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Safety Evaluation and Support of Diversion Tunnel Slope of Hydropower Station

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Abstract. On the basis of analyzing the engineering geological conditions of the inlet slope of diversion tunnel on the left bank of a hydropower station in Jinsha River, the overall three-dimensional geological generalized model of diversion tunnel slope is established according to the geological and topographic data during the construction period. According to the slope excavation and support scheme, the displacement, stress, strength reserve and safety factor of the slope after all excavation are calculated and simulated under the existing support scheme, such as water storage condition, sudden drop of water level condition and transient condition (rainstorm). The strength reduction method is used to calculate the overall safety factor of the inlet slope of the diversion tunnel on the left bank under rainfall, impoundment and sudden drop of water level, and the failure mode of slope instability is predicted and analyzed. The calculation results can provide reference for the safety protection of slope with multiple schemes.

Keywords. Hydropower project, slope excavation, support, safety

1. Introduction

China's hydropower resources are an important part of the energy structure, with abundant hydropower resources. There are a large number of natural slopes and artificial slopes in hydropower projects, among which, the stability of reservoir bank slopes and engineering slopes are related to the safe operation of the whole hydropower project. With the continuous and gradual development of hydropower projects, there are more and more stability problems of engineering slopes, especially after the reservoir is impounded, which further aggravates the potential safety hazards and is very important for the safety and long-term operation of hydropower projects. With the rapid development of water conservancy and hydropower in China, it is of great significance to study the slope excavation, support and stability of hydropower projects in order to ensure the smooth progress of hydropower projects. Because of its diversity and multiplicity, the slope of hydropower engineering has attracted much attention from scholars in the industry. It is necessary to study the stability of slope in the development and construction of hydropower station, and it is also a very important problem in geotechnical engineering. The overall stability evaluation of slope after excavation of dam shoulder in hydropower project is also a key issue in dam design

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and foundation treatment. Some scholars have made extensive research on slope stability by in-situ and indoor experiments, theoretical analysis and numerical calculation methods [1~9]. During the investigation, design, construction and operation of hydropower projects, the slope stability problem is always one of the main engineering geological problems [10]. Therefore, according to the regional geological conditions of large-scale hydropower projects, aiming at the instability prone areas of artificial slopes, we establish a three-dimensional calculation model to calculate the safety factor of diversion tunnel slopes under different working conditions, and the stress of anchor cables and bolts needed for reinforcement. Finally, the displacement, stress and instability mode of slope under multiple working conditions are analyzed and predicted.

2. General Situation of Engineering and Geological Conditions

According to the topography of slope, the slope below 1060 m is steep, with a general slope of 42° ~ 54° and a slope height of about 260 m. The elevation is 1060 m ~ 1230 m, with an average slope of 75° ~ 80° and a slope height of about 170 m. The slope with the elevation of 1230 m ~ 1570 m is about 35° slope topography. The fold basement is below 1060 m elevation, and the lithology of the stratum is very thin ~ thin marble dolomite, with phyllite film of about 0.5 mm~1 mm thick sandwiched between layers, medium thick limestone and medium thick dolomite. The stratum strikes at 290° ~ 320°, inclines to NE, and dips at 16° ~ 30°, that is, gently inclined to the upper reaches of the left bank.

From the geological structure, the main structural features below the elevation of 1060 m are Honggou fault (F_3) and a group of dominant fractures. Honggou fault (F_3) strikes 40° ~ 60°, inclines to SE, inclines to 56° ~ 82°, and has a bandwidth of 2 m~3 m. The structural rock is cataclastic rock, which is affected by the structure. Wrinkling and cleavage are developed in extremely thin rock mass, and the rock mass is broken. The Honggou fault (F_3) cuts the foot of the inner slope near the elevation of 910 m. Faults with an elevation of 1060 m ~ 1230 m are undeveloped, and a group of fractures along the slope, outside the slope and steeply inclined are well developed, with the occurrence of 289°∠ 73°, which are mostly filled with cuttings and mud and calcium, some of which are not filled, and the spacing is generally 2 m ~ 4 m. Controlled by this group of fissures, the potential unstable dumped rock mass on the slope is relatively developed.

