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Applicability for Pipe Curtain Freezing Method with Multi-step Excavation of Gongbei Tunnel

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ABSTRACT: Due to the sensitive location and special soft stratum environment, deformation requirements on Gongbei Tunnel Port excavation of Hong Kong-Zhuhai-Macao Bridge port are very high. To solve the problem of deformation in construction process, the tunnel was designed by the pipe curtain freezing as the advanced support structure and was constructed by the multi-step excavation method, the applicability research was carried out by numerical calculation. The results indicate that numerical calculation of surface subsidence value is about 2.34mm, vault settlement is 2.81mm, and headroom convergence is about 1.82mm, deformation calculation value is small. By comparing with the ratio of calculation value and standard warning value, the ratio of the headroom convergence is the maximum value, which is only 18.2%, far less than the warning value. Pipe curtain freezing method with multi-step excavation has overcome the difficulties in the construction of super-shallow buried tunnel in soft stratum, and has a good applicability in soft soil stratum. It has extensive reference value for super-shallow buried tunneling project with strict deformation requirements.

KEYWORDS: Gongbei tunnel, Pipe curtain freezing method, Multi-step excavation, Applicability analysis

INTRODUCTION

If the tunnel is built in the soft soil area, the surrounding rock is generally characterized by low strength because of the weak surrounding rock, which is mainly consist of the clay, muddy soil and silt and so on. For the tunnel project, the soft rock formation section is easy to produce large construction deformation under the condition of a certain stress level or buried depth. According to the current domestic tunnel construction technology level and the actual situation, for the buried tunnel, the commonly used construction methods are mining method (including the full cross-section method, step method and sub-construction methods (including ring excavation reserved core soil method, CD method, CRD method, etc.)), shield method, pipe jacking method and so on. However, according to the special strata surrounding rock environment in soft soil area, the shield method is dominating in recent years instead of the mining method [1].

Tunnel excavation means removing part of the rock or soil below the surface to complete the new balance from the original balance, which is bound to cause deformation of the surface and the surrounding rock[2]. Peck [3] systematically proposed the concept of formation loss and tunneling settlement estimation method based on the surface subsidence measurement data caused by a large number of tunnel excavations in 1969. O'Reilly et al.[4] studied the problem of formation subsidence caused by different construction methods for different strata. Aitewell et al.[5] assumed that the lateral surface subsidence can be used as a normal distribution, resulting in a three-dimensional surface subsidence formula caused by tunnel construction. From the 1970s, Tongji University began the measurement and theoretical research work on the construction of the surface settlement of the tunnel, and the Shanghai Metro test section and other tunnels were measured and monitored. Based on the Peck method, Liu et al.[6] put forward the "negative formation loss" concept according to the Shanghai Yan'an East Road tunnel construction measured data.

According to the study of the force and deformation in the construction of the step method, Huang et al.[7] studied the mechanical properties in the construction of the step method. Zhang et al.[8], Song et al.[9], Wei et al.[10], Wang et al.[11] studied the deformation rule of the step method construction, and a large number of literatures reported the deformation of the step method[12-13].

Although the results of previous studies show that the step method is commonly used in tunnel construction methods, for soft soil stratigraphy, it is rarely reported step method as a construction method in the tunnel. In this paper, the deformation regular of tunnel and the surrounding environment were studied under the background of Gongbei tunnel excavation in Hong Kong - Zhuhai - Macao Bridge Project which used the pipe curtain plus freezing as the advanced support and the multi-step excavation as the construction method. And then the applicability of multi-step excavation in the tunnel was discussed, which can provide reference for the construction of super-shallow buried tunnel in soft soil.

PROJECT OVERVIEW

The main line of the Zhuhai connecting line in the Hong Kong-Zhuhai-Macao Bridge (hereinafter referred to as the connecting line) is about 12.67 km. The recommended scheme has super bridges, super long tunnel (South Bay Tunnel) and sink long tunnel (Gongbei Tunnel). In addition, three interchanges are set in South Bay, Hengqin North, Hongwan and including the Zhuhai-Macao artificial island connecting ramp project.

