Failure Mechanisms and Mitigation Measures of the G1006 Electricity Pylon Landslide in the Dam Area of the Jinping I Hydropower Station

Y X Yang¹, G Luo¹, Y Y Duan², C Z Zhang¹, Y G Zhang³, and Q Lei¹
¹Department of Geological Engineering, Faculty of Geosciences and Environmental Engineering, Southwest Jiaotong University, Chengdu 611756, China.
²Department of Translation and Interpretation, School of Foreign Languages, Southwest Jiaotong University, Chengdu 611756, China.
³Guizhou Transportation Planning Survey and Design Academe Co. Ltd, Guiyang 550001, China.
Author e-mail: 1034377338@qq.com; corresponding author e-mail: luogang@swjtu.edu.cn

Abstract: On the 29th and 30th of August 2012, more than 100 geological disasters occurred near the dam area of Jinping I Hydropower Station, Xichang, China due to local intense rainstorm. The upper part of the left valley slope, which is 500 m upstream of the dam, failed and slid, exposing the C-pile of the G1006 electricity pylon and threatening the entire power transmission lines. Therefore, ensuring the stability of the residual rock masses in the rear of the main scarp and the safety of the G1006 electricity pylon became a primary emergency task. Field geological survey, topographic mapping, and the instability mechanism study of the G1006 electricity pylon landslide were conducted. Results revealed that the G1006 electricity pylon landslide (hereafter represented as the G1006 EPL) occurred in the middle block cut by two faults, and the rock masses had inferior mechanical properties. Intense unloading effects and frequent microseismic events during the dam construction relaxed the rock mass structural planes and reduced the geotechnical parameters. Under the influence of intense rainfall, the failure mechanisms of the slope were a combination of slope surface effect from rainfall and lateral erosion and undercutting of the slope toe by high flooding. The residual rock masses and landslide deposits around the pylon foundation were unstable under natural conditions and during the rainstorm. To prevent the continuous damage and exposure of C-pile foundation and ensure the stability of pylon foundation, the mitigation measure of “retaining piles + platform + retaining wall” was arranged. Moreover, a check dam was added to stabilize the slope toe and prevent the landslide deposits, which are the starting material source of debris flow that threatens the safety of the arch dam.

Keywords: Flood-erosion landslide; Jinping I Hydropower Station; Failure mechanisms; Slope stability; Mitigation measures

1. Introduction
Jinping I Hydropower Station is located in Muli County, Xichang City and on the west side of the Jinping River Bay, which is in the midstream of Yalong River [1,2] (Figures 1a–c). This hydropower station is a Chinese landmark engineering of the strategy of “West-to-East Power Transmission Project.” Given the complex regional geological process and various engineering geological problems...
in the excavation process, the dam area becomes an important research site for geologists and geophysicists. So far, engineering geological problems, such as high geo-stresses [2,3,4], deep cracks [5,6,7], microseism events during excavation [8,9], dam abutment slope stability [10,11,12], and underground cavern deformation and failure [13,14,15], have been studied.

However, little research has been conducted on the shallow failure of the anti-dip rock slope of the Jinping I Hydropower Station. Once the slope destabilizes, millions of cubic meters of materials enter the reservoir area, thereby threatening the safety of the dam. According to the geomorphologic map, the upstream slope has shown the precursors of instability (Figure 1d).

The G1006 electricity pylon is located at the left valley slope, approximately 500 m upstream of the arch dam and 300 m above the riverbed. The safety of the pylon is significant for power transmission (Figure 1d), and it is an integral part of the 500 kV Electricity Power Transmission Lines Project between the Jinping I Hydropower Station and the Xichang Converter Station. (The distance between the two stations is 72 km.) From August 29th to 30th, 2012, more than 100 geological disasters occurred in the Jinping River Bay Basin due to the “8.30” local intense rainstorm. These disasters caused severe damage to infrastructure, such as roads, communication, and electric power in and out of the construction area [16]. The shallow slope of the G1006 electricity pylon also suffered from local slid, which resulted in the exposure of the C-pile of the pylon foundation. If the pylon topples, then the whole transmission lines paralyze (Figure 1e) and thus result in the direct economic loss of 10 million RMB and a potential economic loss of 50 million RMB.

