Numerical simulation of ground frost heave during tunnel construction with pipe curtain freezing method

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1 Introduction

Pipe curtain freezing method is a new construction method that proposed by Chinese engineers for Gongbei Tunnel. This new type of advanced reinforcement technology not only fully combines the advantages of the pipe-roofing method and the artificial freezing method, but also meets the excavation requirements of the Gongbei tunnel under complex geology. Wang et al. [1] had successfully applied this method in Taiwan tunnel projects combining with the fore-poling method, the plate shield method, and ground improvement method. Avanessian et al. [2] optimized the shape of the pipe roof into an umbrella shape, then simulated the sectional excavation of tunnel No.10 of the Ghazvin-Rasht Railroad, and surprisingly found that it had a great effect.

However, this new construction method will also inevitably bring new technical difficulties. The displacement changes brought by frost heave and the thawing settlement have always been the key problem that underground engineering needs to solve. Once the deformation is not effectively controlled, it will cause irreversible damage to the surrounding environment.

Based on the Gongbei tunnel project of the Hong Kong-Zhuhai-Macao Bridge, the paper analyzes the construction process of the pipe curtain freezing method, predicts the displacement field during the process of frost heave, and prepares adequately for the large deformations in the ground.

2 Background of research project

Gongbei Tunnel, which belongs to Xiangzhou District of Zhuhai City, starts in Gongbeiwan Sea Area, connects with Gongbeiwan Bridge, and finishes in Maoshengwei Management Zone of Guangdong Province. It is the main body of Zhuhai ring line project. The tunnel is a double-deck six-lane monolithic tunnel, with a total length of 255 m, which traverses the limited area of Gongbei Port. The plan layout is shown in Figure 1. And as shown in Figure 2, the tunnel burial depth is 6.98 m. The soil layers traversed by the tunnel exhibit characteristics of interbedded sedimentary deposits: they are soft, saturated, highly compressible, and highly permeable.

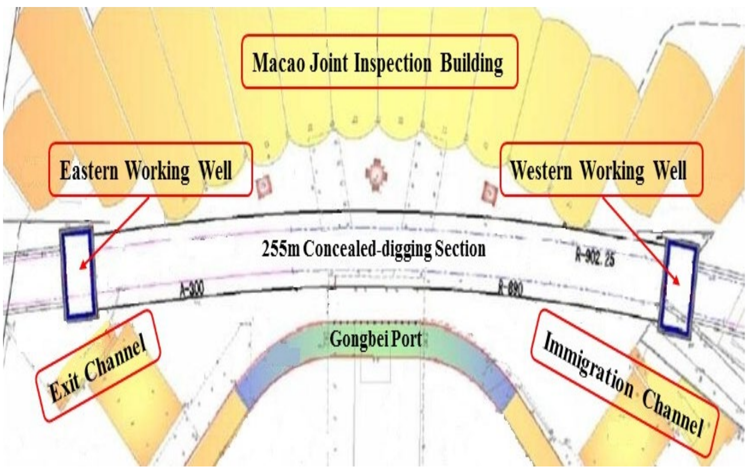

Figure 1. Layout of Gongbei tunnel undercutting section.

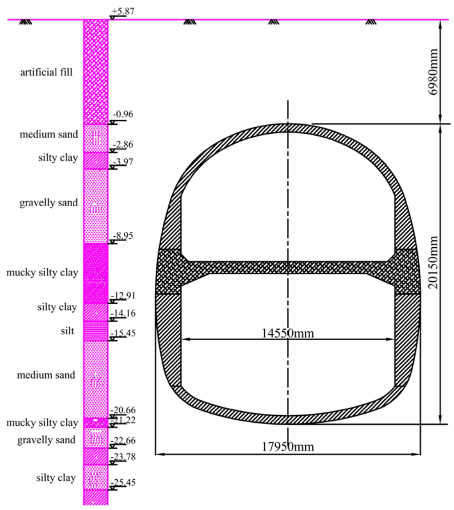

Figure 2. Cross-section Gongbei tunnel.