From weathering and unloading point of view, most of the rock masses below the slope elevation of 1060 m are slightly new. The extremely thin ~ thin marble dolomite belong to the weakly weathered lower zone, and the horizontal buried depth are generally 20 m~30 m. The horizontal depth of strong unloading zone are generally 10 m~20 m, and that of weak unloading zone are generally 16 m~25 m. Most of the rock masses with an elevation of 1060 m ~ 1230 m are slightly new, the lower horizontal depth of strong unloading zone are about 15 m~20 m, and that of weak unloading zone are about 25 m~30 m.

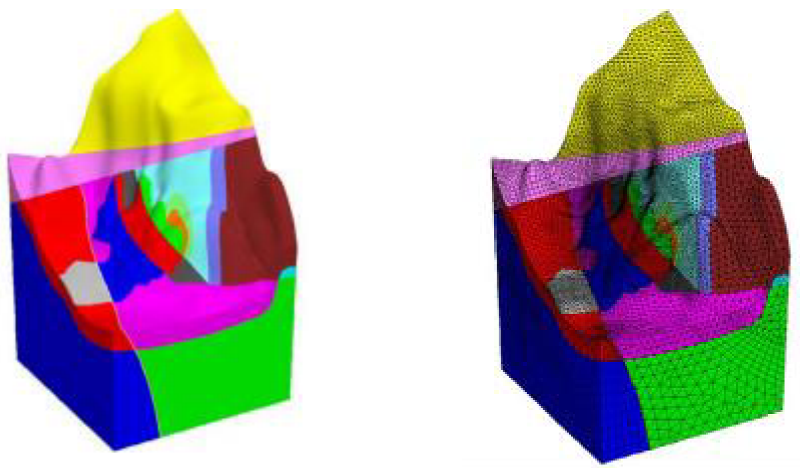
From the point of view of slope excavation, the slope ratio is 1: 0.3 (73 º) for the section with elevation of 910 m~851 m, and 1: 0.3 for the slope below elevation of 851 m. From the perspective of slope structure, the slope strike of pile number 0+106 ~ 0+145 is 33 º, and its included angle with rock stratum strike is 28 º ~ 44 º, which belongs to oblique slope - reverse slope. The section of pile number 0+145 ~ 0+158.2

is an arc section, and the included angle between rock mass strike and rock stratum strike is about 25 º, which belongs to reverse slope. The angle between the slope strike and the rock stratum strike in the section of pile number 0+158.2 ~ 0+189.5 is 80 º, which belongs to the transverse slope.

The slope lithology of this section is Yinmin Formation, in which 0+106 ~ 0+167 section is brownish gray thin and extremely thin marble dolomite, 0+167 ~ 0+189.5 section is gray thick dolomite and medium thick limestone, and the attitude of rock strata changes greatly, with 168 º∠ 49 º in the upstream and 198 º ∠84 º in the downstream. The rock mass is weakly weathered. In addition to the fractures in the stratum, fractures in the group of 262 º ~ 287 º ∠39 º ~ 60 º are relatively developed.

