formation and mechanism analysis of the temperature field of the frozen wall[11–14]. While there are few studies on the stress field and displacement field, and the design theory of frozen wall thickness that can guide the engineering practice is even rare. As a result, the frozen wall design in the actual construction is always general, rough and too conservative. Excessively effective thickness and long freezing time not only cause difficulties in the following excavation and large deformation of frost heave, but also greatly increase the time and economic cost of the project. Related research is urgently needed.

The research of frozen wall design theory is mainly carried out through two methods: theoretical mechanical calculation and numerical simulation calculation[15]. In terms of theoretical mechanical calculations, the design of horizontal frozen wall in engineering is still based on the design theory of vertical frozen wall in mine shafts. However, due to the non-uniform external load of horizontal frozen wall, there is a fundamental difference from the axially symmetric load of the vertical frozen wall. Even the optimal calculation formula on vertical frozen wall is theoretically not applicable to the horizontal one. Based on this, many scholars have done a lot of works on the design theory of horizontal frozen wall, and proposed a series of calculation formulas suitable for the thickness design and many of them have achieved good results[16–18]. However, due to the limitation of the calculation difficulty, the theoretical method can only be carried out on the simplified model, and the research ability of the frozen wall in complex stratum and complex stress environments is limited. In order to intuitively understand the mechanical effects and deformation laws of the frozen wall, and to analyze the influence of tunnel excavation on the stability of the frozen wall, numerical simulation calculation method has become an important means of research.

In terms of numerical simulation and thickness design improvement, many scholars have conducted a lot of researches, and the remarkable results have laid a foundation for subsequent research[19–21]. However, previous studies have only focused on the response of the frozen wall to the in-situ stress field, and have not considered the effect of seepage stress filed yet. In fact, the horizontal freezing method is mostly used in the construction of underwater tunnels or water-rich stratum. The stress redistribution caused by tunnel excavation will further change the distribution of the original seepage field, and the change of the seepage field will in turn affect the stress field[22–25]. Therefore, it is of great theoretical and practical significance to consider the effect of fluid-solid coupling on the stability of the frozen wall in underwater tunnels.

In summary, although scholars from all over the world have made in-depth research on frozen wall design theory and achieved remarkable results, there are still some major shortcomings in general, especially for the typical problems encountered in engineering that have not yet been systematically resolved. The research, which has both theoretical significance and practical value, needs to be developed urgently. In this paper, based on the fluid-solid coupling theory combined with FLAC^{3D} numerical analysis method, the mechanical effect and deformation law of frozen wall in underwater tunnel construction are studied, and then the improvement and optimization of frozen wall thickness design are investigated. The research method and improvement plan can provide a useful reference for the safe construction of similar underwater tunnel projects and the prevention of sand and water inrush disasters.

2 The project

2.1 Project overview

As an important part of the rapid rail transit system in the Pearl River Delta region, the Zhuji Inter-City Project is mainly responsible for the rail transit task connecting the urban area of Zhuhai to the airport section. The geological conditions and surrounding environment of the project are complex. Most of the tunnels are located under the city backbone where the surface construction is densely arranged. There are no traffic relief conditions due to the mountains and the sea nearby. In addition, it is too close to Macau, and passes through the Wan Chai port, with a large flow of people and political sensitivity. In summary, more rigorous and reliable technical measurements must be taken in the construction process to ensure the construction safety.

The Hengqin Tunnel–working well section #3 (hereinafter referred to as the Jinsan Section) is located in the Financial Island of Hengqin District, Zhuhai City. The left line (DK7+957.500–DK9+497.100) of the shield tunnel has a total length of 1.540 km, and the right line(YDK7+987.848–YDK9+541.298) has a total length of 1.553 km. The tunnel adopts shield construction, with double holes and single line. Among them, the line passes through the Maliuzhou waterway within the mileage range of DK8+100–DK8+700. The width of the waterway is about 600 m, the water depth is 5–8 m. The thickness of the overlying soil layer is 30 m. Engineering disasters such as sand and water gushing are prone to occur during the construction, which poses a great threat to the safe and stable construction of the tunnel. According to the relevant regulations and the actual situation on site, the original design selected a frozen wall thickness of 3.0 m and an average temperature which is no higher than −10 ℃. The site investigation suggests that the underground seepage in the construction stratum is active. In order to achieve the expected freezing strength, the actual active freezing time is 80 days.

2.2 Modeling

The Jinsan section is composed of the left and right shield tunnels and three cross-passages, the AGF method is adopted in the cross-passages #3 and #4. This study establishes a numerical model for the two shield tunnels within the range of DK8+140–DK8+220 and the cross-passage #3 at DK8+180, the schematic diagram is shown in Fig.1.