From October 2012 to November 2013, entrusted by China Power Engineering Consulting (Group) Corporation, we successively conducted detailed failure mechanism investigation and emergency disaster reduction. According to the field investigation and research, the G1006 EPL is a shallow strongly weathered bedrock landslide of anti-dip layered rock slope. The geological and environmental backgrounds, failure mechanisms, and mitigation measures are discussed, which can provide reference for similar events in the future.
Figure 1. Geographic location and topographic features of the G1006 EPL. (a) Latitude and longitude region of the G1006, (b) Sichuan Province and Yalong River, (c) Topography of Jinping River Bay (top view), (d) Jinping I Hydropower Station and valley topography, (e) The G1006 EPL (overall view)

2. Background of the Research Area
The research area is located in the “Sichuan-Yunnan rhombus fault block” enclosed by Xianshuihe fault, Anninghe river fault, Zemuhe-Xiaojiang fault, and Jinshajiang-Honghe fault (Figure 2). According to the Chinese National Seismological Bureau and National Seismic Standardization Technical Committee (2015), the seismic intensity in the area is VII, and the peak ground acceleration is 104.3 gal with a response spectrum period of 0.45 s. Moreover, from 1944 to the present, no $M_s \geq 6$ earthquake has occurred; therefore, the research area is classified as a structural stability zone [10,17]. The G1006 EPL, with a front edge elevation of 2065 m and a rear edge elevation of 2175 m, occurred on the steep thin ridge cut by faults F5 and F8 (Figures 1d and 3). The strata consist of metasandstone and silty slate of the Triassic Zagunao Formation ($T_2\beta_3$). The strike of strata is roughly the same as that of the river [1,2,5,10] with the occurrence of $356^\circ \pm 56^\circ$. Two sets of joints exist with the occurrence of $75^\circ \pm 55^\circ$ and $210^\circ \pm 70^\circ$ [10,11,17]. In this study, four cross sections are arranged to assess the stability (Figure 4a).

Figure 2. Historical nearby earthquakes in the dam area (modified after Qi et al. 2004)

Figure 3. Geological plane map of the dam area (modified after Qi et al. 2004)
Figure 4. Engineering geological plane map and the basic features of the G1006 EPL. (a) Engineering geological plane map, (b) feature of the source zone, (c) feature of the deposition zone, (d) feature of the gully

3. Basic Features of the G1006 EPL
The exposed bedrock in the source zone plus the strong weathering and unloading effect cause the cata-clastic structure of the rock masses (Figures 4b and 5b). The main scarp after the landslide may further destabilize after the retrogressive erosion of the rainfall. Some landslide deposits are distributed on the deposition zone, with small gravels, block gravels, and boulders accounting for 33%, 44%, and 23% of the total, respectively (Figures 4c and 5c). Some landslide deposits enter into the downstream of the gully due to flood or dynamic factors (Figures 4d and 5d). In general, landslides are usually the dominant mechanism for conveying large amounts of debris to gullies [18,19]. Under the action of intense rainfalls and gully floods, these landslide deposits may serve as the starting material sources of the debris flow and form the debris flow wash in the dam area.
4. Failure Mechanisms

The structures of fragmentation, plate fracture, and inlay rock masses are the potential causes of the G1006 EPL. The inferior mechanical properties are mainly caused by microseismic events and intense weathering and unloading effects. Strong unloading effects urge shallow rock masses to produce tension cracks. The construction of pile foundations results in the formation of unfavorable interfaces between C-pile and ambient rock masses. From June 2009 to May 2011, more than 1,125 microseism events occurred, and the microseism events of high moment magnitude and high energy were mainly distributed in the dam abutment area at the footwall of F5 and F8 faults [9]. The G1006 electricity pylon is located on a thin ridge in the middle slope where the acceleration amplification effect is more significant, and the dynamic response of the reverse slope is stronger than that of the bedding slope [20,21]. Continuous microseism events aggravate the tensile strain of interfaces and cracks.

According to the data of the field mechanics tests, the cohesion of structural plane and sandy slate is 0.1 and 0.3 MPa, respectively; their corresponding internal friction coefficients are 0.45 (internal friction angle of 24°) and 0.65 (internal friction angle of 33°). Moreover, the longitudinal wave velocity of rock masses is 2,000–3,000 m/s, and the deformation modulus is only 2–4 GPa. However, the maximum cohesion of fresh sandstone structural plane and sandy slate is 1.40 and 4.4 MPa, respectively; their corresponding internal friction coefficients are 0.70 (internal friction angle 35°) and 1.35 (internal friction angle 53.5°). The maximum P-wave velocities of metasandstone and slate are 6,500 m/s and 6,000 m/s, respectively; the deformation modulus reaches 30 GPa. The maximum normal load of rock mass is 10 MPa, whereas the maximum normal load of weak structural plane is 5.6 MPa.

