Deformation Mechanism and Crack Cause Analysis of the Left Abutment Slope of Yangfanggou Hydropower Station

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Abstract. The geological conditions of the left abutment slope of Yangfanggou Hydropower Station are complex, and the unloading effect in the rock mass developing with slope-oriented steep-gentle-dipped fractures is strong. During the excavation of slope, the deformation and cracking response in rock mass on the upstream side of the arch dam foundation have been found successively, the stability of slope and personnel safety has been significantly influenced. Based on engineering geological survey and monitoring data analysis, a discrete element simulation model is built for deformation mechanism and crack cause analysis of the left abutment slope. The calculation results show that: the fault f27 and slope-oriented structural plane with gentle dip are the main factors that influence the deformation response during excavating the slope. During the excavation of the slope above E.L.2000m, f27 has an obvious influence on the local stress at the foot of the slope. The stress will be concentrated in the upper part of f27 firstly and then unloading and relaxed under the combined action of the slope-oriented structural plane. The shear deformation happens along with the fault f27, and the subsidence of its hanging wall caused the crack of the rock mass. The slope stability will be significantly reduced with f27 exposed on the excavation face, there is a large risk of slip and instability. Pre-stressed anchor cables are used to stabilize the foot and strengthen the slope half, which can effectively improve the stability of the slope and control the shear deformation of f27. After the pre-stressed anchor cables are applied, the safety factor of the slope is increased from 0.98 to 1.20, and the monitoring data show that the deformation is controlled successfully.

Keywords: Yangfanggou Hydropower Station, Rock Slope, Deformation and Failure Mode, Crack Cause, Stability Analysis

1. Introduction

In recent years, clean energy has been vigorously developed and constructed in the southwest region of China, and various complex engineering problems have been encountered. For example, to build a 200m high dam in a deep-cut river valley, excavate the slope is inevitable to ensure that the quality of the dam foundation rock mass meets the design requirements. The height of the excavation slope can usually reach 300m~500m[11]. Under the effect of continuous uplift of the Qinghai-Tibet plateau, the geological conditions in the southwestern region are extremely complex, structural planes and faults are developed, the rock mass is strongly unloaded, and the ground stress level is high. The stress will be redistributed with the excavation of the slope, and stress concentration at the toe of the slope. The
rock mass deformation and fracture may occur under the influence of the structural plane, which will seriously affect the project's progress and threaten the safety of personnel. Therefore, the analysis of the deformation mechanism of the high slope is of great significance to the evaluation of slope stability, and it is one of the key technical issues for the success of hydropower project construction. Many scholars have done a lot of research on the deformation mechanism of the high slope, Huang Runqiu\cite{2-3} considered the deformation and instability of high rock slopes to be a dynamic geological historical process based on a large number of on-site investigations and comprehensive analysis. Chang Zhonghua et al.\cite{5} studied the failure mode of the rock slope in the Three Gorges Reservoir and showed that the rock slope may mainly appear bending - tension cracking - dumping failure, shear-sliding failure, wedge collapse-sliding failure, and weathering-exfoliation deformation failure. A large number of western hydropower stations have encountered rock mass cracking problems during the construction process. Cui Huali et al.\cite{5} studied the causes of cracks on the right bank slope of a hydropower station on the Dadu River and pointed out that the deep unloading fissure zone and fault f231 were exposed on the slope surface, which reduced the stability of the slope. If the support is not in time, it will directly lead to the generation of cracks on the slope. Qi Shengwen\cite{6} and Rong Guan\cite{7} believe that the formation mechanism of deep cracks on the left bank of Jinping is that under the specific rock mass conditions of upper soft and lower hard, the river valley cuts down rapidly, and the high ground stress is constantly adjusted inside the slope, which caused the expansion of the original fractures in the rock mass. Zhu Jiewang\cite{8} and Wang Jimin\cite{9} studied the influence of deep cracks on slope stability through numerical analysis and proposed reinforcement measures of shear-resistant tunnels and deep pre-stressed anchor cables. During the excavation process of the dam foundation slope on the left bank of Yangfanggou Hydropower Station, multiple cracks were found on the excavation slope, which has a greater impact on the subsequent construction safety. Based on the engineering geological conditions and monitoring data, this paper uses the three-dimensional discrete element software 3DEC to study the excavation response characteristics of the slope, analyze the causes of cracks and the failure mode of the slope, review the stability of the slope, so as to provide a reference for the formulation of the dam foundation slope reinforcement plan.

2. Engineering Situations
Yangfanggou Hydropower Station is located on the middle reaches of the Yalong River in Muli County, Liangshan Yi Autonomous Prefecture, Sichuan Province. It is the sixth-level hydropower station in this section under planning. The designed normal storage level is 2094m. The dam crest elevation is 2102m. The left bank of the dam area is steep terrain, with a slope of about 45-60° in general. The excavation height of the slope is nearly 385m. The maximum excavation elevation is 2332m. The foundation surface is 1947m. The exposed stratum in the dam area is mainly Yanshanian granodiorite. The characteristics of the geological structure are mainly reflected in 1) Affected by tectonic action, the rock mass has developed large fissures, and the slope is dominated by medium-steep dips. Combining with river valley bank slopes and other near-air conditions, it has caused the complexity of the rock mass structure and the diversity of slope deformation and failure modes; 2) Affected by the strong downward cutting action of the river, the unloading effect of the shallow surface rock mass of the slope is obvious. The maximum horizontal unloading depth is about 11m; 3) The dam site area is dominated by tectonic stress, and the maximum horizontal principal stress on the left bank is 4~14.50MPa. Affected by the stress concentration zone, the initial ground stress near the riverbed shows an increasing trend.