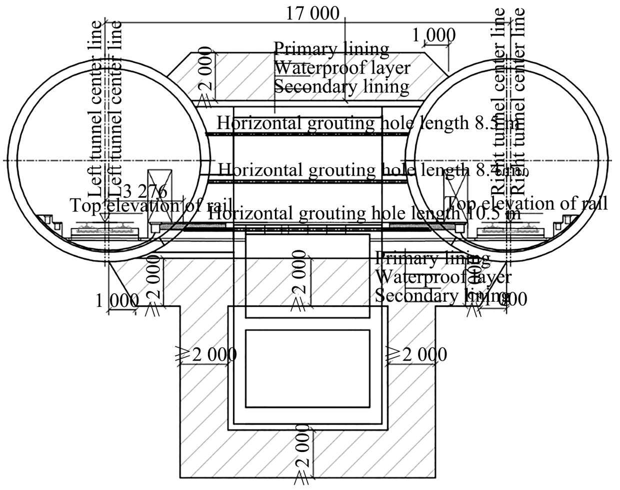

Fig.1 Geometric model of the cross-passage

The calculation model takes the *Y* axis along the tunnel axis, the *X* axis in the horizontal plane perpendicular to the axis of the tunnel, and the *Z* axis vertically up. In order to avoid the influence of the boundary effect on calculation results, according to the principle of St. Venan, comprehensively considering the calculation accuracy and solution time, the model size calculation formula proposed by the German scholar Möller[26] is adopted, the model range ($X \times Y \times Z$) is selected as 240 m × 100 m × 80 m. The three-dimensional numerical model is established through Rhino3D, and the Griddle is used to refine the grids in this model. Finally, the model data is imported into FLAC^{3D} to obtain the numerical calculation model shown in Fig.2.

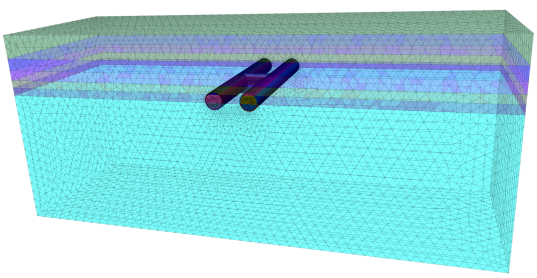

Fig.2 Numerical model

The upper surface of the model is free, and the displacements of the lower surface and the four sides are completely constrained. According to the on-site survey of the tidal level of the Maliuzhou waterway, the water depth of 5 m is selected as the simulation situation, then based on the pressure of the overlying water, the initial in-situ stress field is generated according to the gravity gradient from top to bottom. The initial seepage stress field is based on a fixed head of 5 m above, and the hydrostatic pressure is generated according to the gravity gradient from top to bottom. Due to the poor permeability of the soft clay, the small permeability coefficient, and the relatively large size of the selected model, the outer boundary is almost impossible to drain in a short time of tunnel construction. Therefore, it is assumed that all the outer boundaries except the upper surface are impervious boundaries.

2.3 Parameters

Mohr-Coulomb model is adopted for soil and frozen wall. Considering the difference in permeability coefficients of each soil layer, and using the isotropic seepage model in the same layer, the fluid density is 1000 kg/m^3, the fluid modulus is 2GPa, and the saturation is 1.0. The soil layers of the frozen wall are regarded as impervious models. From the site survey report, the physical-mechanical parameters and the seepage mechanical parameters of each soil layer are shown in Table 1 and Table 2. It is worth noting that, for simulating the improvement effect of simultaneous grouting on the deformation characteristics of weak soil layers, according to the calculation formula of equivalent elastic modulus of grouting reinforced soil[27], the elastic modulus of silty clay and gravel clay are modified from 20.0 MPa and 26.7 MPa to 48.0 MPa and 54.0 MPa, respectively, so as to get close to the actual working conditions.

Table 1 Physical-mechanical parameters of soils

Layers	Bulk modulus /MPa	Shear modulus /MPa	Internal friction angle /(°)	Cohesion /kPa	Natural density /(kg • m^{-3})	Dry density /(kg • m^{-3})
Silt	6.25	2.11	15.0	17.0	1 820	1 230
Coarse sand	25.00	11.50	38.0	0.0	2 000	1 760
Silty clay	11.10	3.70	15.7	33.5	2 010	1 590
Muddy clay	40.00	18.46	17.0	22.0	1 880	1 360
Gravel clay	45.00	20.77	21.0	30.0	1 890	1 430
Fully weathered granite	50.00	23.08	35.0	50.0	2 040	1 740

Table 2 Parameters of seepage property for soils

Layers	Porosity	Permeability/(m^2 • Pa^{-1} • s^{-1})
Silt	0.5	1.18×10^{-12}
Coarse sand	0.5	1.18×10^{-10}
Silty clay	0.5	2.30×10^{-11}
Muddy clay	0.5	1.18×10^{-12}
Gravel clay	0.5	2.30×10^{-11}
Fully weathered granite	0.5	1.18×10^{-10}

Table 3 shows the physical and mechanical parameters of frozen soil in each layer of frozen wall obtained from the laboratory test of artificial frozen soil. The shield segment adopts the elastic model, the elastic modulus is 34.5 GPa, the Poisson's ratio is 0.2, and the density is 2500 kg/m^3. The grouting and shotcrete are simulated by Shell unit, the elastic modulus is 10.5 GPa, the Poisson ratio is 0.25, and the density is 2500 kg/m^3.

Table 3 Physico-mechanical parameters for artificial frozen soils(−10 ℃)

Layers	Bulk modulus /MPa	Shear modulus /MPa	Internal friction angle /(º)	Cohesion /kPa	Density /(kg • m^{-3})
Muddy clay	106.0	57.9	4.99	330.0	1 880
Gravel clay	114.0	61.4	5.20	450.0	1 890
Fully weathered granite	404.0	231.0	5.05	360.0	2 040

2.4 Calculation steps

Based on the fluid-solid coupling theory, the finite difference numerical simulation software (FLAC^{3D}) is used to calculate the structural stability of the frozen wall with a design thickness of 3.0 m. The calculation sequence is as follows:

(i) Under the effect of self-weight stress and hydrostatic pressure, the stratum model reaches the balance of the initial stress field and seepage field before excavation.

