Toppling deformation characteristics and mechanism of bank slope in Xiluodu Hydropower Station, China

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Abstract. Xiluodu Hydropower Station of the Jinsha River started impounding water in May 2013. In June 2013, five cracks occurred on the bank slope of the Xingguang village. By the end of 2019, the number of slope cracks has increased to 13. Based on the detailed field investigation, deformation monitoring, and drilling and adit investigation, the deformation characteristics of the Xingguang bank slope are studied. The results indicate that the Xingguang bank slope is a steep bedding toppling deformation, which is further intensified by the impoundment operation of the reservoir. Monitoring data show that the Xingguang bank slope does not deform toward the free direction, but inclines upstream, and the deformation gradually increases from the top to bottom. According to the change degree of slope surface displacement, the Xingguang bank slope can be divided in to four deformation areas in the plane: intensified strong deformation area, strong deformation area, moderate deformation area, and slight deformation area. Based on the deformation degree of the rock mass, the vertical section is divided into four deformation zones: intensified strong toppling deformation zone, strong toppling deformation zone, moderate toppling deformation zone, and slight toppling deformation zone. Further study reveals that the thin-layer rock mass structure is the material basis of the bank slope toppling deformation, the landform formed by the cutting of the Jinsha River Valley provides favorable boundary conditions for the toppling deformation, and the strong unloading rebound of the rock mass is the key factor of the bank slope toppling deformation.

1. Introduction
In Southwest Chine, numerous large-scale hydropower stations have been built owing to the unique geological conditions and water resources. The bank slope of these hydropower stations contains a lot of toppling deformation bodies. Thus, the water level fluctuation of the reservoir reduces the effective stress of the rock mass, resulting in the loss of bank slope stability, which may create high-speed surges and endanger the safety of the hydropower station.

Currently, scholars at home and abroad have made some achievements in the mechanism and evolution of the toppling deformation body. De Freitas M H et al. [1], in 1973, suggested toppling deformation to be a special type of slope deformation. Then, Goodman et al. [2] conducted a systematic study on the types of toppling deformation and adopted the limit equilibrium method to evaluate the stability of the anti-toppling rock slope for the first time. Subsequently, numerous scholars have started investing in the research of toppling deformation of the anti-toppling slope. Hsu et al. [3] analyzed the deformation and failure characteristics of the anti-inclined soft rock slope based on the discrete element method. They found the existence of signs of sliding and shear failure in the rock plate when it toppled. Australian scholar Adhikary [4], together with his colleagues, conducted a series of centrifuge tests to study the mechanism of the overturning and bending of brittle and flexible joint reverse slope. Goodman

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[5] was able to systematically and comprehensively summarize the toppling deformation characteristics of the reverse-dip slope. Moreover, he analyzed the differences between toppling deformation and the secondary toppling deformation, as well as the block toppling and the bending toppling, by conducting the base friction test. However, in the last 20 years, more large-scale hydropower projects and construction and water storage operation have been established. In the mountainous and canyon areas of Southwest and Northwest China, numerous toppling deformation phenomena have been observed in the slopes with the same inclination as the slope toe and steeper dip angle than the slope toe, with a failure depth of between 200 and 300 m [6]. These findings encouraged us to study the formation and evolution mechanism of the toppling deformation.

The Jinsha River is located in the Southeast of the Qinghai–Tibet Plateau. Affected by complex geological conditions and particular slope structure, the mechanism of these toppling deformation bodies is complex. In this paper, the deformation characteristics and mechanism of the Xingguang bank slope in Xiluodu Hydropower Station was studied. The results of this study can provide technical support and theoretical guidance for engineering construction and also enrich the research on the mechanism of the toppling deformation.

2. Geographical and geological setting
The Xingguang bank slope deformation body is located in Yongshan County, Yunnan Province, China, on the right bank of the Jinsha River, which is about 33 km away from the Xiluodu Hydropower Station dam site area (Figure 1a). The bank slope is about 1500 m long, with an elevation of 420–1400 m and a height difference of 980 m. The slope above 1360 m is a flat platform, and the slope below 1000–1360 m and 1000 m is 25°–30° and 40°–45°, respectively. The two sides of the bank slope are cut by two gullies, in a state of three sides facing the air (Figure 1b). The strike of strata (NNE) and the strike of the river valley (NE) are oblique, and the NNE and NE strike of the deformed body is obliquely intersected. The occurrence of normal rock stratum is N5°~20°W/SWZ65°~85°, which is a steep bedding slope. The rock dip angle greatly changes due to the influence of the bank slope rock toppling deformation, and the slope exhibits an evidently toppling deformation (Figure 1c).

