Stress Mechanism and Deformation Monitoring of Bias Tunnel

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***Abstract* — There are many unsafe factors in the process of tunnel construction, including the bias load, being ultra shallow buried under the surface, etc. Through the analysis of the initial stress field of bias tunnel, it is revealed that the slope angle is an important factor to influence the stress distribution. When the slope angle is more than 30º, the tunnel is prone to shear failure at the arch waist. By monitoring the bending moment of steel support, pressure of surrounding rock and slope deformation in Jinci tunnel, it is revealed that the maximum bending moment of steel support appears at the arch waist near the slope, the maximum pressure of surrounding rock appears at the left arch waist, and the maximum deformation appears at the bottom of the slope. The research results provide guidance for the design and construction of bias tunnels under similar geological conditions.**

Keywords-bias tunnel; stress mechanism; deformation monitoring; stability analysis

I. INTRODUCTION

With the rapid development of economy and society, more and more tunnels are constructed in mountainous area [1]. But for the complexity of mountainous terrain, it is difficult to avoid building bias tunnel, especially in portal section, along the river area, along the mountain area, etc. Because the unsymmetrical load of bias tunnel, it is necessary to study the construction technology in such circumstances. Understanding properly of stress characteristics and deformation law of bias tunnel is necessary to guide the construction, and great efforts have been devoted to it recently [2,3]. Several analysis methods based on numerical simulation have been proposed to describe these problems [4,5]. The works of Liu and Chen are important on understanding the characteristics of bias tunnel, such as the stress mechanism of tunnel structure, the dynamic mechanical behavior of tunnel construction, the interaction mechanism of surrounding rock with structure, the effect of bias angle on structure, etc. Lei and Duan studied the progressive failure mechanism and stress distribution of surrounding rock of bias tunnel by model tests [6,7], the formation of tunnel collapse and the effect of tunnel excavation on stress distribution of surrounding rock were revealed. In order to rationally describe both stress mechanism of bias tunnel and the stability of surrounding rock, some more general works are needed. Object of this study is to properly understand the stress characteristics and to establish evaluation methods to well describe the mechanical behavior and stability of bias tunnel.

II. DISTRIBUTION CHARACTERISTICS OF STRESS FIELD OF BIAS TUNNEL

A. *Initial Stress Field of Bias Tunnel*

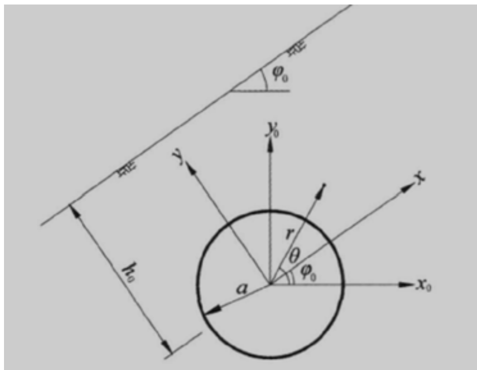

Figure 1. Stress analysis of bias tunnel

Different from the conventional tunnel, the stress of the bias tunnel is influenced by the bias angle of the slope. In Fig. 1, a cross-section view of bias tunnel has illustrated. If the slope angle is φ_0, the tunnel radius is a, the distance from any point to the center of the tunnel is r, the tunnel axis is z coordinate, x_0 - y_0 is the vertical coordinate system, the x - y coordinate system is vertical and parallel to the ground surface respectively, and the formation is a continuous elastic body. Under the plane strain state, the equilibrium equation of the bias tunnel can be expressed as follow:

$$\begin{cases} \dfrac{\partial \sigma_x}{\partial x} + \dfrac{\partial \tau_{xy}}{\partial y} = \gamma \sin \varphi_0 \\ \dfrac{\partial \sigma_{xy}}{\partial x} + \dfrac{\partial \tau_y}{\partial y} = \gamma \cos \varphi_0 \\ \dfrac{\partial \sigma_{xz}}{\partial x} + \dfrac{\partial \tau_{yz}}{\partial y} = 0 \end{cases} \tag{1}$$

Where γ is the unit weight of rock and soil mass, $\mathrm{Kg/m^3}$.