3. Computational Model

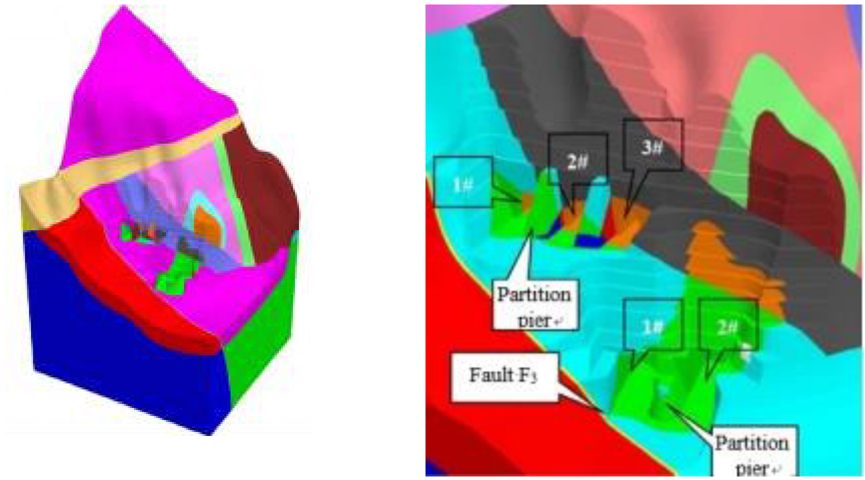
On the basis of analyzing the engineering geological conditions of the inlet slope of the diversion tunnel on the left bank, the overall three-dimensional geological generalized model of the inlet slope is established according to the geological and topographic data during the construction period (see figure 1 and figure 2). The calculation range of the model is 550 m in *X* direction, 500 m in *Y* direction and from 500 m elevation to surface in *Z* direction, where *X* axis takes the entrance of No.2 spillway tunnel as origin, parallel tunnel face slope points out of the mountain as positive, *Y* axis points downstream as positive, and *Z* axis points vertically upward as positive. Thin marble dolomite, medium thick limestone, medium thick dolomite, weathering unloading zone and F_3 fault are simulated in the calculation domain. The model is divided into 86707 nodes and 437641 units.



(a) Model diagram (b) Grid diagram

Figure 1. Three-dimensional numerical calculation model diagram of inlet slope of diversion tunnel on the left bank.

The finite difference method is used to study the mechanical response, deformation and failure mechanism, potential instability mode and stability coefficient of the inlet slope under excavation unloading condition. In numerical calculation, the simulated excavation sequence is carried out step by step according to the actual excavation on site, and anchor piles, anchor rods and prestressed anchor cables are supported at the same time. The elastic-plastic constitutive model of joints is used to simulate the macroscopic layered rock mass equivalently.



(a) Overall drawing (b) Partial enlarged drawing

Figure 2. Model diagram after excavation.

4. Calculation Scheme and Working Conditions

The inlet slope of the diversion tunnel on the left bank is located on the mountain surface, and the river valley slope section is weathered and unloaded strongly. In addition, there is lateral cutting of Honggou fault on the upstream side, so it is difficult to accumulate high structural stress within the influence range of the excavated slope. Therefore, the initial stress field is calculated according to the self-weight stress field.

According to the adjusted slope excavation and support scheme, the displacement, stress and safety factor of slope strength reserve are calculated and simulated when the slope is completely excavated under the existing support scheme under the conditions of water storage, sudden drop of water level and short-term conditions (rainstorm).

5. Anchor Cable and Bolt Stress

After the slope excavation is completed, the stress and growth distribution ratio of support of horse road at all levels in each slope section are shown in tables 1~2.

From table 1, it can be seen that the average stress of anchor cables at elevation 1015 m ~ 1030 m of front slope is 1503 kN, and that at elevation 875 m ~ 890 m is 1512 kN. Due to the lag of upper excavation slope support, the stress change of prestressed anchor cables in this area is generally small. The average stress of the anchor cable at the elevation of 860 m ~ 875 m on the front slope is 1572 kN, the maximum stress of the anchor cable is about 1647 kN, and the stress increment exceeds 100 kN, accounting for 32.0%. The average stress of the anchor cable at the elevation of 847 m ~ 860 m on the front slope is 1639 kN, and the maximum stress of the anchor cable is about 1719 kN, with the stress increment exceeding 100 kN accounting for 74.2% and exceeding 200 kN accounting for 8.6%. The maximum stress of anchor cable below 847 m elevation of tunnel face slope is about 1727 kN, and the average stress of anchor cable is 1664 kN, with the stress increment exceeding 100 kN accounting for 70.4% and exceeding 200 kN accounting for 20.5%.

Table 1. Stress statistics of anchor cable.

Place	**Anchorage force /kN**		**Distribution proportion of anchoring force increment relative to initial value (%)**		
	Maximum	**Average value**	**>200 kN**	**100-200 kN**	**<100 kN**
Elevation 1015 m～1030 m	1507	1503	0.0	0.0	100.0
Elevation 875 m～890 m	1530	1512	0.0	0.0	100.0
Elevation 860 m～875 m	1647	1572	0.0	32.0	68.0
Elevation 847 m～860 m	1719	1639	8.6	74.2	17.2
Tunnel face slope with elevation below 847 m	1727	1664	20.5	70.4	9.1

Table 2. Statistical table of bolt stress.

