Study on Deformation Failure Mechanism and Control Measures of Toppling Slope

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Abstract. Aiming at the large range and depth of toppling and cracked deformation occurred in a typical toppling slope during the excavation in Miaowei hydropower station on the Lancang River, through geological survey, the classification standard system for toppling deformation rock has been established based on the main characteristic indexes of rock mass, and the mechanism of the toppling and tensile deformation of the slope at Miaowei is revealed. Comprehensive rescue reinforcement measures were implemented to control the development of deformation and to maintained the stability of the slope, which included prestressed anchorage and systematic drainage. Numerical simulation was implemented to predict the deformation and guide the reinforcement. The numerical and monitoring results both show that the deformation has been effectively controlled and the slope is already in a stable state with the completion of reinforcement measures. The study on the deformation mechanism and the successful practice of treatment of typical toppling slope in Miaowei hydropower station provide a constructive reference for similar complicated slopes.

Keywords: Toppling slope; Classification Standard of toppling; Deformation mechanism of toppling; Reinforcement; Safety factor; Monitoring.

1. Introduction

Toppling slope[1,2] is one of special kind of slope different from the conventional slope of sliding mode. With the rapid development of hydropower and mining projects in China, toppling is encountered more frequently and becomes the vital engineering issue in lots of projects such as Laxiwa hydropower station in Yellow River, Jinping I hydropower station[3] in Yalong River, Zipingpu in Ming River, Xiaowan in Lancang River, and Hutiaoxia in Jinsha River as well.
Miaowei hydropower station is located in middle stream of Lancang River in Yunnan Province of China. The gravel soil core rockfill dam is adopted as the retaining building, which is 131.30m height, the discharge structure is spillway on the left bank, and both the diversion power generation system and the sanding and putting holes are arranged between the dam and the spillway, and the ground plant is laid behind the left of dam as well. The installed capacity is 1400MW. The geological condition in dam site of Miaowei is very complicated, and typical toppling slopes with widely range and depth exist in both banks. Affected by excavation of the dam foundation in the right bank in 2013, toppling and tensile deformation emerged(Figure 1.) and about 250~300 cubic meters volume covering layers collapsed, which may cause collapse of the entire slope in right bank. Emergency reinforcement had to been carried out immediately.

2. Characteristics of Toppling Deformation Rock Mass in Miaowei Project

2.1. Classification Standard System for Toppling Rock Mass

Typical toppling rock mass widely exits in both banks of Miaowei hyarowper station. According to the on-site geological survey, a standard system for classification of toppling rock mass is established, which is extremely toppling class of A, highly toppling class of B (which includes upper B1 and lower B2), and weak toppling class of C. Classification standard is listed in Table 1.

In the right bank slope, the rock mass of extremely toppling class of A distributes in depth from 0 to 15m, the rock mass of highly toppling class of upper B1 distributes in depth from 29m to 67m, and lower B2 distributes in depth from 64m to 101m.
Table 1. Classification Standard of Toppling in Miaowei.

| Classification Indicators | Extremely Toppling Class of A | Highly Toppling Class of B | Weak toppling Class of C |
|---------------------------|------------------------------|-----------------------------|--------------------------|
|                           |                              | Upper B1                    | Lower B2                 |
| Deformation Characteristics| The rock mass is severely broken, overturned, entirely cracked and relaxed, partially overhead. The opening width of the fissure is several centimeters to tens of centimeters. | The rock mass is topping strongly and relatively loose. The tension in the layers is strong. The rock is loose. Slow-inclined tensile shear fractures develop across the layers. The opening width of the fissure is a few millimeters to a few centimeters. | The rock mass is topping weakly, and shear dislocations in the layers are shearing shift. The rock mass in the layer is slightly cracked and deformed. The opening width of the fissure is generally less than 3 mm. |
| Rock mass Structure       | Fragment Structure           | Cataclastic Texture         | Block Structure          |
| Inclination of Layer(°)   | 14–49                        | 31–66                       | 36–80                    |
| Maximum Tension(mm)       | 4–70                         | 2–80                        | 1–54                     |
| Tension in Unit(mm/m)     | Hard Rock 26.8–47.4          | 20.5–33.1                   | 14.9–26.5                |
|                           | Soft Rock                    | 10.3–32.9                   | 11.1–29.36               |
| Longitudinal Wave Velocity(m/s) | 1017–1405                   | 1290–2111                   | 1845–3000                |
| Typical photos            |                              |                             |                          |

2.2. Toppling Deformation Characteristics in the Right Bank Slope of Miaowei

The slope in the right bank was excavated down to 1312 meters elevation in August 4, 2012, and tension cracks appeared in April 16, 2013. In May 27, 2013, the local covering layers collapsed within the range from 1384m to 1366m elevation, the volume preliminarily estimated was 250–300 cubic meters. Simultaneously, Tensile cracks widespread throughout the surface of slope and across the exploration adit of PD20 in 1408m elevation, which shown that a widely range of seriously toppling deformation was emerging. And surface monitoring correspondingly indicated that deformation was developing slowly and the entire collapse of the slope was possible.

