Analysis of the deformation mechanism and stability of bedding soft rock slope

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Abstract: The lithology of the inlet side slope of the diversion tunnel on the right bank of Wudongde Hydropower Station is dominated by thin marbled dolomite. During construction, numerous cracks form along the elevation direction, and large monitoring deformation values appear in the consequent slope section. In this study, engineering geological analysis, deformation monitoring data analysis, and three-dimensional numerical simulation are combined to investigate the formation mechanism of cracks, the range of local deformed bodies, and the deformation and failure mechanism of deformed bodies. The stability of the slope is rechecked via the rigid-body limit equilibrium method based on the above analysis. Results show that the local convex terrain in the consequent slope section is cut through unfavorable structural surfaces and form a deformable body. Under the influence of unfavorable factors, such as the bedding cut foot caused by the lower excavation unloading and rainfall, the deformation of the shallow slope surface continuously increases; as a result, the shotcrete layer cracks. The deformation force comes from the middle and rear parts of the slope, and the instability mode slides along the bottom boundary level. After prestressed cables are added, the safety factor of the deformed part can satisfy the code requirements, and the existence of the deformed part does not affect the overall slope stability. Therefore, this study can provide technical support for engineering construction and a reference for similar slope engineering research.

1. Introduction

Rock masses with natural layered structures account for about 77% of the land area in China. A layered rock mass is usually distributed with a set of dominant structural planes. The shear strength along the structural plane is much smaller than that in the vertical direction and has obvious anisotropy. Layered rock slopes are the most common and widely distributed slopes. However, layered rock masses have stability problems in human engineering activities (CHEN Zhijian, 2001, HUANG Runqiu, 2007).
Wudongde Hydropower Station is a world-class giant hydropower station located in the lower reaches of the Jinsha River and has a total installed capacity of 10,200 MW. The inlet slope of the diversion tunnel on the right bank contains three typical layered rock slope structures, i.e., consequent slope, oblique slope, and transverse slope, because of the spatial variation in rock formation and the different section strikes of the designed slope. During construction, numerous cracks are distributed along the elevation direction and have large deformation monitoring values.

In this study, slope deformation mechanism and excavation slope stability are qualitatively and quantitatively evaluated through engineering geological analysis, deformation monitoring data analysis, and numerical simulation (ZHANG Lian, 2013, 2019).

2. Mechanism analysis and stability evaluation of slope deformation

2.1. Engineering geological conditions

According to the different excavation trends of the slope, the inlet slope of the diversion tunnel on the right bank is divided into three sections from upstream to downstream: the consequent slope (No. 0-230–0-30), the oblique slope (No. 0-30–0+20), and the transverse slope (No. 0+20–0+108). The excavation slope ratio of the consequent slope is 1:0.3–1:0.75, the slope toe is EL812 m, the slope top is EL940 m, the maximum excavation slope height is 128 m, and the angle between the slope strike and the rock strike is 11°–27°. The lithology is weakly weathered thin marble dolomite with a layer of about 1 mm thick phyllite. The quality of the rock mass is grade IV. The strata strike is generally 30°–57°, dip SE, and 45°–65° dip angle.

In May 2013, when the consequent slope was excavated to EL854–840 m, cracks were found on the slope surface and raceway with No. 0-80–0-140 and EL930–1000 m. It had 23 deformation cracks, including two long cracks, with a length of 1–5 m and a width of 0.5–2 cm. The two cracks are LT1 with an extension length of 38 m and LT2 with an extension length of 74 m. The specific distribution of fractures is shown in Figure 2.
2.2. Analysis of deformation monitoring results
The inlet slope of the diversion tunnel on the right bank has three monitoring sections. The cracks mainly appear near the third monitoring section (No. 0-125) equipped with a multiposition extensometer at EL890–930 m.

The monitoring data show that the deformation of the superficial layer rock mass initially increases rapidly from the excavation of the lower part at an elevation of 875 m. The cumulative deformation of the orifice monitored by the multiposition extensometer at an elevation of 930 m reaches 57.6 mm. The cumulative deformation of the orifice is at an elevation of 890 m up to 37.9 mm. The deformation and the deformation rate at the elevation of 930 m are greater than those at the elevation of 890 m. The deformation is mainly concentrated in the superficial layer rock mass, and the deformation value of the rock mass 15 m deep from the orifice is small.