The flash flood triggered by the “8.30” local intense rainstorm formed high flood, which intensely eroded and damaged the G1006 electricity pylon slope toe—the trigger factor of the landslide. Under the influence of local intense rainstorm, the failure mechanisms of the slope were a combination of slope surface effect from rainfall and lateral erosion and undercutting of the slope toe by high flooding. Considerable research and statistics indicate that short-term intense rainfall and long-term preceded rainfall are two important triggers for shallow landslides [22,23]. So far, the failure mechanism of rainfall-induced landslides is revealed to be based on several viewpoints, such as the hydraulic characteristics of source masses [24], variation of groundwater pressure [25,26,27,28], negative and
positive pore water pressures [29], matric suction [30,31], ground water-level fluctuation [32,33], seepage variation [34,35], effect of initial soil moisture on the increase of pore water pressures [36], and basal erosion by the ingress water [37,38,39]. Moreover, under the condition of rainfall with similar durations and total amounts, the early high rainfall peak intensity and relatively uniform rainfall low peak intensities exert stronger destabilizing effects than the delayed rainfall peak intensity [40]. According to the precipitation data in August (Figure 6), the rainfall peak intensity mainly occurs in the early and middle stages, which is in line with the view of Fan et al.

Figure 6. August data of rainfall in the Muli County and Yanyuan County

However, note that this area belongs to a subtropical monsoon climate area, and the rainy season is from May to October, with rainfall accounting for 90% in the whole year. Specifically, from June to September, local strong convective storms with rainfall sometimes occur more than 30 mm/h. Therefore, this kind of storm is considered a key factor of residual diluvial, pluvial, and colluvial soil movements and flash floods. According to the data of Xichang Meteorological Station, the annual average precipitation in this area is 1000.4 mm; the maximum daily precipitation is 135.7 mm; the maximum hourly precipitation is 30 mm; the maximum 10-minute precipitation is 15 mm. However, Figure 6 illustrates the daily average of regional rainfall about Muli County and Yanyuan County in August. Moreover, the rainfall, which occurred on August 29 and 30, was low and in the normal range of fluctuation. Undeniably, the temporal and spatial distribution of precipitation in mountainous areas is uneven. Given that no rainfall monitoring station exists at Jinping I Hydropower Station, based on the announcement of the Ministry of Land and Resources, the rainfall on August 29 and 30, 2012 was a once-in-a-century occurrence. In addition, the flood caused by rainstorm inundated the G1006 electricity pylon slope toe within a short time.

Compared with stable nearby slopes with the same material composition but steep topography, the intense rainfall does not seem to be a decisive factor (Figure 1d). It is mainly related to the geotechnical properties of the slope. Soil slope is prone to instability under the condition of the rainfall [41,42], which is determined by the properties of soil particles. However, G1006 slope is an anti-dip rock slope. Under the influence of complex geological process and unloading effect, the soft rock strata are deformed, and the hard rock strata are broken. Unloading fractures, rock joints, and interlaminar dislocation faults widely exist even in intensely weathered rock masses. The rainfall cannot be retained in shallow rock masses to form additional fissure water pressure. Although the rock
masses have a mosaic structure and high weathering degree, intense rainfall does not change their stress environment; therefore, the situation cannot lead to the failure of shallow slope, which is why no large area of slope instability exists before the formation of gully flood.

GeoStudio is a numerical simulation software based on limit equilibrium theory. It is widely used in geotechnical engineering and has high credibility. The original topography of G1006 electricity pylon slope is simulated using the geotechnical mechanical parameters in Table 1. The result shows that the stability coefficient is greater than 1.0 and is stable under natural conditions and during rainstorms (Figure 7). Thus, the steep slope topography (approximately 53°), intensely weathered rock masses, and intense rainfall cannot be decisive factors.