Place	**Anchorage force / MPa**		**Distribution proportion of anchoring force (%)**			
	Maximum	**Average value**	**>300 MPa**	**200-300 MPa**	**100-200 MPa**	**<100 MPa**
Elevation 1015m～1030m	5	3	0.0	0.0	0.0	100.0
Elevation 988m～1015m	8	3	0.0	0.0	0.0	100.0
Elevation 955m～988m	12	3	0.0	0.0	0.0	100.0
Elevation 925m～955m	25	5	0.0	0.0	0.0	100.0
Elevation 907m～925m	89	9	0.0	0.0	0.0	100.0
Elevation 890m～907m	128	18	0.0	0.0	1.6	98.4
Elevation 875m～890m	129	29	0.0	0.0	2.4	97.6
Elevation 860m～875m	152	41	0.0	0.0	3.0	97.0
Elevation 847m～860m	278	53	0.0	0.5	1.9	97.6
Tunnel face slope with elevation below 847 m	310	89	6.9	15.3	30.3	47.5
Partition pier	310	128	15.0	20.9	20.4	43.7

It can be seen from table 2 that the application sequence of slope support is: slope support with elevation of 875 m and above lags behind, and slope with elevation below 875 m supports in time with excavation step, so the stress value of anchor rod of slope with elevation above 875 m is generally small, and the average stress value is generally between 3 MPa and 29 MPa. The closer to the lower cave face slope, the greater the stress value of anchor rod. The average stress value of anchors with elevation of 860 m ~ 875 m on the front slope are generally 41 MPa, and the maximum value is 152 MPa. The average stress value of anchors with elevation of 847 m ~ 860 m on the front slope are generally 53 MPa, the maximum value is 278 MPa, and the stress exceeding 200 MPa accounts for 0.5%.

The maximum stress of anchor rods below 847 m elevation of tunnel face slope is about 310 MPa, which appears near the entrance of diversion tunnel. The average stress of anchor rods is 89 MPa, about 6.9% of which yield, and 15.3% of which exceed 200 MPa.

The maximum stress of the anchor rod at the partition pier is about 310 MPa, which appears near the entrance of the diversion tunnel. The average stress of the anchor rod is 128 MPa, about 15% of which yield, and 20.9% of which exceed 200 MPa.

6. Slope Instability Mode and Safety Factor

After the excavation of the slope and diversion tunnel are completed, the displacement nephogram and displacement vector diagram of the slope in critical state are shown in figure 3 and figure 4. It can be seen from the figures. that the unstable area of the slope is concentrated in the rock stratum of the front face slope of the diversion tunnel and the slope section below the elevation of 907 m inside the mountain. The trailing edge of the unstable region extends to the rock interface, and the lower shear outlet is roughly bounded by the top arch of the diversion tunnel. In the unstable region, the upper part of rock mass is deformed greatly, showing a downward dumping trend. Combined with the large incremental deformation of slope rock mass caused by the excavation of the inlet section of diversion tunnel, we can see that the excavation of the inlet section leads to a large hollowing-out rate of local mountains, which has a great influence on the overall stability of the slope.