Based on the stress-strain relationship and partial differential Equation (1), the calculation formula of initial stress field of bias tunnel can be described as follow:

$$\begin{cases} \sigma_x^0 = \gamma(h_0 - y)(\dfrac{\mu}{1+\mu} + \tan^2\varphi_0)\cos\varphi_0 \\ \sigma_y^0 = \gamma(h_0 - y)\cos\varphi_0 \\ \tau_{xy}^0 = \gamma(h_0 - y)\sin\varphi_0 \end{cases} \tag{2}$$

Where μ is the Poisson's ratio of rock and soil mass, h_0 is the distance from tunnel center to ground, m.

From the Equation (2), it can be known that the initial stress is not only related to the mechanical parameters of rock and soil, but also to the depth of tunnel and the slope angle. The shear failure of surrounding rock increases with the increase of the slope angle. Therefore, the supporting strength of the bias tunnel should be increased.

When the bias load is zero, namely $\varphi_0 = 0$, the Equation (2) can be described as follow:

$$\begin{cases} \sigma_x^{0'} = \gamma(h_0 - y)\dfrac{\mu}{1+\mu} \\ \sigma_y^{0'} = \gamma(h_0 - y) \\ \tau_{xy}^{0\,'} = 0 \end{cases} \tag{3}$$

B. Influence Parameters of Initial Stress Field of Bias Tunnel

From the comparison of Equation (2) and Equation (3), it can be known that the horizontal stress increases with the increase of the slope angle, and the vertical stress decreases with the increase of the slope angle. In order to analysis the variation of initial stress field with the slope angle, the dimensionless parameters η_x and η_y are defined as the horizontal stress ratio and the vertical stress ratio of the bias tunnel.

$$\begin{cases} \eta_x = \dfrac{\sigma_x^0}{\sigma_x^{0'}} = [(\dfrac{\mu}{1+\mu} + \tan^2\varphi_0)\cdot\cos\varphi_0] / (\dfrac{\mu}{1+\mu}) \\ \eta_y = \dfrac{\sigma_y^0}{\sigma_y^{0'}} = \cos\varphi_0 \end{cases} \tag{4}$$

From the Equation (4), it can be known that the initial stress field distribution characteristics of the bias tunnel are related to the Poisson's ratio of the rock and soil μ and the slope angle φ_0. The Poisson's ratio of rock and soil mass is generally between 0.2 to 0.45, and the slope angle is generally between 0° to 60°. According to the characteristic values of Poisson's ratio and slope angle, the horizontal stress ratio and the vertical stress ratio of bias tunnel are calculated. Firstly, the horizontal stress ratio increases with the increase of the slope angle, when the angle is less than 20°, the horizontal stress ratio increases slowly, but when the angle is more than 30°, the horizontal stress ratio increases rapidly, the vertical stress ratio changes in the opposite. Secondly, the horizontal stress ratio decreases with the increase of Poisson's ratio at the same slope angle, and the larger slope angle, the more decrease trend of horizontal stress ratio. Therefore, the main factor that affects the horizontal stress is the slope angle.

In short, the distribution of the stress field is changed by the bias field, the shear stress and the horizontal stress increase with the increase of the slope angle. That is to say, the bias load reduces the stability of the surrounding rock, and increases the risk of tunnel construction. When the slope angle is more than 20º, the tension stress zone appears in the surrounding rock. When the slope angle reaches 30º, the maximum shear stress occurs in the vault, the arch foot and the side wall, about 2 times the non bias tunnel. In addition, the formation stress decreases with the increase of the distance from the center of the tunnel, and it will not changing at 2 times the tunnel diameter. Therefore, the boundary value of shallow buried tunnel can be regarded as 2 times the tunnel diameter.

III. CASE STUDY ON JINCI TUNNEL

Jinci tunnel has a bias section on DK14+970~DK15+090, the height of the slope reaches about 16m, the tunnel axis is parallel to the bottom of the slope, and the minimum depth is only 5.7m, so it belongs to the ultra shallow buried tunnel. In Fig.2, the topographic and geologic map of the bias tunnel has illustrated.

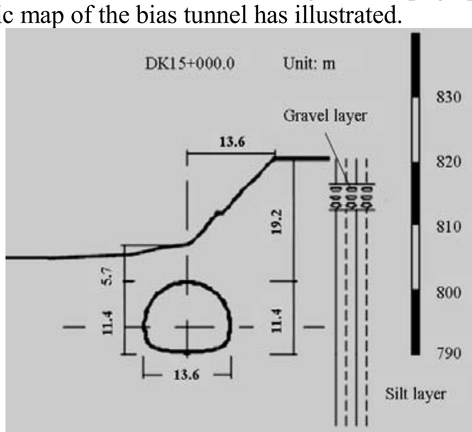

Figure 2. Topographic and geological map of bias tunnel

A. Construction and Monitoring of Bias Tunnel

In order to ensure the stability of surrounding rock during tunnel excavation, the three-bench seven-step excavation method is adopted, Fig.3 shows the construction process of the tunnel. Fig.4 is the layout of slope displacement monitoring, the stress and displacement monitoring of tunnel surrounding rock are arranged as shown in Fig.5.