Table 1. Physical and mechanical parameters of rock and soil masses

| Parameters of source masses | Dry or wet | Density (kgm⁻³) | Cohesion (kPa) | Internal frictional angle (°) | Elastic modulus (MPa) | Poisson’s ratio |
|----------------------------|-----------|-----------------|----------------|-----------------------------|----------------------|----------------|
| Natural state Soil         | D         | 2120            | 30.0           | 32.0                        | 25                   | 0.35           |
| Rainfall state Soil        | W         | 2280            | 22.0           | 27.0                        | 11                   | 0.37           |
| Natural state Strongly weathered rock masses | D | 2520 | 200.0 | 37.0 | 2300 | 0.25 |
| Rainfall state Strongly weathered rock masses | W | 2680 | 130.0 | 31.0 | 2300 | 0.25 |
| Natural state Landslide deposits | D | 2320 | 0.0 | 28.0 | 1300 | 0.28 |
| Rainfall state Landslide deposits | W | 2420 | 0.0 | 25.0 | 1100 | 0.30 |

When the high flood generated by “8.30” local intense rainstorm flows into the gully, it can cause intense lateral erosion and damage to the slope toe and gully bed. The sharp changing position of inclination and gradient of the gully bed, such as concave bank and cascade, can be an area prone to landslides under the superimposed condition [43]. The rock masses at the turn (the strike changes from 315° to 290°, and the deflection angle is 25°) of the long gully are sharply scoured by the upstream flow. When the gradient of the sharp turn suddenly decreases from 34° to 12°, the flood produces the erosive turbulence in the gully and impulse the erosion. Therefore, the slope toe is severely affected by the lateral erosion and scouring of the flood (Figures 3a and 8). The failure of the slope toe makes the front edge of the slope lose support and form collapse, which produces a chain effect. The collapse develops upward, and then develops into a landslide. From the movement form of the landslide, G1006 EPL belongs to the traction landslide.
Figure 7. Stability of the original G1006 slope under different conditions before sliding (3-3' cross section). (a) In the natural state, the strongly weathered bedrock is taken as the slip surface. (b) In the natural state, the colluvium is taken as the slip surface. (c) In the rainfall state, the colluvium is taken as the slip surface. (d) In the rainfall state, the strongly weathered bedrock is taken as the slip surface.

Figure 8. DEM of the G1006 EPL
5. Mitigation and Control Countermeasures

The mitigation policy is “zonal prevention.” The mitigation measure of source zone is “initiative protective systems,” whereas that of the zone around the C-pile is “retaining piles + platform + retaining wall.” The check dam is adopted at the downstream boundary of the deposition zone to compress and consolidate the source materials (Figure 9).

The bedrock on the upper left slope of the source zone is exposed, whereas the unloading cracks in the bedrock are common. The phenomenon of weathering, disintegration, and block falling can also be found everywhere. Some red blocks may collapse and ravel, which may lead to further destabilization. Therefore, the initiative protective systems (short bolts + flexible protective net) are arranged in this area to prevent rock blocks from falling and to ensure the safety of temporary construction and permanent protection of slope.

For the mitigation measures of the lower right slope of the source zone, we can have a variety of options. According to the scale and stability of the landslides, mitigation measures have many kinds, such as anchor rod (cable), retaining piles, retaining wall, and anchor rod (cable) frame beam [44]. However, based on the anchorage failure [45,46,47], especially under the condition of slope erosion from rainfall and water and soil loss, a mitigation measure of “retaining piles + platform + retaining wall” is eventually adopted at the lower right slope of the source zone. The retaining piles can maintain the stability of the upper slope, but steep slope and weak rock are unsuitable for retaining wall foundation. Therefore, a platform is built on the pile foundations by longitudinal rebars, and the 8 m inclined retaining wall is set on the platform (Figure 10). They are all poured with C30 concrete. Two rows of retaining piles (seven piles in the back row and eight piles in the front row) are arranged outside the G1006 pylon foundation. The length of piles in the front row is 10 m, with an anchoring section of 5 m; the length of piles in the back row is 6 m, with an anchoring section of 6 m. The center distance between the two adjacent piles is 5 m, and the section size is 1.0 × 1.0 m. The lengths of the front and back parts of the platform are 36 and 31 m, respectively; whereas the width is 5.5 m. The retaining piles maintain the stability of the slope around the C-pile, whereas the platform has the function of “umbrella,” which prevents the soil erosion of the slope around the retaining piles, and the retaining wall protects the safety of the C-pile. Although the cost is high, and the construction is complicated, the G1006 electricity pylon is still worthy of application, considering the economic benefits of its long-term safety.
Figure 9. Mitigation measures of the G1006 EPL