Cracks within slope of 1390m–1410m elevation were less than 2m length, less than 5mm width and less than 1m depth. The tensile cracks followed the rock orientation direction of the slope. Cracks within slope of 1450m–1490m elevation were intermittently distributed, and in general were 1–2m length. The width is initially less than 2cm, and significantly expended with several days of observation. There were two main groups of crack strike, one was EW and the other was NW–NNW. Both of two groups cracks respectively tracked the joint strikes of EW and NWW. Overall, the cracks on slope were tensile rather than shear and slip.

In adit PD20 in 1408m elevation, cracks observably distributed along the floor in depth from 7.5m to 31m, and the strike was basically N10°–30°W, consistent with the rock orientation. Some of the crack
shown the state that the outside was higher than the inside, which indicated the typical toppling deformation characteristics and the judgement that the fully sliding surface in slope rock mass had not yet formed.

3. Toppling Deformation Mechanism

Researches on deformation development trend of toppling slopes indicate that toppling deformation might stop developing if stress and strain make a balance, otherwise, toppling would eventually evolve into landslide. The process from toppling deformation to landslide can be divided into four stages\[5-7\]. The first stage is the initial toppling and cracking. In this stage, rocks dump to the free surface under the load of gravity, which results in the rupture of the rock and the tensile cracks in rock mass. The second stage is a strong toppling deformation, and the main features are intensified deformation and emergence of intermittent potential fracture surface. The third stage is the creep deformation, the main features are creep along the potential fracture surfaces, and toppling deformation further intensified with the possibility of local landslide. The fourth stage is the sliding failure of the slope, the main features are toppling deformation has been completed, and the fractures have been completely evolved into sliding surface, along which the entire slope would collapse.

From the perspective of geological conditions of the right bank slope in Miaowei hydropower station, the rock orientation was parallel to the excavation direction of the right dam foundation. The dam foundation excavation partially cut the bottom of the slope into steeper slope, and reduced the thickness of the lower rock supporting the upper toppling rock, so the slate rock at the bottom undertook compressive deformation from the gravity of the upper rock mass. Due to unfavorable rock orientation, unloading and relaxation of lower rock provided space for toppling deformation of upper rock, which leaded to intensified deformation throughout the slope and occurred newly toppling-tension deformation.

In summary, Unfavorable rock orientation, toppling and broken rock mass, and poor integrity are the basic factors for widely range of toppling deformation in the right bank slope, and excavation of dam foundation is the predisposing factor.

4. Reinforcement Measures of the Right Bank Slope

Due to the risk of entire landslide of the right bank slope, comprehensive rescue measures had to take into implementation. The prestressed anchorage was the main measure and drainage to be as auxiliary. In ensuring the safety of the conditions, reinforcement should be phased carried out from the top to the bottom. Specific measures were as follows:

(1) Sub-regional anchorage has been taken to reinforce the toppling slope under 1460m elevation in right bank slope(Figure 2). According to the order of reinforcement implementation and the corresponding geological conditions, six anchorage sub-regions had been divided and marked as I1, I2, II, III1, III2, and IV. 2000kN and 1500kN prestressed tendon of 40m and 50m length had been employed. To enhance the integrity of anchoring, external anchorage section of cable been connected each other with concrete frame beam. In order to adapt to the possible subsequent deformation of the slope, Prestressed tendon without bond was employed and lock-off load was 15% lack of design tension. Aiming at the slope rock mass under 1350m elevation mainly of soft slate, where stress usually is concentrated, prestressed tendon combined with concrete slab of 1m thick formed concrete anchor plate to strengthen the support effect.

(2) While prestressed anchoring, in order to reduce the pore pressure in the slope rock mass, systematic drainage holes were arranged on the slope. Within the slope above the normal water level of 1408m elevation, 10m and 20m length drainage holes were drilled, and within the water level change area between 1398m and 1408m elevation, 30m length drainage holes were employed to strengthen the drainage effect.