Pipe curtain freezing method is adopted for tunnel construction. As shown in Figure 3, the pipe curtain is composed of 36 steel pipes with the diameter of 1620 mm, each section length is 4 m, and the jacking pipe spacing is 357 mm. The odd number of pipe curtain deviates 0.3 m inward, the excavation section area is 337 m^2, and the soil thickness covered on the top of the pipe curtain is about 4-5 m.

In Figure 3, The circular freezing pipes are arranged in the odd-numbered steel jacking pipes, while the shaped freezing pipes are arranged in the even-numbered steel pipes. Finally, the odd-numbered steel pipes are filled with C30 concrete before the tunnel excavation, while the even-numbered steel pipes are filled with micro-expansive concrete after

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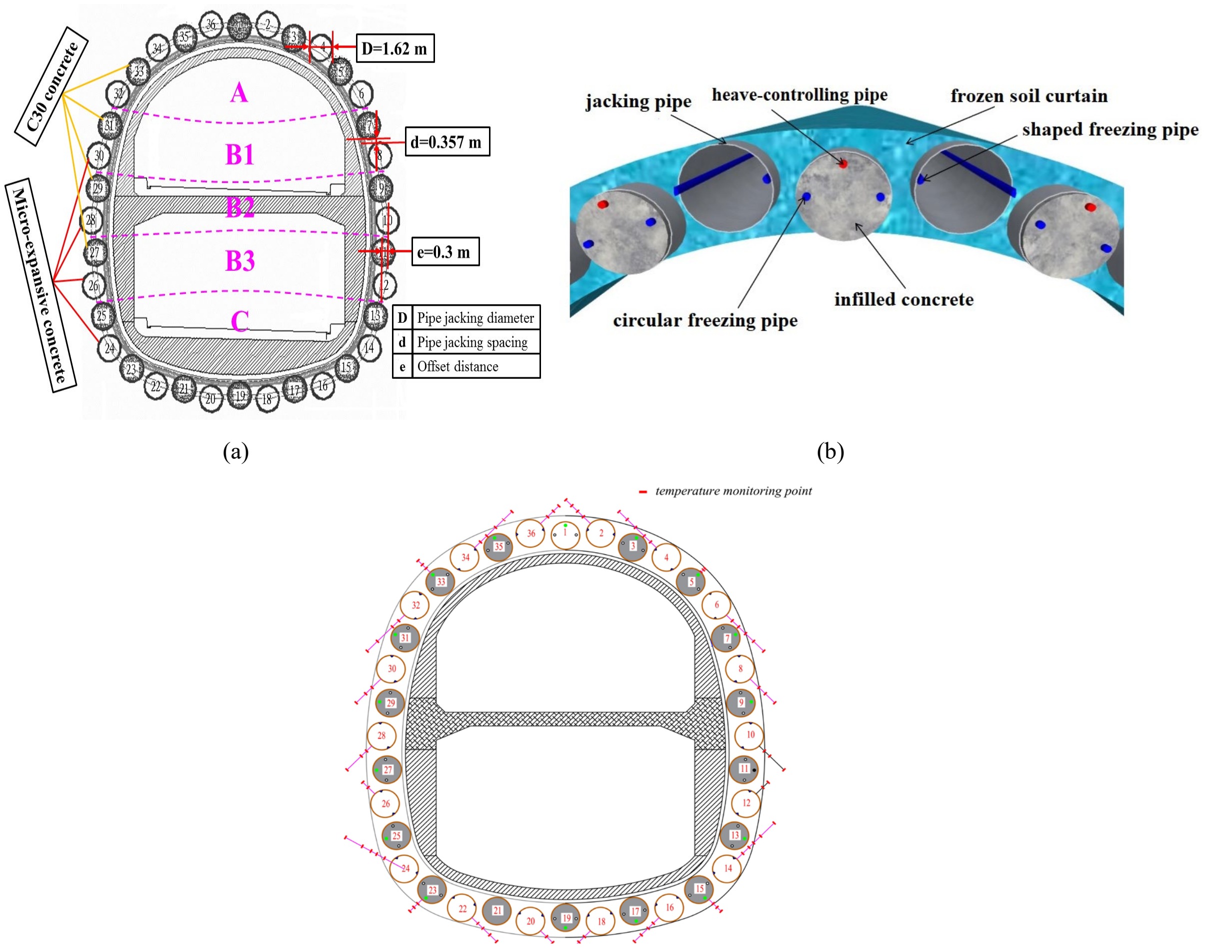
excavation. The frozen soil curtain formed by the pipe curtain freezing method runs through the tunnel construction stage and provides strong support for the development of underground engineering.