To prevent the debris flow formed by the mixture of the landslide deposits and the flood under the condition of rainstorms, a check dam is set to compress and consolidate these landslide deposits in the gully (Figure 11). The check dam is designed according to the frequency of debris flow formed by a 20-year rainstorm and checked by a 50-year rainstorm. The specific design is to build a check dam at the downstream boundary of the gully at the front edge of the landslide and pour the dam with C20 rubble concrete. The dam is 21.8 m in top length, 7.0 m in bottom length, and 10.0 m in effective height. The top width of the dam is 2.0 m, and the bottom width is 8.6 m. The upstream and downstream slopes are 1:0.6 and 1:0.05, respectively. The dam foundation is embedded in the bedrock with the buried depth of 1 m. The top of the dam is provided with an overflow port with a width of 8.0 m and a depth of 1.0 m. Moreover, four rows of drain holes are arranged in the dam body.

Figure 10. Mitigation measures of “retaining piles + platform + retaining wall” are adopted in the zone around the C-pile (4-4’ cross section)
6. Discussion

Many large hydropower stations and corresponding transmission pylons have already been located in southwest China, and more of them will be found in the future. The timely provision of electricity supply to outward regions is critical for the successful completion of the hydropower station. Therefore, the safety of the electricity pylon is particularly important. Previous engineering experiences have indicated that stable ridges are highly suitable for the foundation of electricity pylons. However, various combinations of geological phenomena can trigger large-scale landslides in such mountainous regions. These combinations include strong unloading effects, complex characteristics of rock and soil masses, rapid crustal uplift, unremitting river incision, and unique hydrological conditions [48]. Therefore, exploring failure mechanisms and mitigation measures is particularly important. The G1006 electricity pylon has been relocated as an emergency measure, but the arrangement of mitigation measures is unaffected. The investigation of the G1006 EPL provides a valuable engineering lesson, from which the following discussions and conclusions can be acquired:

1. Risk evaluation should be conducted prior to electricity pylon construction, considering shallow accumulation landslides or debris flows that may result from blasting vibrations and lateral erosions. Fissures and cracks must be sealed at all costs to prevent the infiltration of surface water into the pylon region. Advanced reinforcement for the interfaces among the deposits, bedrock, and slope toe of the pylon foundation slope should be performed before the excavation of the electricity pylon foundation.

2. During periods of flooding, turbulence flow and lateral erosion are produced at the sharp changing position of the strike direction and the gradient of narrow, deep-incised gullies. These factors can potentially destabilize shallow deposits. Johnson and Rodine (1984) described the phenomenon as the “fire hose effect.” Therefore, the stability of shallow deposits under flood conditions should be carefully evaluated, keeping in mind the potential effects of saturation and erosion.

3. The assumption is made that lateral erosion by flooding or runoff significantly affects the stability of the bank slope. Henceforward, calculation models, which consider erosion rates at different flow velocities and water levels and corresponding modeling experiments, should regard the topography variation of gullies as a topic of further research.
7. Conclusion
The G1006 EPL is a shallow strongly weathered bedrock traction landslide, which threatens the safety of the entire transmission networks. The steep interface between the deposits and the bedrock, continuous vibrations from blasting, and intense rainfall are key causes of the landslide. Significantly, the superimposed effect of slope surface, which is induced by long-term precipitation and lateral flood erosion in the gully converged from a short-period runoff, can be a crucial trigger on the landslide occurrence.

A sharp bend in deep-incised gullies where the gully bed gradient vertically reduces from 34° to 12° and the strike that horizontally deflects from 315° to 290°, can produce turbulence flow locally. Therefore, similar topographical effects can intensify lateral erosion from short-term flooding and destabilize the electricity pylon slope. To avoid similar landslides, the advanced reinforcement of unfavorable structural planes should be implemented when selecting sites for the construction of electricity pylons in alpine valleys. Advanced reinforcement must also be implemented at the slope toe.

Mitigation and control countermeasures should be considered for different zones of the landslide. Weathering and erosion should be prevented primarily in the main scarp. Mitigation measures must be arranged to control the downward movement of landslide deposits, especially the transformation from landslide deposits to debris flows.

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