Gongbei tunnel's recommended scheme adopted the initial design stage of the K line double-layered underground excavation program, using pipe-curtain method through the Gongbei port limited area, the port set up a total of two work wells (east and west sides set one). The remaining sections of the tunnel are excavated by the open excavation method. Gongbei tunnel is a long tunnel, the hole formed for going into and out adopted shade, lighting, mechanical ventilation. Meanwhile, considering the poor conditions of the strata in Gongbei Port, the geographical location is special and the tremendous political significance, the program of adding working wells, segmented straight pipe curtain is proposed based on the consideration of construction difficulty, technical risk, traffic organization, project cost, duration and coordination factors. Site plane of Gongbei underground excavation tunnel is shown in FIG.1.

Figure 1. Site plan of Gongbei tunnel.

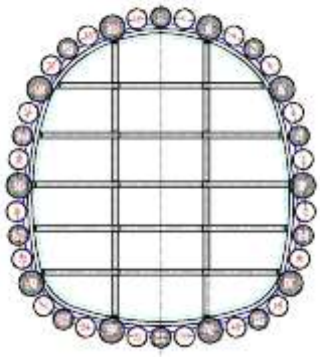


Figure 2. Arrangement of the pipe curtain.

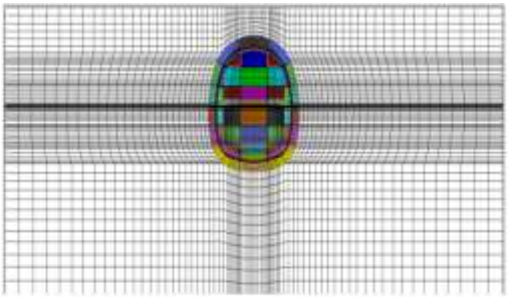
The Gongbei underground excavation tunnel is a control project of the Hong Kong-Zhuhai-Macao Bridge, because of its sensitive location and special soft stratum environment. The underground excavation of the project adopts the "pipe curtain plus freezing method" construction, the pipe curtain designing involving 10 steel pipes of 1880mm and 30 steel pipes of 1440mm. The radius of curvature R is about 885.852m ~ 906.298m. After the completion of the pipe jacking, before the excavation construction, the pipe curtain will be frozen, the frozen thickness of the upper tunnel half is 1.45 ~ 1.8m, the lower tunnel half is 1.45 ~ 2.4m or so. Using the method of frozen reinforcement can turn the soil between the pipes into permafrost, which will be composed with pipe jackets together to form a closed curtain to provide the suitable tunnel excavation construction conditions.

The excavation area is more than 330 square meters, the structure circumference is 65m, the excavation width is 18.7m, the excavation height is 20.8m, the section is super large, and the engineering geological and hydrogeological conditions of the tunnel area are poor, the surrounding environment is complicated, the deformation of the formation is strictly required, the project should be adopted multi-step excavation method. Therefore, in combination with the arrangement of the large pipe jacking and for the benefit of the construction of the follow-up medium plate, the design adopts the 6-step scheme, which is shown in FIG.2. In addition, in order to improve the structural stress state and control the surface deformation, the design adopts the vertical partitions and horizontal straight support form according to experience.

NUMERICAL MODELLING

With 3D finite element software named ANSYS, the whole process of construction was obtained by dynamic numerical simulation. Mohr-Coulomb elastoplastic constitutive model was used in all rock, soil and tunnel lining solid elements. The safety of tunnel support system was analyzed through deformation of initial support and temporary support, hole circumference displacement. And then the dynamic changes of tunnel surrounding rock and support structure were calculated, their deformation characteristics would be obtained at the same time, so preferred design scheme could be proposed in the end.

The size of this calculation model is that: the transverse direction is 120m, 60m on each side and 59.08m in the vertical direction. The top is taken to the surface, and the groundwater level is 2m below the surface. The model consists of 7904 units and 16110 nodes. Using multi-step division excavation method, the model was divided into six steps and includes left, middle and right three guide pit. Diagram of unit material model is shown in FIG.3.