(ii) The tunnel excavation on the left and right lines is carried out in sequence, and the excavation length is 8 m per cycle step, which is completed in 10 cycles. The mechanical and fluid-solid coupling fields are calculated after each step.

(iii) Activate the frozen wall by assigning frozen soil mechanical parameters to the certain zones, and complete the fluid-solid coupling calculation at the corresponding time.

(iv) The cross-passage adopts the full-section one-time excavation without applying the secondary lining, which means the most unfavorable situation is simulated. By simulating the construction process of pre-grouting, excavation and initial lining spraying, the stability and deformation of frozen wall structures are analyzed based on the changes of stress and displacement at the monitoring points, and the plastic yield zone.

2.5 Results and analysis

From the comparison of the displacement change of each characteristic point with the on-site monitoring data (see Figs.3 and 4), it can be seen that the deformation laws are basically the same and the deformation values are roughly consistent. It shows that the numerical model can objectively and truly reflect the mechanical effect and deformation law of the frozen wall during the cross-passage excavation, and can be used for the subsequent comparative study of the stability of frozen wall with different thicknesses.

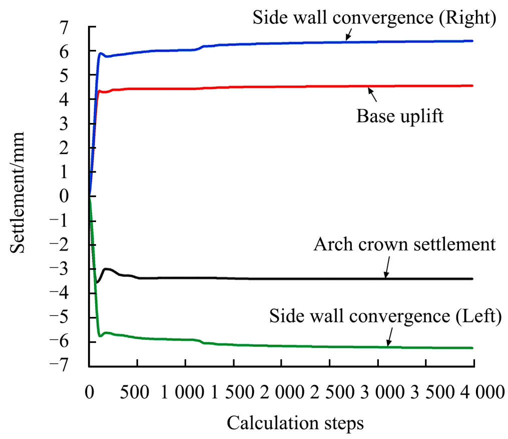

Fig.3 Predicted displacement of monitoring points

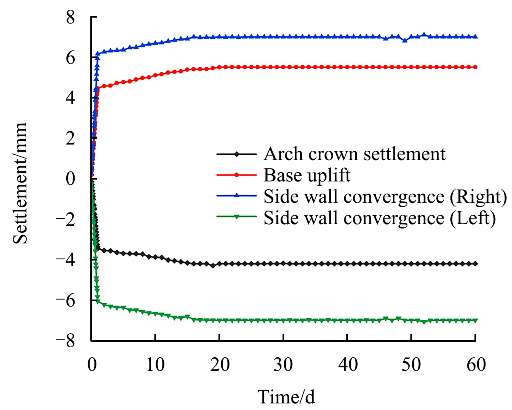

Fig.4 Field measured displacement of monitoring points

The calculation results of the plastic yield zone of frozen wall (see Fig.5) shows that except for the interface area between the bell mouth at both ends of the frozen wall and the shield segment, which partially enter the plastic zone due to the stress concentration effect, the rest of the structure is intact and stable, showing a good consistency with the actual monitoring results. In actual construction, due to the active heat exchange with the outside at the interface area between the bell mouth of

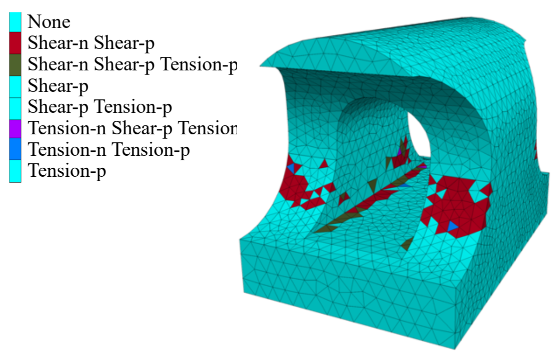

Fig.5 Plastic zone of frozen wall

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the frozen wall and the segment, the strength of the frozen wall is prone to be lower, so the interface area should be paid more attention to in the design stage, because the numerical simulation reveals the stress concentration in the area.

3 Design and optimization of frozen wall

Underwater tunnels have special requirements for the design of frozen wall thickness. In order to ensure the safe and stable construction of the entire project, a frozen wall thickness of 3.0m is required by design agency for the cross-passage #3 of Zhuji Inter-City Rail Transit Project undercrossing the Maliuzhou waterway section. In order to achieve the expected freezing effect, the active freezing period of the freezing station is up to 80 days, and the time and economic costs far exceed the construction of the ordinary tunnel freezing method under the same working conditions. In addition, during the actual excavation of the subsequent cross-passage, due to the excessively long freezing time, the soil in the excavation area is also affected by the freezing, which makes the excavation much more difficult. Common tools such as pneumatic pick are difficult to construct normally, and the local blasting has to be used to remove the soil. In view of the above engineering problems, a study is conducted on the optimal design of the frozen wall thickness of the cross-passage #3 passing through the Maliuzhou waterway.

The calculations are divided into the non-seepage model and the fluid-solid coupling model. Based on the original thickness of 3.0 m, the frozen wall thicknesses of the non-seepage models are set to be 2.5 m, 2.0 m, 1.5 m, and 1.0 m, respectively, for comparative study. Similarly, the frozen wall model with the same thickness gradient is applied to the fluid-solid coupling model. The purpose of the above consideration is to discuss the mechanical characteristics and deformation laws of the frozen wall under different models through longitudinal and horizontal comparative analysis.