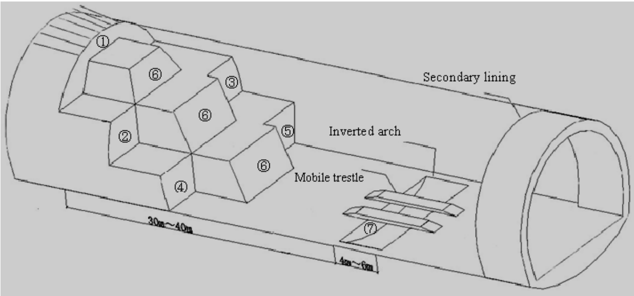

Figure 3. Excavation process of bias tunnel

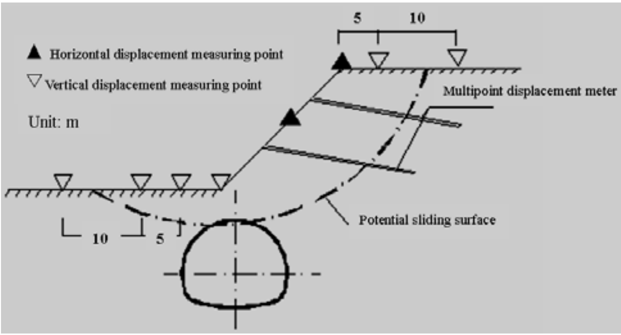

Figure 4. Slope displacement measuring plan

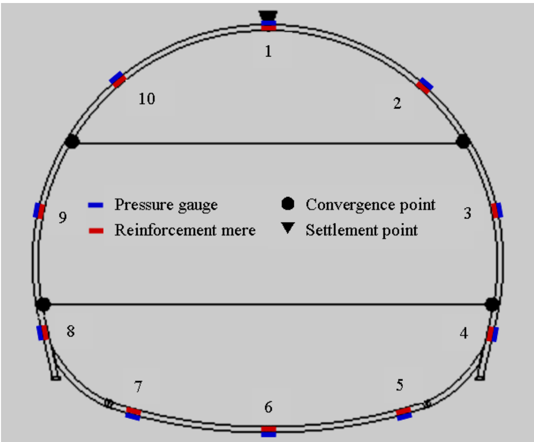

Figure 5. Stress and displacement measuring of tunnel surrounding rock

B. *Stress and Deformation Laws of Bias Tunnel*

From the deformation of steel support and the stress between surrounding rock and primary support, the distribution of bending moment of steel support in tunnel excavation is obtained, as shown in Fig.6, and the stress distribution of surrounding rock and primary support is obtained also, as shown in Fig.7.

The internal force of steel support is constantly changing in the process of tunnel excavation, the maximum bending moment appears at the right arch waist, and the minimum bending moment appears at the left corner. The maximum change of bending moment appears at the left arch waist and reaches 4000N•m. So the maximum stress appears at the arch waist near the slope, and the support should be strengthened in this position.

In the process of tunnel excavation, the contact pressure between primary support and surrounding rock is constantly changing. Unlike the bending moment of steel support, the maximum contact pressure appears at the left arch springing, and the minimum contact pressure appears at the right arch waist. The maximum change of contact pressure appears at the left arch springing and reaches 80kPa.

In short, the primary support changes the stress distribution of bias tunnel, and the maximum contact pressure appears at the left arch springing for the combined action of vertical and horizontal pressure. So the primary support should be formed into a ring rapidly to resist external loads, and the support should be strengthened at arch springing position.