Before excavation, low-temperature(-28°C) brine circulates in the freezing pipes to form a frozen soil curtain. The circular freezing pipes would keep cooling operation for 70 days firstly, and then the special-shaped pipe for 20 days, until the thickness of frozen soil curtain meets the sealing requirements. In order to control the frost heave of surface, the thickness of frozen soil curtain in the upper half of tunnel (i.e. frozen zone A and B1) should be controlled within 2.3 m, and the thickness of frozen soil curtain in the lower half of tunnel (i.e. frozen zone B2, B3 and C) should be controlled within 2.6 m. The required thickness is controlled by the in-site soil temperature monitoring system as shown in Figure 3c.



(a) (b)

(c)

Figure 3. Schematic layout of (a) jacking pipes, (b) freezing pipes and (c) layout diagram of temperature monitoring points.

3 Numerical simulation

The two-dimensional plane strain model, which was 160 m in length and 98.5 m in height with 12848 elements, was established based on ABAQUS software. The meshing is shown in Figure 4.

In the numerical simulation, the behavior of the unfrozen soil is assumed to be governed by an elastic-plastic constitutive model based on the Mohr–Coulomb criterion, and the frozen soil is assumed to be an elastic material. The thermophysical parameters and mechanical parameters of soil are shown in Table 1.

A coupled thermo-mechanical constitutive model proposed by Cai et al. [3] was imported into the ABAQUS software for calculation of frost heave. As shown in Eq. (1), ε_f^T , regarded as the temperature-dependent instantaneous volumetric strain, is also called frost heave ratio of soil, which can be obtained from the indoor frozen soil test. Both the elastic modulus E and Poisson's ratio μ are functions of temperature variation, which are expressed in terms of $E(T)$ and $\mu(T)$.

As shown in Figure 5, after 90 days of active freezing, a reliable and sealed frozen soil curtain has been formed, whose thickness meets the design requirements.

$$
\begin{aligned}
\varepsilon_x &= \frac{1-\mu(T)^2}{E(T)}\left[\sigma_x - \frac{\mu(T)}{1-\mu(T)}\sigma_y\right] + \frac{1+\mu(T)}{3}\varepsilon_f^T \\
\varepsilon_y &= \frac{1-\mu(T)^2}{E(T)}\left[\sigma_y - \frac{\mu(T)}{1-\mu(T)}\sigma_x\right] + \frac{1+\mu(T)}{3}\varepsilon_f^T \\
\varepsilon_{xy} &= \frac{2[1+\mu(T)]}{E(T)}
\end{aligned} \tag{1}
$$

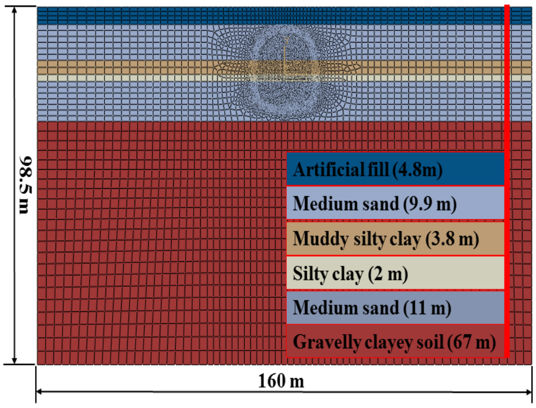


Figure 4. Meshing and soil stratigraphy of model.

Table 1. Parameters of each soil layer.