3.1 Mechanical effect analysis

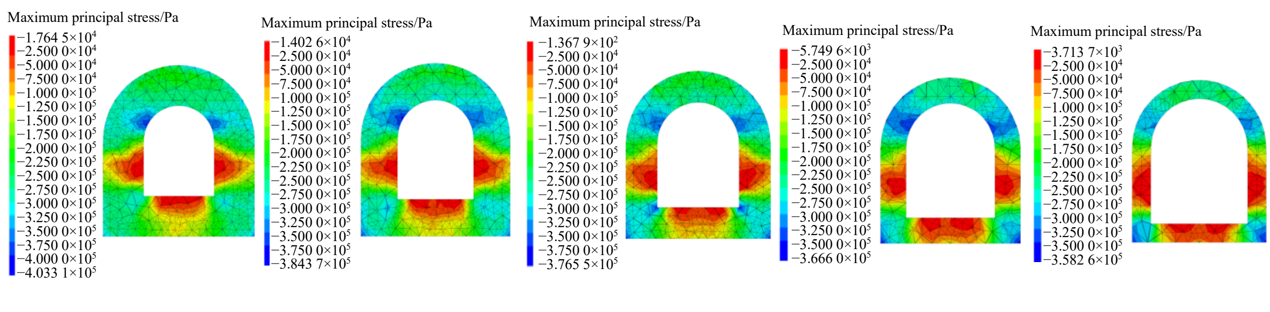
It can be seen from the comparison of the calculated maximum principal stress (Fig.s 6 and 7) that in the non-seepage model, the frozen wall section is under overall compression, and compressive stress concentration is likely to occur near the arch legs and arch shoulders on both sides. The compressive stresses of the frozen wall with different thicknesses are similar, but it shows a decreasing trend from the inner wall to the outer wall. Tensile stress has not yet appeared in the studied frozen wall section, but there is a tendency to develop tensile stress near the arch waist and the arch bottom on both sides, and there is also a tendency to decrease from the inner wall to the outer wall. The overall stress law of the frozen wall is approximately the same with that in the non-seepage model, but the overall pressure value is about 0.15 MPa higher than the non-seepage ones, and the average increase is about 40%. In summary, the effect of water is obvious. When designing the freezing wall of an underwater tunnel, the water effect cannot be ignored. At the same time, the seepage action makes the stress on the frozen wall tend to be "uniform", and the phenomenon of stress concentration is alleviated. From the view of uniform force, the presence of water is conducive to the bearing of the frozen wall. However, it is worth noting that the compressive stresses on the side walls and base are reducing, and there is a tendency to further develop into tensile stresses, that is, the presence of water tends to change the force form of the frozen wall. Because the compressive performance of the frozen wall is much greater than the tensile performance, and the appearance of tensile stress is not conducive to the stability of the structure. Therefore, the high water pressure puts forward higher requirements on the mechanical properties of the frozen wall, and special attention should be paid.

From the comparison of the calculated maximum shear stress (see Fig.s 8 and 9), it can be seen that in the non-seepage model, the distribution laws of the maximum shear stresses of frozen walls with different thicknesses are roughly the same. The concentration of shear stress at the arch waist and arch foot on both sides is manifested as an area prone to damage. The shear stress at the top and bottom of the arch is relatively small, which corresponds to the state of the main bearing in the maximum principal stress diagram. In terms of the magnitude of shear stress, the difference between frozen walls of different thicknesses is not significant, but the proportion of high shear stress areas penetrating the frozen wall increases with decreasing thickness. Compared with the non-seepage model, in the fluid-solid coupling model, the distribution laws of the frozen wall shear stress are similar, but the overall value is 0.02 MPa higher in average, with an increase of about 5%. Similarly, the seepage effect makes the distribution of the shear stress of the frozen wall tend to be "uniform", but the expansion of the high shear stress area increases the risk of shear failure of the frozen wall, which is not conducive to the stability of the frozen wall. In particular, it is noted that the high shear stress that originally only exists locally on the arch legs on both sides has expanded into larger areas on both sides of the arch base.

3.2 Deformation analysis

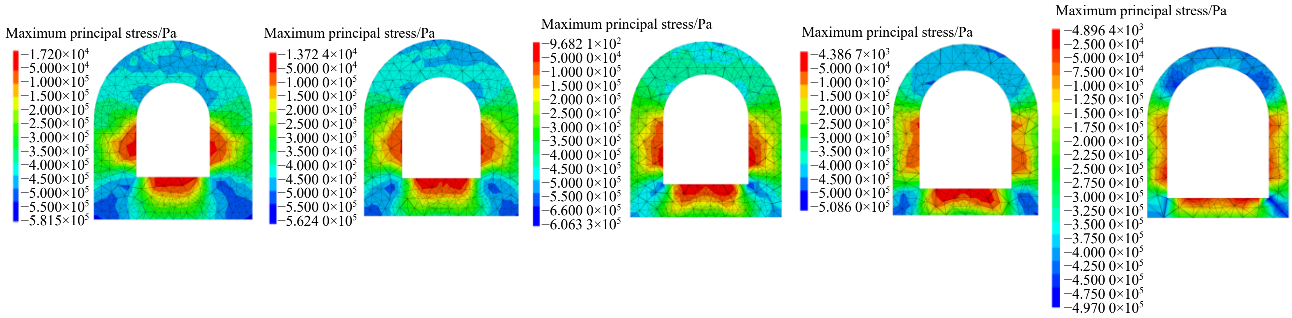
By setting up long-term deformation monitoring points at each characteristic part of the center section of the frozen wall and comparing the distribution of the plastic failure area, the stability of the frozen wall and its deformation law can be obtained more intuitively.