The main factors influencing the rapid growth of slope deformation are the lower excavation and rainfall, which can be roughly divided into two stages. (1) The first stage is from May 10 to May 23. In this period, deformation is mainly induced by the excavation disturbance of the lower part of the slope, and rainfall infiltration intensifies slope deformation. (2) The second stage occurs after May 24. The increase in rainfall is the main factor influencing the continuous increase in the superficial slope deformation.

![Displacement curve of the multiposition extensometer at EL930 m of the third section](image_url)
2.3. Slope stability analysis

An overall 3D geological generalized model of the slope is established on the basis of geological and topographical data. The FLAC$^{3D}$ software is used to study the mechanical response of the inlet side slope of the diversion tunnel on the right bank under excavation unloading conditions, the deformation and failure mechanism of the slope, the potential instability mode, and the overall stability safety factor. The layered rock mass is represented by a ubiquitous joint plasticity model, which can simulate the shear failure and tensile failure along the rock stratum and the rock mass. In addition, the anisotropy of the strength of the rock mass parallel and vertical to the rock stratum is considered.

![Figure 4. Displacement curve of the multiposition extensometer at EL890 m of the third section](image)

After the slope is completely excavated, the deformation of the consequent slope is dominated by unloading rebound. The overall deformation occurs toward the outside of the slope. The horizontal displacement toward the outside of the slope is greater than the vertical displacement. The deformation in the lower part of the slope is larger than that in the other parts, and the maximum deformation is located at EL812 m, with a deformation of 75–76 mm. Along the elevation direction, the horizontal deformation of the middle and upper parts of the slope is generally larger than that of the lower part of the slope. The maximum horizontal deformation appearing at EL915 m is 45.8 mm.

The strength reduction method is used to analyze the stability of the consequent slope. The potential instability area and the corresponding safety factor after slope excavation are obtained. The instability mode of the slope slides along the rock stratum. The instability area is concentrated in the area between 0–197 and 0–63, the trailing edge extends to EL1074 m, and the lower shearing outlet is about EL834 m. The safety factor of the slope under different working conditions is between 1.13 and
1.38, and the overall stability of the slope in the consequent section satisfies the requirements, but the safety margin is limited.

Table 1. Mechanical parameters of rock mass and structural plane

| Divided Areas | γ (kN/m³) | E (GPa) | μ | f  | c (MPa) |
|---------------|-----------|---------|---|----|---------|
| New           | 27.3      | 4       | 0.3| 0.8| 0.7     |
| Pt2y¹ Weak    | 27.3      | 2       | 0.33| 0.7| 0.4     |
| layer         | —         | —       | —  | —  | 0.5     |
|               | —         | —       | —  | —  | 0.1     |

Figure 6. Slope displacement and potential instability area after excavation

2.4. Stability analysis of locally deformed body

The monitoring data and crack investigation results reveal that the deformation of the shallow rock mass in the section of 0–080 m to 0–140 m along the slope is large, forming a local deformation body. The geological data show that the interface at the bottom of the local deformation body in this range turns in space, which can be regarded as two different layers at 140° < 45° and 120° < 45°. The local deformation body can be divided into two parts.

Part 1 covers No. 0-080 m–0-100 m, where the maximum horizontal buried depth is at EL930 m, about 19 m outside and 6 m inside the EL930 m raceway. The sliding surface area is 2840 m², and the volume is 15,860 m³.

Part 2 spans No. 0-100 m–0-140 m, where the maximum horizontal buried depth is at EL930 m, about 19 m outside and 7 m inside the EL930 m raceway. The sliding surface area is 7000 m², and the volume is 43,720 m³.

The rigid-body limit equilibrium method is used to check the stability of a locally deformed body. The deformed body creates double-sided sliding along the intersection line of 120° < 45° and 140° < 45°,
with a total volume of 59,580 m³ and bottom sliding surface areas of 7000 and 2840 m². The support measures are rechecked according to the safety factor of 1.15. After these measures are considered, 33 prestressed cables of 150 tons should be added.