Through field investigation and data analysis, it is found that the front edge of the bank slope is mainly composed of shale, mudstone, and argillaceous sandstone of the Hongshiya Formation of the Ordovician system (O1h), which are soft in nature. The middle and lower parts of the bank slope are mainly composed of dolomite, limestone, and dolomitic limestone of the Erdaoshui Formation of the Cambrian system (C3e), which are hard in nature. The middle part of the bank slope is mainly composed of argillaceous siltstone and silty mudstone of the Xiwangmiao Formation of the Cambrian system (C2X), which are soft in nature. The middle and upper parts of the bank slope are mainly composed of dolomite and limestone of the Cambrian system, which are hard in nature.
Figure 1. Xingguang bank slope location and engineering geological plan. **a** Xingguang bank slope location; **b** 3D model of the Xingguang bank slope; **c** engineering geological plan of the Xingguang bank slope
3. Toppling deformation characterization

3.1. Surface deformation characteristics

3.1.1. Tension crack.

The reservoir began impounding water in May 2013. Before the impoundment, five large-scale cracks were observed in the slope (Figure 2a). The distribution elevation of these fractures is between 1085 and 1255 m, and the fracture strike is between N15° and 30°E, which is basically consistent with the stratum strike. After the impoundment, the number of cracks increased to 13 (by the end of 2019). To some extent, the reservoir impoundment worsens the slope toppling deformation (Figure 2b).

3.1.2. GNSS deformation monitoring.

Analysis of landslide disaster requires continuous high-frequency surface displacement monitoring in numerous places related to landform. This problem can be effectively solved by a monitoring technology that is based on the global navigation satellite system (GNSS) [7]. After the impoundment of the Xiluodu Reservoir, 10 GNSS monitoring stations (Figure 1c) were installed on the bank slope. The plane displacement vector graph obtained from the monitoring data from June 15, 2014, to April 20, 2016, is presented in Figure 3. The monitoring results indicate that the main deformation area of the Xingguang bank slope is near the Taoerpo Valley and the lateral gully area of the mountain, all of which are in the gully. Moreover, the degree of deformation of the other areas is small. The Xingguang bank slope is not deformed toward the free direction, but inclined upstream, and the deformation gradually increases from the top to bottom.

3.1.3. InSAR deformation monitoring.

Monitoring of the deformation of landslides by using spaceborne synthetic aperture radar (SAR) is a mature technology [8]. The selected 31 scenes of Sentinel-1A from January 21, 2018 to December 30, 2019, were utilized for the analysis of the bank slope deformation. As presented in Figure 4, the deformation can be divided into four areas according to its speed: the red area indicates the intensified strong deformation area, with a deformation rate of about 120–143 mm/a; the orange area indicates the strong deformation area, with a deformation rate of about 100–120 mm/a; the yellow area indicates the moderate deformation area, with a deformation rate of about 50–120 mm/a; and the green area indicates the slight deformation area, with a deformation rate of about 0–50 mm/a. The laws reflected by the InSAR deformation monitoring are consistent with the results of the GNSS monitoring.
Figure 3. Displacement vector diagram of the GNSS monitoring station
3.2. Deep deformation characteristics

3.2.1 Deformation and failure characteristics of the rock mass.

The mechanical properties of various kinds of rock mass are different. This causes the rock mass to present different processes and results in the toppling deformation. According to the deformation characteristics of the rock mass in the adit, the deformed rock mass in the bank slope can be divided into three types: (1) toppling and falling, (2) toppling and bending, and (3) toppling and breaking.

(1) Toppling and falling. The toppling and falling deformation mainly occurs in the shallow part of the slope. The fracture phenomenon of the rock mass is evident, the internal tension fracture deformation of the rock mass is strong, and the partial or overall separation of the rock mass in the tension fracture zone occurs, as well as some displacement. Cavities are apparent in some parts, which fill the block stone and debris (Figure 5).

(2) Toppling and bending. Under the action of dead-weight bending moment, the cantilever beam bends toward the free direction, and the mutual dislocation between the thin layers in the rock mass further develops. This kind of deformation mainly developed in the soft rock stratum, such as argillaceous siltstone and mudstone, which are generally characterized by bending deformation without
discontinuous fracture. Although the dip angle of the rock stratum significantly changes, no discontinuity mutation occurs (Figure 6).

![Figure 6. Toppling and bending of the rock mass](image)

(3) Toppling and breaking. Under the action of great gravity bending moment, tension fracture occurs in the bending part, and the cantilever beam type fracture of transverse bending “beam plate” occurs. This forms the tension or tension shear fracture zone inclined to the outside of the slope, as well as the intermittent extension. Moreover, this causes the dip angle of the rock stratum to abruptly change. This kind of deformation mainly occurs in limestone, dolomite, and other hard rock layers (Figure 7).

![Figure 7. Toppling and breaking of the rock mass](image)

3.2.2 Vertical zoning of toppling deformation.
Some researchers have developed a standard classification scheme for the toppling intensity of a rock mass [9,10]. On the basis of some factors, such as the dip angle, maximum width of the opening crack, unloading intensity, weathering intensity, and speed of the elastic wave, these researchers classified toppling rock masses into four deformation grades. As can be seen from Table 1, the deformation of the Xingguang bank slope is divided into intensified strong toppling zone, strong toppling zone, moderate toppling zone, and slight toppling zone, according to the difference of the rock dip angle, deformation characteristics, and weathering degree. Figure 8 presents the typical geological engineering profile.