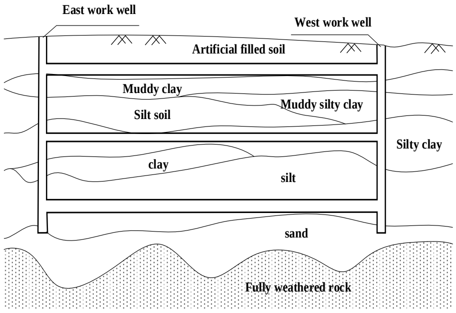


Figure 3. Unit material model diagram. **Figure 4. Stratigraphic section of Gongbei tunnel.**

Ground Configuration

Gongbei tunnel is in the shallow sea or coastal alluvial plains, the soil layer that the tunnel through are flow-soft plastic silt or muddy soil, clay, loose-slightly fine sand that the soil physical and mechanical property are poor. The stratigraphic section along the tunnel longitudinal section is shown in FIG.4. Ground Parameter was adopted according to the detailed survey data which is shown in Table 1.

Table 1. Physical and Mechanical Parameters of Soil.

Soil Layer	H (m)	c (kPa)	φ (°)	r (kN/m3)	E_0 (MPa)
Plain Fill	5.8	20	10.5	18.5	8.5
Mucky Soil	3	20	14	16.9	4.7
Silty Clay	5	36	18	19.9	5
Mucky Soil	3	20	14	16.9	4.7
Coarse Sand	2.5	2	35	18	15
Silty Clay	5	36	18	19.9	5
Gravelly Sand	4.5	5	35	18	24.7
Sand and Gravelly Clay	5.8	48	20	18.5	7
Completely Decomposed Granite	5.8	24	32	18	9
Intensely Weathered Granite	9.6	13	32	18	10

Support Configuration

According to the initial lining and the support structure type, the model establishment support parameter selection is shown in Table2.

Table 2. Parameters of Tunnel Support.

Advanced Support	Lining Structure			Temporary Support	
	Lining of the first layer	Lining of the second layer	Lining of the third layer	Steel arch	Jet concrete
Big pipe Freeze seal	C25 spray mix with 30cm thick, I22b steel arch	C35 mold concrete with 30cm thick, light steel frame	C50 steel concrete, arch with 60cm thick, Side wall for the variable section: 60-145cm, Invert arch 70cm	H40b, 1.2m spacing	40cm thick

Control Point Setting

In order to analyze the applicability and safety performance of the multi-step excavation method, the subsidence of the tunnel, the settlement of the vault in the tunnel, and the headroom convergence of the tunnel were recorded in the excavation simulation process. Control point distribution is shown in FIG.5.

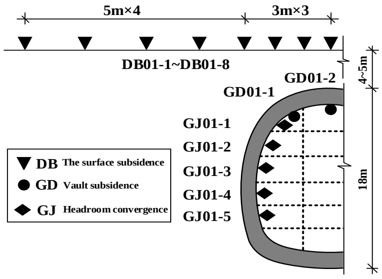


Figure 5. Control point distribution.

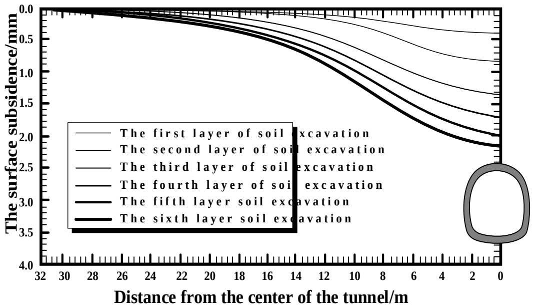


Figure 6. Surface subsidence curve.

CALCULATION ANALYSIS

Surface Subsidence

FIG.6 shows the surface subsidence distribution troughs on a particular section of soil. It can be seen from the curve that the surface subsidence caused by the excavation in the first three layers is faster. And when it comes to the fourth layer, the surface subsidence gradually stabilizes. The maximum settlement value of the surface is about 2.34mm, which is located right above the tunnel. The surface above the tunnel is in the form of normal distribution, and the settlement bending point is located in the range of 12 ~ 16m from the center of the tunnel. The influence of surface subsidence is about 30m, which is about 1.5 times the depth of the tunnel.