![Figure 7. Geological profile of the local deformation body on the consequent slope (red is shallow slip surface)](image)

2.5. Analysis of slope deformation mechanism

In view of the crack of concrete spray layer in the slope section of 0-080–0-140 m and EL930–1010 m, the construction geological data, monitoring data, and stability calculation results are systematically analyzed.

The slope with the crack is affected by local topographical conditions, forming a locally convex terrain, with obvious grooves on upstream and downstream sides. The angle between the strike of the rock strata and the strike of the slope is only 11°, and the rock dip is 45°, which is less than the slope gradient (53°–73°). However, the rock slope toe of the consequent slope is cut, thereby posing a problem.

The deformed body is mainly formed by the cutting of the unfavorable geological structure surface. The upstream groove of the LT2 fracture corresponds to the exposed part of structural plane Tb1 that occurs at 120°–140° ⊥ 45°. The downstream groove of the LT1 fracture corresponds to the exposed part of the steep structural plane T1 found at 200° ⊥ 80°. The bottom of the deformed body is composed of rock mass structural surfaces forming the bottom sliding interface.

Cracks occur when the lower part of the local deformation body becomes excavated, the bedding cutting range expands, and the deformation of the upper part of the slope continuously grows. Since the end of May, rainfall has been concentrated and has increased significantly. Consequently, the structural surface properties weaken, and the seepage pressure of the slope increases, thereby reducing the stability of the slope. Furthermore, the shallow rock mass deforms and fractures.

The deformed body is cut and formed by the local topography and an unfavorable structural surface. After a prestressed cable is added, stability can be greatly improved. The three-dimensional numerical analysis reveals that original support measures can ensure the overall stability of the consequent slope without considering local unfavorable geological conditions. The reinforced support of a deformation body eliminates the influence of unfavorable geological conditions on slope stability. After the support
is strengthened, the existence of a deformed body does not affect the overall stability of the consequent slope.

3. Conclusions

The deformation mechanism of the slope is comprehensively analyzed on the basis of the geological information, monitoring data, and calculation results of slope stability. The following conclusions are obtained:

(1) The local convex terrain in the consequent slope section is cut by unfavorable structural surfaces, thereby forming a deformable body. Under the influence of unfavorable factors, such as the bedding cut foot caused by lower excavation unloading and rainfall, the deformation of the shallow slope surface continuously increases. Consequently, the shotcrete layer cracks.

(2) The instability mode of the deformable body slides along the layer forming the bottom boundary, and the safety factor can satisfy the requirements after prestressed cables are added. The strengthening support of the deformation body eliminates the adverse effect of unfavorable geological conditions on slope stability, and the existence of the deformation body does not influence the overall stability of the slope section.

(3) Blasting intensity should be strictly controlled at the site of slope excavation to avoid cracking and damaging the rock mass caused by blasting vibration. This engineering practice shows that the quality and stability of rock masses can be improved by controlling blasting.

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References

[1] CHEN Zhijian. Theory and key technology of monitoring and evaluation model establishment on layered rocky slope engineering[D]. Hohai University, 2001

[2] ZHANG Lian, WU Yongjin, LU Bo, et al. Study on deformation body and stability of tunnel face and pier slope of right bank diversion tunnel entrance of Wudongde Hydropower Station in Jinsha River [R]. Wuhan : Key Laboratory of Geotechnical Mechanics and Engineering of Ministry of Water Resources, 2013. (in Chinese)

[3] HUANG Runqiu, ZHAO Jianjun, JU Nengpan, et al. Study on deformation mechanism and control method of bedding rock slope along Tangtun expressway [J]. Chinese Journal of Rock Mechanics and Engineering, 2007, 26(2) : 240–246. (in Chinese)

[4] ZHANG Lian, WU Yongjin, HUANG Shuling, DING Xiuli. Cracking mechanism analysis and stability evaluation of steeply inclined consequent slope [J]. 5th ISRM Young Scholars'
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