3. The Excavation Response of Dam Foundation on Left Bank

3.1. The description of rock cracking
The excavation of the left abutment slope in Yangfanggou hydropower station began in June 2016. During the excavation between the elevations of 2030m~2000m from April to May in 2018, the rock cracking took place and 18 rock fractures were found (13 fractures around the fault f27 were at
discharging platform in elevation of about 2102m; 5 fractures on the slope were found in elevation of 2060m–2080m). The width of fractures was in general 2~5mm, the maximum width was 10mm and the maximum length was about 17m. The fracture geometry and its distribution were described in Figure 1 and Figure 2.

![Figure 1. Distribution of fractures on the slope](image1)
![Figure 2. Fracture geometry around the fault f27](image2)

### 3.2. Monitoring results analysis

During the formation and development of cracks, the monitoring data represented that the rock deformations increased significantly. The monitoring locations were described in Figure 3. Figure 4 represented the deformation of each monitoring location for the excavation up to 2000m. The upper deformation was larger than the below deformation, and it was in the range of 1mm and 10mm.

![Figure 3. Description of monitoring locations](image3)
![Figure 4. Deformation of each monitoring location (excavation up to 2000m)](image4)

Figure 5 illustrated that the relationship between displacement and time at two measuring points in elevation of 2085m. The maximum deformation increased up to 10mm, and the deformation occurred in a depth of more than 17m. The thickness of rock mass above the fault f27 was small, although the fault f27 was not exposed in this stage. The rock cracking took place in the exploration tunnel PD15 at the elevation of 2075m. The monitoring results illustrated that the maximum shear displacement was about 4mm, as shown in Figure 6.

During the excavation of the slope, the stress is released and the deformation rate increases gradually. With the excavation stopped, the deformation rate decreased gradually and tended to convergence,
which represented a stable state of the slope. However, a prediction for the deformation development during further excavation on the slope (2000m~1947m) was required.

![Typical displacement-time curves](image)

Figure 5. Typical displacement-time curves

![Shear deformation and time along the fault](image)

Figure 6. The relationship between the shear deformation and time along the fault f_{27}

4. DEM Numerical Model

4.1. Material parameters

Depending on the results of in-situ shear tests\textsuperscript{[10]}, the material parameters of each type of rock mass are shown in Table 1, and the parameters of the structural plane in the rock mass are shown in Table 2.

| Classification of rock mass | Young's modulus(GPa) | Poisson's ratio | Shear strength \( \phi (^{\circ}) \) | c(MPa) |
|----------------------------|----------------------|----------------|----------------------------------|--------|
| II                         | 13.0                 | 0.23           | 53.5                             | 1.10   |
| III\(_1\)                  | 9.0                  | 0.26           | 48.0                             | 1.05   |
| III\(_2\)                  | 5.0                  | 0.27           | 42.0                             | 0.80   |
| IV                         | 3.0                  | 0.28           | 37.0                             | 0.60   |

| Structural planes | \( k_h \) (GPa/m) | \( k_s \) (GPa/m) | \( \phi \) (°) | c(MPa) |
|-------------------|-------------------|-------------------|----------------|--------|
| IV structural planes | 6                 | 1.2               | 26.5~31        | 0.1~0.15 |
| III structural planes | 5                 | 1                 | 17~22          | 0.05~0.1 |
4.2. Numerical model
The deformation and stability of slope were analysed using the program 3DEC based on the discrete finite method (DEM). The rock mass on the slope was classified in terms of the weathering degree of rock mass and the structural planes in the rock mass, as described in Figure 7.

![Numerical model in program 3DEC](image)

Figure 7. Numerical model in program 3DEC

4.3. Initial in-situ stress
According to the results of the back analysis conducted by Zhou [11], the horizontal tectonic stress in the dam area mainly pointed to the NWW direction. In the excavation area around the arch dam foundation, the maximum principal stress was in the range of 6~18MPa, and the minimum principal was in the range of 1~5MPa. The initial in-situ stress was larger, and this maximum principal stress was up to 20MPa, as shown in Figure 8.

![Distribution of the initial in-situ stress](image)

(a) Maximum principal stress (b) Minimum principal stress

Figure 8. Distribution of the initial in-situ stress

5. Analysis of deformation mechanism of slope

5.1. Numerical analysis of slope deformation

5.1.1. Excavation in 2102~2030m for left abutment slope.
It shows the deformation increment distribution after excavation in 2102~2030m for the left abutment slope, as shown in Figure 9 and Figure 10. The rock mass is dominated by upward unload and rebound
deformation in this excavation stage. The deformation increment is generally 6~16mm, and the rock mass on both sides of $f_{27}$ and other faults has no obvious discontinuous deformation.