Reinforcement construction started from June, 2013, and completed by April, 2014.
5. Evaluation of Reinforcement in the Right Bank Slope

5.1. Stability Analysis under Reinforcement

As the general method, rigid body limit equilibrium method (LEM) was used to calculate the safety factor of slope. Considering that toppling slope has more complicated failure mechanism different from general slope in sliding mode [8,9], simultaneously, discrete element method (DEM), which is both suitable for large deformation and discontinuous deformation simulation, has been applied to analysis the stability of slope (Figure 3). LEM analysis indicated that, under the reinforcement, the safety factors of the right bank slope are respectively 1.39 in enduring condition, 1.317 in transient condition encountered rainstorm, and 1.228 in occasional conditions encountered by an earthquake. Meanwhile, DEM analysis indicated that the strength reduction factor of slope under reinforcement is 1.28, which is slightly smaller than result of LEM. Safety factors obtained by the two methods indicate that the slope is in a stable state, and the reinforcement measures are effective.

![Profile map of anchorage in the right bank slope.](image1)

**Figure 2.** Profile map of anchorage in the right bank slope.

![Analysis model of DEM of the slope.](image2)

**Figure 3.** Analysis model of DEM of the slope.
5.2. Monitoring Data Analysis

Combined with the reinforcement, monitoring program has been systematically arranged to provide guidance for reinforcement execution and to real-time assess stability of the slope, which mainly include: surface deformation monitoring, deep deformation monitoring such as multi-point displacement meter, and anchor structural force monitoring such as cable dynamometers.

![Displacement curve of surface displacement monitoring of R16.](image1)

Figure 4. Displacement curve of surface displacement monitoring of R16. R16 at 1466m elevation is the example for surface deformation monitoring of the slope. The largest accumulated deformation was 62.1mm, among them, the largest accumulated settlement deformation is 41.5mm. From Dec 6, 2013 to Mar 8, 2014, largest rate of deformation was 0.15mm/d, and 0.1mm/d in average, among them, the largest rate of settlement was 0.1mm/d, and 0.014mm/d in average. Figure 4 shows the displacement-time curve of surface displacement of R16, where, X indicates north, Y indicates east, and Z indicates downward.

![Monitoring curve of multi-point displacement meter M1.](image2)

Figure 5. Monitoring curve of multi-point displacement meter M1.

Multi-point displacement meter M1 at 1466m elevation is the example for deep deformation monitoring of the slope. From Dec 6, 2013 to Mar 8, 2014, the largest amount of displacement was 3.75mm, and average rate was 0.011mm/d. Figure 5 shows the displacement-time curve of M1.

![Load curve of anchor dynamometer D1.](image3)

Figure 6. Load curve of anchor dynamometer D1.
Cable dynamometer D1 at 1412m elevation is example for anchorage structural force monitoring of the slope. From Dec 6, 2013 to Mar 8, 2014, cable force was stable in the design range, and changed within -88.24kN~9.9kN, average rate of change was -10.2kN/d. Figure 6 shows the force-time curve of D1. Both surface and deep monitoring data are in convergent state, which indicates that the slope is in a stable state. Figure7 is the full view comparison of the right bank slope before and after the reinforcement.

![Figure 6: Force-time curve of D1](image1)

![Figure 7: Full view comparison of the right bank slope before and after the reinforcement](image2)

6. Conclusion

(1) Typical toppling slope widely exists in Miaowei hydropower station project. On the basis of on-site geological survey, according to the main characteristic indexes of toppling rock mass, the classification standard system has been established, in which, toppling rock mass has been divided into three classifications: extremely toppling class of A, highly toppling class of B (which includes upper B1 and lower B2), and weak toppling class of C.

(2) According to the research of the toppling deformation from appearance to landslide, the process is divided into four stages. And the factors of toppling in Miaowei are summarized as follow: unfavorable rock orientation, toppling and broken rock mass, and poor integrity are the basic factors for widely range toppling deformation of the right bank slope, and excavation of dam foundation is the predisposing factor. On the basis of detailed analysis of the toppling deformation characteristics and crack distribution of the right bank slope in Miaowei, the mechanism of the toppling and tensile deformation was revealed.

(3) Based on the analysis of geological conditions and deformation mechanism, comprehensive rescue measures were carried out to reinforce the right bank slope. Reinforcement measure was prestressed anchorage as mainly and drainage as auxiliary. Prestressed tendons combined with concrete frame beam were employed in six sub-regional of slope to provide anchoring force, and drainage holes were arranged to reduce the pore pressure in the slope rock mass. Reinforcement construction started from June, 2013, and completed by April, 2014.

(4) LEM and DEM were both implemented to stability analysis of the right bank slope under reinforcement, and the stability safety factor of the slope under various working conditions were obtained. Meanwhile, the surface and deep monitoring data from Dec 6, 2013 to Mar 8, 2014 have been in convergent state. Both stability analysis and monitoring results indicate that the slope is stable, and the reinforcement measures are effective.

(5) The study on the deformation failure mechanism of typical toppling slope and the successful practice of treatment in Miaowei hydropower station provide a constructive reference for similar complicated slopes.
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