Soil layer		Density kg/m^3	Thermal conductivity kcal/(m·d·°C)	Specific heat kcal/(kg·°C)	Latent heat kcal/kg	Elastic Modulus /MPa	Poisson's ratio
Artificial fill	Frozen	1660	40.560	0.324	8.840	10.667+4.3|T|	0.26
	Unfrozen		33.552	0.338		20	0.30
Medium sand	Frozen	2020	42.144	0.324	7.401	19.333+4.7|T|	0.29
	Unfrozen		34.536	0.341		25	0.25
Silty clay	Frozen	2010	43.776	0.352	9.990	-10.667+7.8|T|	0.31
	Unfrozen		36.888	0.374		28	0.32
Muddy silty clay	Frozen	1820	45.432	0.371	13.550	4.667+6.6|T|	0.28
	Unfrozen		33.648	0.388		4	0.35
Gravelly clay soil	Frozen	1890	42.960	0.350	11.790	34+1.2|T|	0.30
	Unfrozen		34.608	0.376		30	0.25
Concrete		2400	55.730	0.210	---	30000	0.20
Steel		7830	887.400	0.100	---	210000	0.27

After 90 days of freezing, the vertical displacement field of the ground frost heave is shown in Figure 4, and the horizontal displacement field of the ground frost heave is shown in Figure 5.

It can be seen from Figure 6 that the vertical frost heave displacement caused by the pipe curtain freezing is approximately normal distribution, taking the centerline of the tunnel as the axis of symmetry. As the number of freezing days increases, the maximum vertical frost heave of the surface also increases. After 90 days of freezing, the maximum frost heave value of the surface is 154.6 mm at the surface top of tunnel centerline.

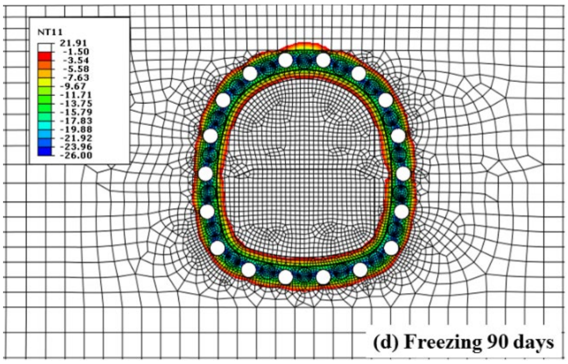


Figure 5. Temperature field contour plots of frozen soil curtain (unit: °C).

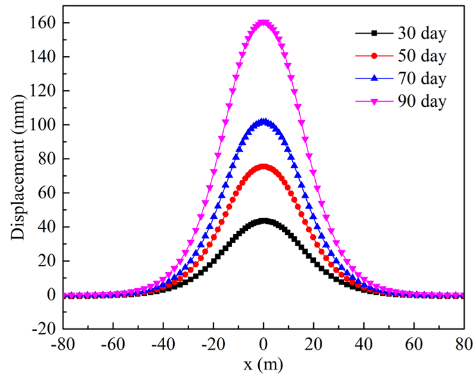


Figure 6. Variation of vertical frost heave of the surface.

Usually, measures need to be taken to reduce the frost heave, in order to avoid destroying the surface stability on top of the tunnel. In the field, based on the temperature monitoring system as shown in Figure7, the thickness of the frozen wall is controlled by circulating “high-temperature” (2~8 °C) brine within the heave-controlling pipes (shown in Figure 3.) after 70 days of freezing for other freeze pipes.

4 Conclusions

In this paper, the simulation correctly predicted the frost heave displacement field. The main research results are as follows.

(1) After 90 days of active freezing, the tunnel forms a frozen soil curtain with an effective thickness of more than 2 m, which meets the design requirements.

(2) During the tunnel freezing period, the soil around the top pipe of the tunnel produces an upward frost heave displacement, and the soil layer at the bottom of the tunnel produces a downward frost heave displacement. After 90 days of freezing, the maximum vertical frost heave displacement of the ground is 154.6 mm, which shows that it is necessary to take corresponding frost heave control measures to reduce the ground frost heave deformation.

References

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