From the comparison of deformation (see Fig.10), it can be seen that in the non-seepage model, the deformation of the frozen wall is only determined by the in-situ stress field, the deformation rules of the frozen wall with different thicknesses



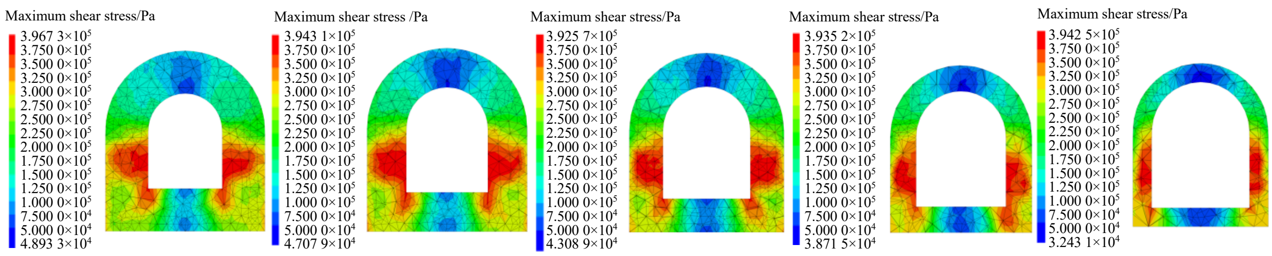
(a) 3.0 m (b) 2.5 m (c) 2.0 m (d) 1.5 m (e) 1.0 m

Fig.6 Comparison of the maximum principal stress between frozen walls with different thicknesses without the influence of seepage



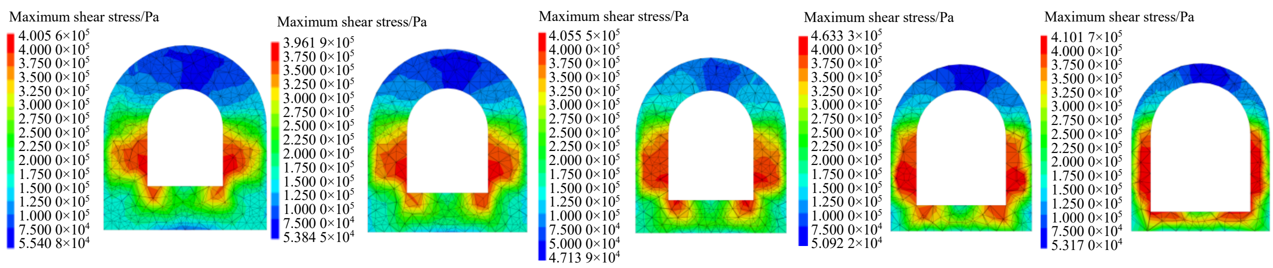
(a) 3.0 m (b) 2.5 m (c) 2.0 m (d) 1.5 m (e) 1.0 m

Fig.7 Comparison of the maximum principal stress between frozen walls with different thicknesses under the influence of fluid-solid coupling



(a) 3.0 m (b) 2.5 m (c) 2.0 m (d) 1.5 m (e) 1.0 m

Fig.8 Comparison of the maximum shear stress between frozen walls with different thicknesses without influence of seepage



(a) 3.0 m (b) 2.5 m (c) 2.0 m (d) 1.5 m (e) 1.0 m

Fig.9 Comparison of the maximum shear stress between frozen walls with different thicknesses under influence of fluid-solid coupling