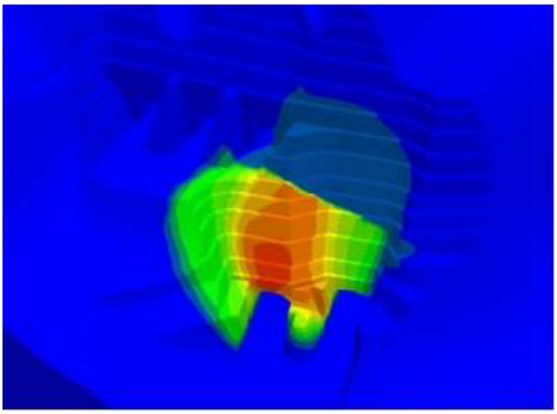
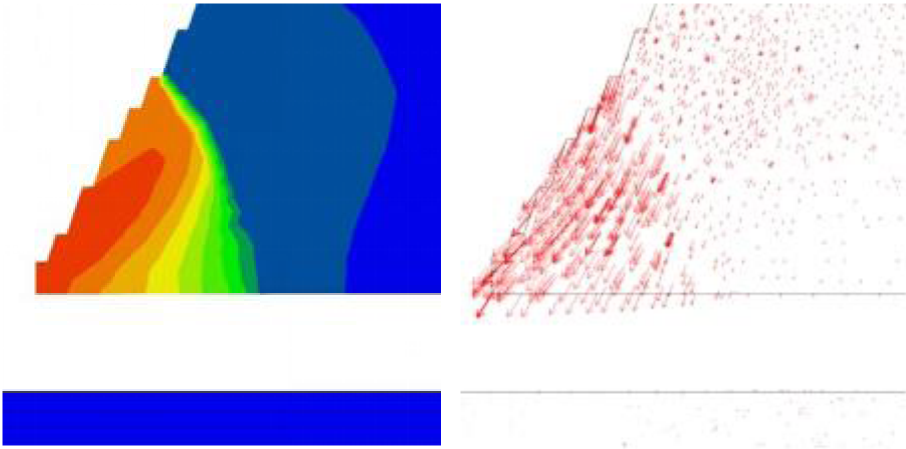


Figure 3. Instability area (without support) of slope in critical state after excavation of diversion tunnel.

The strength reduction method is used to calculate the overall safety factor of the slope at the entrance of the diversion tunnel on the left bank under the existing support scheme under the conditions of rainfall, impoundment and sudden drop of water level.



(a) Displacement nephogram (b) Displacement vector diagram

Figure 4. Instability area (without support) of slope section in critical state after excavation of diversion tunnel.

The calculation results of slope safety factors of different slope sections under different working conditions are shown in table 3. The "impoundment" water level is 872 m, and the "sudden drop of water level" means that the water level drops from 872 m to 830 m.

Table 3. Table of slope safety factor under different working conditions.

Schemes	Analysis working condition	Safety factor
①	Slope excavation + diversion tunnel excavation + no support	1.42
②	Slope excavation + diversion tunnel excavation + support	1.50
③	Slope excavation + diversion tunnel excavation + support + rainfall	1.32
④	Slope excavation + diversion tunnel excavation + support + water storage	1.30
⑤	Slope excavation + diversion tunnel excavation + support + sudden drop of water level	1.25

It can be seen from table 3 that the safety factor of the whole slope under unsupported working condition can be taken as 1.42. The safety factors of the slope are 1.50, 1.32, 1.30 and 1.25 respectively under the four working conditions of supporting, rainfall, reservoir impoundment and water level drop. The slope under study belongs to Grade II slope in the hub project area. According to the Specification for Slope Design of Hydropower and Water Conservancy Projects (DL/T5353-2006), the safety factor of the slope under permanent working condition is controlled by 1.15 ~ 1.25, and that under short working condition (rainfall) is controlled by 1.05 ~ 1.15. The above-mentioned slope stability calculation and analysis results meet the design and specification requirements.

7. Conclusion

Based on the engineering geological conditions of the slope, a three-dimensional numerical model of the inlet slope of the diversion tunnel is established according to the geological and topographic data during the construction period. The strength reduction method is used to calculate the overall safety factor of the inlet slope of the diversion tunnel on the left bank under rainfall, impoundment and sudden drop of water level under the existing support scheme. In numerical calculation, excavation simulation is carried out step by step according to the actual construction sequence of the site, and anchor piles, anchor rods and prestressed anchor cables are supported at the same time. The excavation of the inlet section of the diversion tunnel leads to a large hollowing-out rate of the local mountain, which has a great influence on the overall stability of the slope. The unstable areas of slope are concentrated in the front face slope of diversion tunnel and the rock stratum in the slope section below 907 m elevation inside the mountain. After slope support, the safety factor is improved, and security under both permanent and short-term working conditions meet the design and specification requirements.

Acknowledgments

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