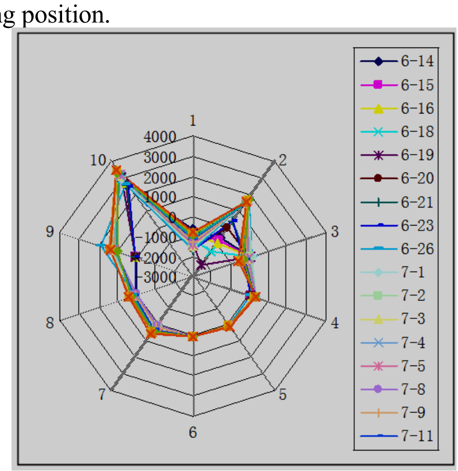

Figure 6. Bending moment distribution of steel support

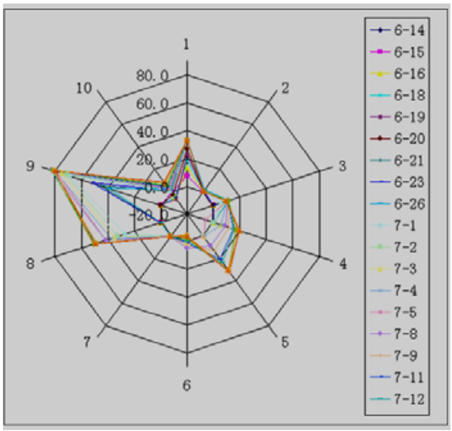

Figure 7. Stress distribution of surrounding rock and primary support

C. *Influence of Tunnel Construction on Slope Deformation*

From the monitoring results of horizontal displacement, it is found that the tunnel excavation has an important influence on the stability of the slope. The maximum horizontal displacement is more than 90mm and appears at the bottom of the slope, and the minimum horizontal displacement appears at the top of the slope.

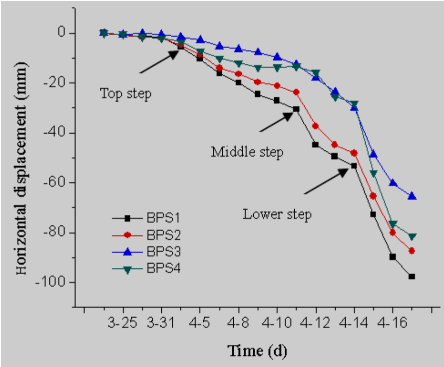

Figure 8. The relationship between horizontal displacement and tunnel excavation (DK15+000)

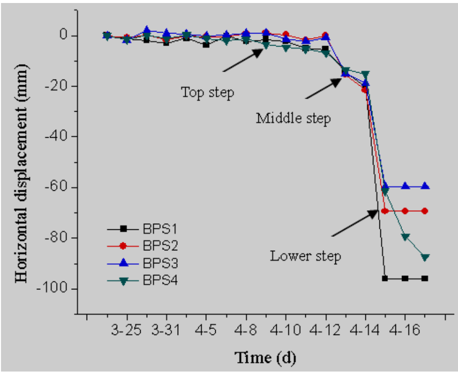

Figure 9. The relationship between horizontal displacement and tunnel excavation (DK15+010)

The two monitoring sections are in the inner and outer side of the pipe shed support, and their deformation and stress are not synchronized. In the DK15+000 section (inner of pipe shed support), the horizontal displacement of the slope increases slowly before the middle bench, but it increases quickly after the middle bench. It is a typical three-bench progressive variation. For the DK15+010 section (outer of pipe shed support), the horizontal displacement of the slope increases slowly before the top bench, and it increases quickly after the middle bench. It is a typical two-bench jump variation.

IV. CONCLUSIONS

The deformation and stress of the bias tunnel are more complex than those of ordinary shallow buried tunnels. Through the analysis of the initial stress field of bias tunnel, combining with the monitoring results of surrounding rock pressure, bearing capacity of steel support and slope deformation, the principal conclusions are obtained.

Slope angle is the main factor that affects the horizontal stress. When the slope angle reaches 30°, the maximum shear stress occurs in the vault, the arch foot and the side wall, and the tunnel is prone to shear failure in these locations. The boundary value of shallow buried tunnel can be regarded as 2 times the tunnel diameter.

The maximum stress appears at the arch waist near the slope. The maximum bending moment appears at the right arch waist, and the minimum bending moment appears at the left corner. A pressure increased line from arch springing, the medial arch waist to the center of slope is formed in bias tunnel, and it is the main influence area of tunnel supporting structure and surrounding rock pressure.

The maximum horizontal displacement appears at the bottom of the slope, and the minimum horizontal displacement appears at the top of the slope. The horizontal displacement is a three-bench progressive variation in pipe shed support section, and it is a two- bench jump variation in non-pipe shed support section. Pipe shed support and grouting reinforcement can slow down the deformation rate of the slope, prevent the mutation and slip above the slope, and ensure the stability of slope and tunnel.

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