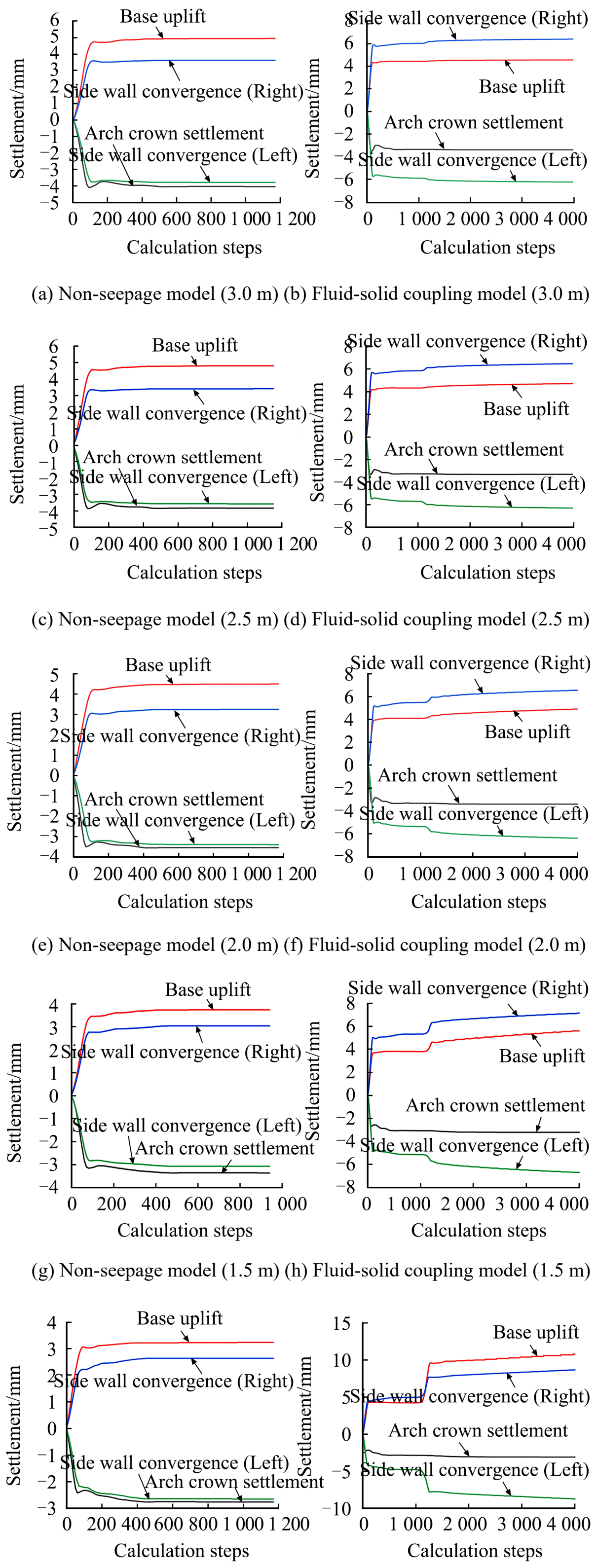
are the same, and the displacement values are roughly consistent. About settlement and uplift of approximately 4 mm occur in the arch crown and the arch base, respectively, and horizontal convergence of about 3 mm toward the free surface occurs on both side of the arch waist. Compared with the non-seepage model, in the fluid-solid coupling model, the deformation of the frozen wall is determined by the in-situ stress field and the seepage field, and the deformation toward the free surface are the same in both vertical and horizontal directions. However, except that the displacement value of the arch crown settlement does not change much, and remains at about 3 mm, other displacement values increase significantly, and the horizontal convergence displacement increases to 6 mm, with an increase of near 100%. The uplift displacement of the arch base shows a certain variation law with the thickness of the frozen wall. The uplift displacement of the 1.0 m thick frozen wall arch base increases from about 3 mm to about 10 mm, the 1.5 m thick frozen wall increases to about 6 mm, and the uplift displacements of 2.0 m thickness and above do not change much, and are basically stable at about 4 mm.

The above rules are consistent with the actual situation. The existence of water pressure makes the frozen wall subject to greater compressive stress. However, due to the excellent compression resistance of the frozen wall and the relatively small contact area between the upper circular arch and the surrounding soil, the increase of vertical compressive stress will not cause significant changes in the settlement of the vault. From the foregoing analytical results, it can be seen that the presence of water expands the high-stress area of the arch waist on both sides. In addition, the contact area between the side walls and the soil is large, so after considering the fluid-solid coupling, the horizontal convergence displacement increases significantly. The uplift displacement of the arch base is caused by the superposition of the deformation of the structure itself and the upward buoyancy of water, which causes a significant increase in the displacement.

By longitudinally comparing the displacement changes of frozen walls with different thicknesses under the action of fluid-solid coupling, it can be found that there is a clear growth step in the curves of 2.0 m thick and below models. Essentially, this sudden change is because in the numerical calculation, the mechanical equilibrium calculation must be completed before the full fluid-solid coupling calculation, that is, when the fluid-solid coupling calculation is started, the curve has a sudden growth increase. However, it can also be seen from the different sensitivities to the reaction of the same calculation process, when the design thickness of the frozen wall is too small, the seepage effect has a great influence on the structural stability, and the effect of water is obvious and cannot be ignored. The reasonably designing the frozen wall based on the fluid-solid coupling theory can really meet the stability requirements in actual engineering. When the thickness reaches 2.0 m, the mutation phenomenon is significantly improved, and there is basically no mutation phenomenon when the thickness exceeds 2.5 m.

In summary, from the perspective of deformation control, the 2.5 m frozen wall can meet the design needs.

It can be seen from the comparison of the calculated plastic yield area (see Fig.11) that the plastic yield mainly occurs in the area of the two arch waists and arch feet inside the frozen wall. In the non-seepage model, as the thickness of the frozen wall decreases, the plastic yield range gradually expands. When the frozen wall thickness is reduced to 1.5 m, the plastic zone increases significantly, but no penetrating plastic yield zone is formed, and the structure can still play its supporting role. When the thickness is reduced to 1.0 m, a plastic yielding area has been formed on both sides of the arch, and the frozen wall is hardly able to bear the surrounding load and has a high risk of damage. The above rules are consistent with the content of



(a) Non-seepage model (3.0 m) (b) Fluid-solid coupling model (3.0 m)

