Numerical analysis of tunnel deformation affected by spatial position of landslide-tunnel system

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Abstract. In order to reveal the deformation law of tunnel structure under different spatial positions of landslide tunnel system, the rock deformation around tunnel under 12 working conditions was compared and analyzed by numerical simulation method. The results show that the vertical displacement distribution of rock around the tunnel at different locations is determined by the upper and lower regions of the sliding zone, and the settlement around the tunnel is greater than that of the tunnel under the sliding zone. The settlement decreases with the increase of the distance from the slip zone. The analysis results can provide reference for the design and construction of tunnel site selection.

1. Introduction

The hydrogeological environment of the tunnel is constantly changing due to its rock and soil mass. Under the action of long-term in-situ stress and groundwater, the rock mass structure in the slope reduces its own strength due to rheology, and forms a creeping landslide along the joint fissure surface; the landslide causes lining cracking and inverted arch uplift of operating tunnel, which seriously affects the traffic safety.

According to the different spatial positions of landslide and tunnel system, scholars have carried out a lot of research work. Based on the results of field investigation, landslide monitoring and laboratory test, the causes of creep landslide and the mechanism of tunnel deformation and cracking are analyzed(Zhang Luxin and Zhou Depei 1999). The finite element method of contact problem is applied to study the interaction mechanism between landslide and tunnel and the law of stress and deformation. (Zhou Depei, Mao Jianqiang, Zhang Luxin et al. 2002). Long-term monitoring using a multi-point displacement meter was used to analyse the deformation characteristics of a rock slope with weak bedding structural planes under tunnel excavation.(Danqing, Song , C. Jundong , and C. Jianhua .2018)

It can be seen from the above research that the current research mostly uses engineering investigation and indoor test to summarize the stress and deformation of landslide tunnel system, which belongs to qualitative analysis. Therefore, through the numerical analysis method, relying on the engineering examples, this paper makes a comparative analysis of the structural deformation of the tunnel under 12 different spatial positions in the landslide tunnel system, so as to provide reference for the site selection design and construction of the tunnel in the landslide tunnel system.
2. Engineering background
Goudong tunnel has been in operation for 15 years. Five years ago, a large number of cracks appeared in the tunnel lining structure, including longitudinal cracks, transverse cracks and circumferential cracks. Most of the fractures are small and the shear dislocation is not obvious. At the same time, there are obvious tensile cracks on the surface of the east side of the upper slope of the tunnel. Through geological mapping and drilling, it is preliminarily considered that the structural cracks in the tunnel are caused by the creep of the slope. The relationship between the slope and the tunnel is shown in Figure 1 (a), the swelling of the drainage ditch at the toe of the slope is shown in Figure 1 (b), and the cracks in the tunnel lining structure are shown in Figure 1 (c).

(a) The relationship between the slope and the tunnel (b) The swelling of the drainage ditch (c) the cracks in the tunnel lining

Figure 1. The excavated slope

3. Numerical analysis
3.1. Numerical model establishment
The relative position relationship between tunnel and sliding surface is the main factor to determine the deformation characteristics of tunnel. In this paper, the tunnel center is located in the sliding zone as the reference condition (0d, D is the diameter of tunnel). The tunnel is translated by 1.0d, 3.0d and 5.0d in the four directions of up, down, left and right as the comparison conditions. As shown in Figure 1.

Figure 2. Schematic diagram of model calculation conditions

All kinds of rock and soil parameters are obtained from the tunnel site and landslide rock and soil tests, and the supporting structure parameters are obtained from relevant specifications and documents. Plane strain element is used to simulate rock mass; beam element is used to simulate shotcrete and steel frame composite system in initial support. The physical and mechanical parameters of the model are shown in Table 1.

| Material parameter table |
|--------------------------|
| Density (kg/m³) | Elastic modulus (MPa) | Poisson's ratio | Cohesive force (kPa) | Cohesive force (°) |
|-----------------|----------------------|----------------|----------------------|-------------------|
The tunnel is less affected by the tectonic stress, so only the self weight stress is considered in the local stress field. The boundary conditions are as follows: horizontal constraint of left and right boundary, vertical constraint of lower boundary, and free surface. The horizontal length of the model is 305 m, the height of the upper slope is 155 m, and the height of the downhill is 105 M. The model grid is shown in Figure 3.

3.2. Simulation process

The calculation process of the numerical model is as follows, which is divided into three steps:

1. The gravity is applied to balance the initial geostress and the displacement is cleared.
2. The sliding zone unit is activated to realize landslide sliding.
3. Some surrounding rock of tunnel excavation is passivated and initial support structure of tunnel is activated.

4. Analysis of numerical results

4.1. Displacement vector diagram of surrounding rock

Figure 4 shows the displacement vector diagram of surrounding rock around the tunnel when the tunnel and sliding zone are in different spatial positions.

![Displacement vector diagram of surrounding rock](image)

(a) Upper-3D condition (b) Cross condition (c) Lower-3D condition

Figure 4. Displacement vector diagram of surrounding rock

It can be seen from Fig. 4 (a). When the tunnel is located at the upper part of the sliding zone, the tunnel slides down with the sliding mass, and a certain degree of deflection torsion occurs in the tunnel, with the direction from the right upper arch shoulder to the left lower side wall foot, and the maximum displacement occurs at the right arch shoulder and left wall foot.