Vault Settlement

FIG.7 shows the variation curve of vault settlement with time during tunnel excavation. It can be seen from the figure, the overall vault settlement presents the downward trend in decline. In the excavation of the first layer, as the excavation surface is relatively small, the settlement of the vault is small. When the second and third layers are excavated, the settlement rate increases because of the increase of excavation surface and span scale. When it comes to the fourth layer, the excavation span is gradually fixed. With the upper lining construction completed, the vault settlement gradually stabilized in the sixth layer, showing a slow decline trend. During the period from the completion of excavation to the demolition process of temporary support, vault settlement has the accelerating trend again, which is caused by the released stress due to temporary support demolition. The maximum dome settlement is the GD02-2, while the specific is about 2.81mm.

Headroom Convergence

FIG. 8 shows the time-dependent curves of headroom convergence during the tunnel excavation process. It can be seen that the net convergence during the tunnel excavation process shows an increasing trend. With the tunnel dug layer by layer, we set the headroom convergence points from JZ01-1 to JZ01-05 one by one. As JZ01-2 and JZ01-3 are located in the upper part of the tunnel, during the excavation process their increase speed is larger than that of JZ01-1. When the temporary support demolition process is completed, JZ01-2 has the maximum value of 1.82mm. While the JZ01-4 and JZ01-5 points in the middle and lower part of the tunnel have slower convergence rate, which also leads to smaller final convergence data.

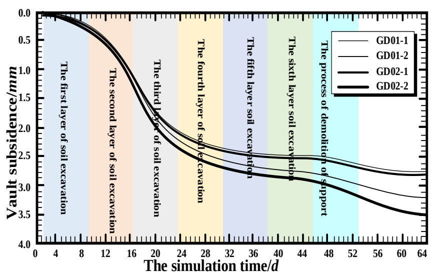


Figure 7. Vault settlement curve.

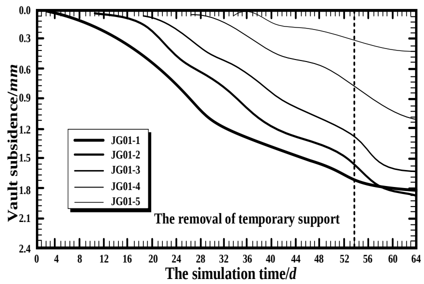


Figure 8. Headroom convergence curve.

DISCUSSION

In this paper, we use numerical calculation to discuss the deformation law of the tunnel and surrounding environment during the super-shallow buried tunnel construction process when we use pipe curtain plus freezing method as the advanced support, and multi-step method inside. The design warning values are shown in Table3.

Through the comparison with the warning value, it can be seen that using pipe curtain freezing method with multi-step excavation in Gongbei tunnel of Hong Kong-Zhuhai-Macao Bridge excavation process has a little influence on the tunnel itself and the surrounding environment, while the tunnel safety performance is also better. The advanced support and excavation method has good applicability in soft soil stratum.

Table 3. Comparison Table of Values and Design Values.

Monitoring Program	Surface Subsidence	Vault Settlement	Headroom Convergence
The Maximum Value of Monitoring (mm)	2.34	2.81	1.82
The Warning Value of Deformation (mm)	30	30	10
The Ratio of Deformation/%	7.8	9.37	18.2

CONCLUSION

ANSYS software were used to carry out three-dimensional numerical calculation of Gongbei underground excavation tunnel with multi-step excavation method for Hong Kong-Zhuhai-Macao Bridge. By analyzing the numerical results, the following conclusions were obtained:

(1) The deformation of the tunnel itself and the surrounding surface in the tunnel excavation process is relatively small. The maximum amounts of each calculation are: the surface subsidence 2.34mm, vault settlement 2.81mm, and headroom convergence 1.82mm.

(2) Compared with the calculated value and the given warning value, it can be seen that the deformation value of the surface and vault settlement is less than 10% of the warning value, and that of headroom convergence is less than 20% of the warning value.

(3) Pipe curtain freezing method with multi-step excavation has a good applicability in soft soil stratum. It has extensive reference value for super-shallow buried tunneling project with strict deformation requirements.

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