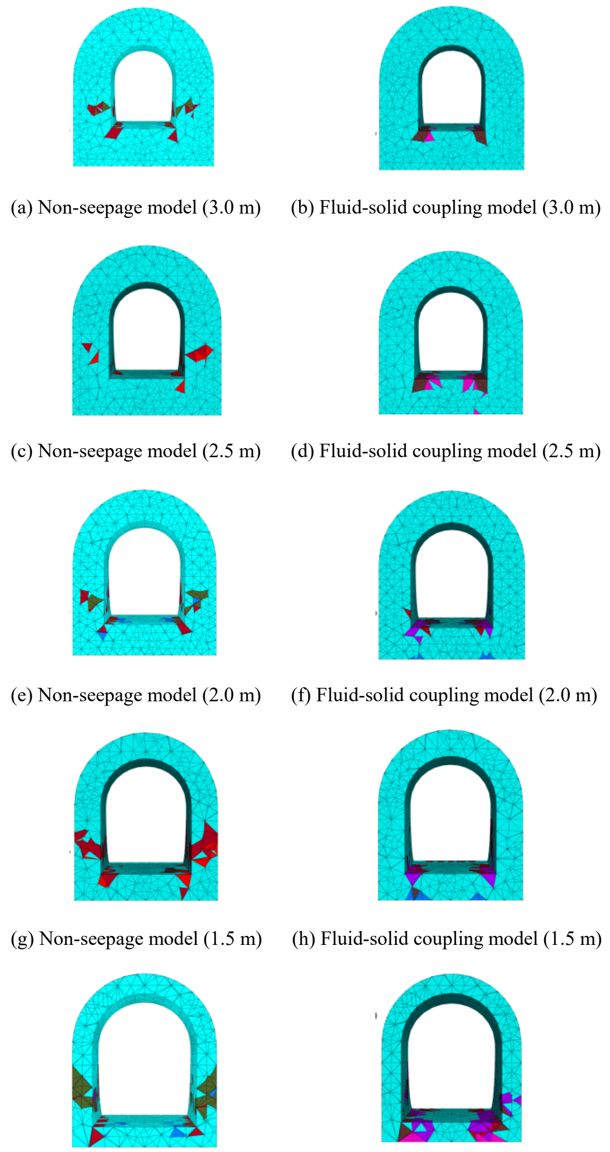
(c) Non-seepage model (2.5 m) (d) Fluid-solid coupling model (2.5 m)

(e) Non-seepage model (2.0 m) (f) Fluid-solid coupling model (2.0 m)

(g) Non-seepage model (1.5 m) (h) Fluid-solid coupling model (1.5 m)

(i) Non-seepage model (1.0 m) (j) Fluid-solid coupling model (1.0 m)

Fig.10 Comparisons of displacement between frozen walls with different thicknesses



(a) Non-seepage model (3.0 m) (b) Fluid-solid coupling model (3.0 m)

(c) Non-seepage model (2.5 m) (d) Fluid-solid coupling model (2.5 m)

(e) Non-seepage model (2.0 m) (f) Fluid-solid coupling model (2.0 m)

(g) Non-seepage model (1.5 m) (h) Fluid-solid coupling model (1.5 m)

(i) Non-seepage model (1.0 m) (j) Fluid-solid coupling model (1.0 m)

Fig.11 Comparisons of plastic zone distribution between frozen walls with different thicknesses

the design thickness of the frozen wall recommended in the current "*Technical Code for Cross-passage Freezing Method*"[15], indicating that the numerical simulation can better reflect the objective rules in actual construction.

However, it should be noted that the thickness recommended in the current regulations is for the design of general metro tunnels. The thickness of the frozen wall of underwater tunnels should be determined by considering the complex hydrogeological conditions. Compared with that in the no-seepage model, the distribution of the plastic zone in the fluid-solid coupling model corresponds to the distribution of the maximum shear stress. Although the distribution area of high shear stress on both side walls are enlarged, the concentration of shear stress is alleviated, and the extreme value is reduced, leading to a reduction in the plastic zone. The increase in shear stress on both sides of the arch base results in the plastic zone changing from being more distributed on the side walls to being more concentrated on the arch foot area on both sides. The plastic zone range increases as the thickness of the frozen wall decreases. The models with frozen wall thickness of 3.0 m, 2.5 m, and 2.0 m are all intact and have high safety reserves. The plastic zone on both sides of the arch base of the model with a frozen wall thickness of 1.5 m is close to penetration. The arch base of the model with a frozen wall thickness of 1.0 m has formed obvious penetrating damage, making it difficult to ensure safe and stable construction.

In summary, based on the results of numerical analysis, an optimized plan with a frozen wall design thickness of 2.5 m is proposed by considering that the mechanical response and the degree of deformation of the frozen wall must meet the requirements of the regulations.

4 Application of frozen wall optimization for cross-passage

In Jinsan section undercrossing the Maliuzhou waterway, the cross-passage #4 adjacent to the cross-passage #3 and with similar hydrogeological conditions was selected for the construction period monitoring test (without consideration of the operation period), as shown in Fig.12.