It can be seen from Fig. 4 (b): when the tunnel is located at the sliding belt, the sliding belt directly runs through the tunnel from the right spandrel to the left foot of the wall. The tunnel is divided into three parts. The rock around the tunnel above the sliding zone not only compresses the tunnel face, but...
also slides with the landslide mass. Because the strength of the sliding zone is lower than that of the landslide mass, there is a downward sliding relative to the landslide mass, which is reflected in the difference between the curvature of the deformation contour line of the right arch shoulder and the left foot of the wall with the two sides. Under the action of the sliding rock and soil, the rock around the cave under the sliding zone has upward reaction, which results in the upward uplift of the rock around the cave under the sliding zone, mainly the inverted arch structure. There is almost no displacement on the right side wall.

It can be seen from Fig. 4 (c): when the tunnel is located at the lower part of the sliding zone, the surrounding rock at the lower part of the sliding zone moves in the opposite direction to the sliding direction due to the reaction force of the sliding mass. Similar to the tunnel in Fig. 3 (a), the tunnel is located at the upper part of the slip zone, and the deflection torsion direction is opposite to that in Fig. 3 (a). The difference is that the inverted arch structure is uplifted upward, which is due to the fact that the lower part of the sliding zone is bedrock and the surrounding rock strength is relatively high.

To sum up, the tunnel is located at different locations of the slip zone, and the deformation law of surrounding rock around the tunnel is quite different.

4.2. Displacement distribution of joints around the tunnel

In order to quantitatively analyze the rock deformation around the tunnel under different working conditions, the vertical and horizontal deformation of the surrounding rock under various working conditions is distributed on the horizontal axis. The arch and side wall are marked with red number from left to right, and the node number is from 1 to 19; the inverted arch is marked with blue number from left to right with node number of 1-11. The schematic diagram of node numbers around the tunnel is shown in Figure 5. Node 10 and node 6 are the midpoint of arch and invert.

![Figure 5. Schematic diagram of node number around surrounding rock of the tunnel](image)

The vertical displacement distribution of rock around the tunnel under different working conditions is shown in Fig. 6. The positive value in the figure is the subsidence of surrounding rock, and the negative value is the upward uplift of surrounding rock. For the convenience of understanding, the triangle direction is used to represent the displacement of each working condition relative to the reference condition, the hollow mark represents 1D working condition, half filling represents 2D working condition, and adding a line represents 3D working condition.

It can be seen from Fig. 6 (a): due to the intersection of tunnel and slip zone in 0d condition and 1D condition on the right, there is significant asymmetry in surrounding rock deformation. Combined with the displacement vector diagram in Fig. 4 (b) and slope deformation nephogram in Fig. 6 (b), it can be seen that under the condition of 0d, due to the part of the right side wall located in the bedrock part below the sliding zone, the downward sliding of the sliding zone and the soil above caused the reverse extrusion effect on the upper right, resulting in the significant reduction of the settlement value of this part. The displacement difference of side walls on both sides is 25mm. In the case of right 1D, because the left side of the arch is located in
the sliding area, the settlement value of this part increases. The maximum settlement point of the arch occurs at the intersection of the left side of the arch and the sliding, about 29mm.

![Graph](image1)

**Figure 6.** Vertical displacement of rock joints around the tunnel

From the overall point of view, the maximum settlement occurs in the vault. The settlement of the arch decreases gradually from the crown to the foot of the arch. The settlement of the side wall area shows wave phenomenon. Except for the downward condition, the maximum vertical displacement decreases with the increase of the distance between tunnel and landslide. With the increase of distance from the landslide, the effect of buried depth is greater than that of landslide, so it shows a different trend from other conditions.

It can be seen from Fig. 6 (b): due to the intersection of inverted arch and sliding belt, the settlement curves of basic working condition and left 1D condition are quite different. The settlement law of inverted arch under other working conditions shows two laws: the lower part of sliding belt is larger in the middle and smaller in both ends, and the maximum value is about 27mm under 5D working condition; the upper part of sliding belt is small in the middle and large in both ends, and the maximum value is about -9mm under 3D condition.

The horizontal displacement distribution of rock around the tunnel under different working conditions is shown in Fig. 7. The horizontal displacement in the figure is positive to the right.

![Graph](image2)

**Figure 7.** Horizontal displacement of rock joints around the tunnel

It can be seen from Figure 7 that the horizontal displacement is more significant than the vertical displacement partition, and the horizontal displacement direction of different regions is opposite. In the lower part of the sliding zone, the horizontal displacement of the arch and side wall is opposite to the
sliding direction of the landslide, which is positive. In the upper part of the sliding zone, the horizontal displacement of the arch and side wall is the same as the sliding direction of the landslide, which is negative. The horizontal displacement value is concentrated in the range of 0 mm-5 mm in the upper part of the sliding belt, and it is concentrated in the range of -10 mm-15 mm in the upper part of the sliding belt. The variation of horizontal displacement in 1d-5d range is about 5mm. The maximum value of horizontal displacement is located at node 7 and 13 at the waist of arch, and the position of invert is located at node 3 and 9, and both decrease with the increase of sliding distance.

5. Conclusion
In this paper, through the numerical analysis method, relying on the engineering examples, the structural deformation of the tunnel under 12 different spatial positions in the landslide tunnel system is compared and analysed. The conclusion is as follows.

The tunnel is located in different positions of slip zone, and the deformation law of surrounding rock around the tunnel is quite different.

The vertical displacement distribution of rock around the tunnel at different locations is determined by the upper and lower areas of the sliding zone, and the settlement around the tunnel under the condition of the tunnel located at the upper part of the sliding zone is greater than that at the lower part of the sliding zone. The settlement decreases with the increase of the distance from the slip zone.

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