Figure 9. Deformation increment distribution after excavation in 2102~2030m for left abutment slope

Figure 10. Deformation vector distribution after excavation in 2102~2030m for left abutment slope

5.1.2. Excavation in 2030~2000m for left abutment slope.
It shows the deformation increment distribution after excavation in 2030m~2000m for the left abutment slope, as shown in Figure 11 and Figure 12. The results show that the deformation of the slope is obvious along the slope structural planes $f_{27}$ and $f_{15-1}$. The rock mass on both sides of fault $f_{27}$ at the foot of the slope has obvious discontinuous shear deformation, and the deformation direction is inclined downward the blank surface. Meantime, the maximum deformation value is 20~30mm.

Figure 11. Deformation increment distribution after excavation in 2030~2000m for left abutment slope

Figure 12. Deformation vector distribution after excavation in 2102~2030m for left abutment slope

5.2. Mechanism of slope deformation
It shows that the deformation and cracking of the unloading platform and the excavation slope are closely related to the fault $f_{27}$ for excavation in 2030m~2000m. The spatial combination relationship between the original controlling structural plane (such as $f_{27}$) and slope surface is changed by the slope excavation. The rock mass on the hanging wall of the fault gradually becomes thin in the process of gradually exposing the controlling structural plane, and its bearing capacity decreases. In addition, the stress concentration at the toe of the slope results in obvious damage and fracture of the rock mass. The compressive shear slip deformation along with the fault $f_{27}$ and the sinking hanging wall rock
mass is under the gravity field, which results in the deformation and cracking of the unloading platform and the rock mass on the excavation slope.

6. Slope stability and reinforcement treatment

6.1. Slope stability analysis
The strength reduction method\(^\text{(12)}\) is used to analyze the stability of the slope:

\[
c_t = c/F_t \\
\varphi_t = \arctan (\tan\varphi/F_t)
\]

\(F_t\)—strength reduction factor.

The strength reduction method is to adjust the shear strength of the structural plane by changing the reduction factor \(F_t\), and then analyze the stable state of the slope based on DEM. The reduction factor when the slope reaches critical failure is the safety factor.

Firstly, the stability characteristics of the slope without support are analyzed. Figure 13 shows the deformation and failure of the slope when the strength reduction factor is 1.05, showing that the slope sliding failure is mainly controlled by fault \(f_{27}\). Figure 14 shows the relation curve between slope deformation and strength reduction factor without support. When the strength reduction factor is greater than 0.98, the slope deformation increases significantly, indicating that the factor of safety is less than 0.98 and the slope stability is poor, reinforcement treatment should be taken to improve the stability of the slope.

![Figure 13. Deformation and failure characteristics of the slope](image)

![Figure 14. The relation curve between slope deformation and strength reduction factor without support](image)

6.2. The effectiveness of reinforcement treatment
The prestressed anchor cable reinforcement is used to improve the slope stability. As shown in Figure 15, 6 rows of 3000kN prestressed anchor cables are arranged at the toe of the slope to limit the shear deformation of fault \(f_{27}\), and 15 rows of 1000kN–3000kN prestressed anchor cables are arranged in the upper part of the slope to strengthen the slope half.

Figure 16 shows the relation curve between slope deformation and strength reduction factor after reinforcement. The factor of safety of the slope is 1.20, which is improved compared with that without support.

The monitoring data shows (Figure 17) that during the excavation of the slope from 2000m to 1947m, the deformation of the measuring point 2-1 only increased by about 3mm, indicating that the reinforcement treatment scheme has a good control effect on the slope deformation.

![Figure 15. Prestressed anchor cable reinforcement](image)

![Figure 16. Relation curve between slope deformation and strength reduction factor](image)

![Figure 17. Monitoring data during slope excavation](image)
7. Conclusion
Based on the engineering geological conditions, monitoring data, and numerical simulation, the deformation mechanism, and crack cause were analyzed, and the stability of the slope was rechecked. The main conclusions were as follows:

(1) Fault $f_{27}$ is the main reason for the rock mass crack. With the excavation of the slope, $f_{27}$ is gradually exposed on the slope, and the rock mass of the fault hanging wall becomes thinner and the bearing capacity is reduced. Under the action of high stress, the rock mass at the foot of the slope is damaged and fractured. The shear deformation happens along the fault $f_{27}$ driven by gravity, and the subsidence of its hanging wall caused the crack of the rock mass.

(2) Numerical analysis results show that the excavation slope is in an unstable state without support, the safety factor is less than 0.98, and the failure mode is sliding failure along fault $f_{27}$ and slope-oriented structural plane.

(3) Pre-stressed anchor cables are used to establish the foot and strengthen the slope half, which can effectively improve the stability of the slope and control the shear deformation of $f_{27}$. After the pre-stressed anchor cables are applied, the safety factor of the slope reached 1.20, and the monitoring data show that the deformation is controlled successfully.

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