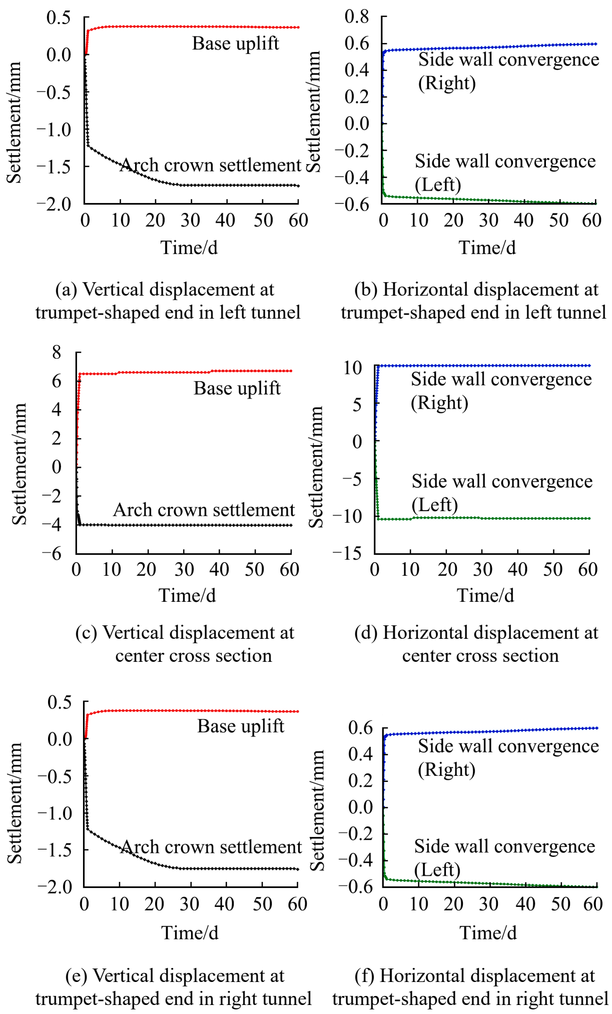
(a) Freezing station (b) Active freezing

(c) Excavation (d) Displacement monitoring

Fig.12 On-site construction monitoring for cross-passage #4

After the overall primary lining and secondary lining were completed, three characteristic cross-sections, located at the bellmouth of both ends and the middle of cross-passage #4, were selected to monitor the settlement of the arch crown, the uplift of the base and the horizontal convergence of the side walls. Since the exposure time after the completion of the overall initial liner usually did not exceed 24 h, an interval of 1h was for monitoring the displacement of the primary liner, and the monitoring lasted for 24 h. An interval of 1d for the second liner, and lasted for 60 d.

Figure 13 shows that the deformation of each point gradually increases after the initial liner is completed and has a continuous development trend, but no mutation deformation is seen. The settlement of the crown and the uplift of the base are about 8 mm, respectively. The horizontal convergences on both sides are about 6 mm, respectively. After the second liner is completed, the deformation increases slowly, and gradually stabilizes after 30 days, and the cumulative displacement increment does not exceed 1 mm.



(a) Vertical displacement at trumpet-shaped end in left tunnel

(b) Horizontal displacement at trumpet-shaped end in left tunnel

(c) Vertical displacement at center cross section

(d) Horizontal displacement at center cross section

(e) Vertical displacement at trumpet-shaped end in right tunnel

(f) Horizontal displacement at trumpet-shaped end in right tunnel

Fig.13 Displacement curves of field monitoring points at characteristic sections

On-site displacement monitoring results show that the improved scheme of frozen wall thickness is effective and feasible. The cumulative displacements in vertical and horizontal directions are both below 10 mm, which is much lower than the warning value of 30 mm specified in the regulations. In addition, during the excavation of cross-passage #4 by mining method, there was no problem similar to the difficult excavation of cross-passage #3. At the same time, when the active freezing reaches 60 days, the thickness of the freezing wall can reach the design requirement of 2.5 m. Compared with the original design of 80 days, the construction period has been greatly shortened, saving manpower and material costs.

In summary, the optimization scheme for frozen wall thickness is effective and feasible, and has great advantages in both terms of technicality and economy.

5 Conclusions

Compared with the non-seepage model, the force laws of the frozen wall in the fluid-solid coupling model are approximately the same, but the overall value is significantly improved. The average increase in the maximum principal stress is up to 40%, and the average increase in the maximum shear stress is up to 5%, showing that the seepage stress has obvious effect. Thus, the effect of water cannot be ignored when designing the freezing wall of underwater tunnel.

The presence of water makes the stress on the frozen wall tend to be "uniform", and the stress concentration phenomenon is alleviated. However, the expansion of the high shear stress zone increases the risk of frozen wall shear failure. And the force of the frozen wall shows a trend of changing from compression to tension, which is not conducive to its structural stability. The higher requirements should be made for the mechanical properties of the frozen wall subjected to the seepage action, and the special attention should be paid to in this case.

Compared with the non-seepage model, the deformation of the frozen wall in the fluid-solid coupling model is significantly increased. The horizontal convergence on both sides increase to 6.0 mm, an increase of nearly 100%. The uplift of the arch base shows a clear increasing trend with decreasing thickness of the frozen wall. When the thickness is 1.0 m, the deformation increases from about 3.0 mm to about 10.0 mm. When the thickness is 1.5 m, it increases to about 6.0 mm. When the thickness reaches 2.0 m and above, it basically stabilizes at about 4.0 mm.

Compared with the non-seepage model, the plastic zone of the fluid-solid coupling model has changed from being distributed mostly on side walls to being mainly concentrated on the arch foot area on both sides, and the range increases as the thickness of the frozen wall decreases. The 3.0 m and 2.5 m models are generally intact. In the 2.0 m model, opposite developing plastic zone appears at arch foot. The thickness of the plastic zone in the 1.5 m model is close to penetration. The arch feet on both sides of the 1.0 m model have formed obvious penetrating damage.

Based on the fluid-solid coupling theory, the improved design thickness of frozen wall is selected as 2.5 m by constructing a multi-model numerical simulation test and comparatively analyzing the mechanical effects and deformation laws of different thickness models after excavation. This optimization scheme is directly applied to the construction of the cross-passage #4 in the same section. The on-site monitoring data indicate that the deformation of each feature point is within a reasonable range, and the frozen wall meets the relevant requirements of the current regulations, which verifies the effectiveness and feasibility of this optimization scheme.

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