**Table 1. Index of the toppling deformation zone of the Xingguang bank slope**
4. Influencing factors of toppling deformation

4.1. Erosion of the Jinsha River
The influence of the Jinsha River erosion on the Xingguang bank slope is mainly manifested in two aspects:
(1) River erosion changes the stress field state of the slope, and the Xingguang bank slope is overturned and deformed under unloading. (2) River erosion provides favorable topographic conditions for bank slope toppling deformation, and the 3D free state provides good free conditions for the occurrence of toppling deformation.

4.2. Hardness difference in rock mass
The bank slope composed of the soft rock is easily eroded due to its low shear strength and creep deformation in the steep terrain. Conversely, the bank slope composed of hard rock exhibits high strength, and the primary deformation and failure is collapse. When the slope is composed of a combination of soft rock and hard rock, the hard rock can resist the weathering and denudation and keep the slope high and steep, whereas the soft rock can prevent the slope from forming through the structural plane. Thus, it is easy to develop a large-scale toppling deformation body. The soft and hard interbedded distribution on the Xingguang bank slope rock mass is conducive to the formation of the toppling deformation body.

4.3. Thin-bedded rock mass
In general, the thinner the rock layer, the more likely it is that the rock will fall in a free direction under the action of gravity bending moment. According to the field investigation and statistics, the starlight toppling deformation body is mainly composed of a thin-layer structure, and the thickness of the rock layer is between 5 and 20 cm, which is one of the critical factors for the toppling deformation.
5. Mechanism and evolution of toppling deformation

The formation and evolution of the toppling deformation body is divided into three stages, and the deformation mechanisms of each stage are presented as follows:

(1) Unloading deformation stage. During the Jinsha River excavation, the rock mass on the slope surface rebounded, and the stress field was greatly adjusted. The maximum principal stress at the front edge of the bank slope is basically parallel to the free surface of the bank slope. The stress released in the vertical direction, which reduces the rock mass, is confining pressure; and it causes the vertical rebound of the rock mass and the rock mass. The deformation enables the original near plane to relax to a certain extent, which results in the decrease in interlaminar shear strength. The stress redistribution results in the decrease in normal stress and the increase in tangential stress, eventually leading to the shear dislocation of the rock mass of the bank slope at the initial stage of toppling deformation.

(2) Time-dependent deformation stage. With the further cutting of the Jinsha River, the interlaminar dislocation deformation is further intensified. The rock mass at the foot of slope starts to bend toward the free face due to the strong compression of the upper rock mass. The deformation of the rock mass at the front of the bank slope provides the deformation space for the upper rock mass. Under the action of maximum principal stress parallel to the slope surface, the neutral soft rocks (such as argillaceous siltstone and shale) on the bank slope exhibit plastic deformation, demonstrating the toppling and bending phenomena. Due to the increasing shear along the weak rock zone, the tensile effect in the layer of the neutral hard rock (such as dolomite and limestone) on the bank slope should be gradually enhanced. When the tensile stress of the rock plate between the staggered planes exceeds its tensile strength, brittle deformation occurs in the rock mass, which results in tensile fracture in the layer and shear fracture in the cutting layer. Once the hard rock is toppled and broken, the local stress will be concentrated on the soft rock, which further worsens the toppling and bending of the soft rock. In this cycle, progressive deformation and bank slope failure occur.

(3) Catastrophic instability stage. Catastrophic instability stage. At the later stage of the toppling deformation, the bank slope collapse deformation further develops under good free conditions. With the intensified collapse bending deformation of soft rock, the soft rock changes from plastic deformation to brittle deformation, and the tensile fracture and shear fracture occur in the maximum bending position or the original structural plane position. The collapse and fracture deformation of the hard rock...
continuously extend to the depth and lower part. Finally, the bending part of the rock layer is connected, forming the intermittent tension fracture surface inclined to the outside of the slope. Under the action of the earthquake, rainfall, and long-term reservoir water, the broken section will be connected to form a unified sliding surface and landslide disaster.

6. Conclusion
(1) According to the monitoring data and field investigation, the starlight toppling body deformation is not the traditional deformation in the free direction but inclined upstream. Moreover, the deformation gradually increases from top to bottom.

(2) According to the slope surface and degree of deformation of the slope rock mass, the toppling deformation body can be divided into four deformation areas in the plane: intensified strong deformation area, strong deformation area, moderate deformation area, and slight deformation area. In space, it can be divided into four deformation zones: intensified strong toppling deformation zone, strong toppling deformation zone, moderate toppling deformation zone, and slight toppling deformation zone.

(3) The Xingguang bank slope is a thin layer of soft and hard rock mass, which is the material basis of the toppling deformation. The erosion landform of the Jinsha River provides a good condition for the toppling deformation; the strong unloading rebound is a significant factor affecting the deformation of the front of the Xingguang bank slope.

(4) There are three stages in the evolution process of the Xingguang bank slope deformation body: unloading deformation stage, time-dependent deformation stage, and catastrophic instability stage.

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