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Failure Mode and Stability of a Landslide under Water Level Fluctuation

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ABSTRACT

The failure mode and mechanism of a landslide are vital to landslide reinforcement design. The Tanjiawan landslide was used as an example to investigate into the failure mode and mechanism of the landslides in the Three Gorges Dam Reservoir, China. The structure of the landslide was analyzed through a lot of field investigations. Moreover, the failure mode of the landslide was studied with the data obtained by an integrated monitoring system, including GPS monitoring, extensometer and inclinometer monitoring. Finally, the stability of the landslide was evaluated with the rigid-body limit equilibrium method. It can be concluded that the landslide is a pushing landslide containing two main sub-landslides. The deformation of the Tanjiawan landslide develops from back to front relative to the Yangtze River. And the failure of this landslide is caused by the coupled actions of the rainfall and water fluctuation. The inclusions reported in this paper provide some useful suggest for the stability analysis and control structure design of landslides with a similar slope structure in the Three Gorges Reservoir region.

KEYWORDS: reservoir landslide; slope structure; failure mode; stability; monitoring system;

INTRODUCTION

Three Gorges Dam on the Yangtze River is the largest hydro-electricity project in the world[1-4]. The project was finished in 2009. The maximum daily electricity power could reach as much as 4.3 kilowatt-hours. The Dam site is located in Sandouping village, Zigui County, Hubei Province. The highest water level is 175m in elevation and the reservoir reaches at Chongqing Municipality upstream, the whole length is more than 660 km[5-10].

Since the first impoundment of the reservoir in 2003, about 525 landslides occurred, and another 5386 potential landslides are possible to occur due to the water level changing. The landslide and the consequent pulse wave have been a huge threat to the dam and the people living in the reservoir area. Several cities such as Badong, Wushan and Yunyang et al. has been relocated to new places because the slope where the city was located before deforms severely, and more than 100 thousand people have been transferred. The Qianjiangping landslide, situated in Shazhenxi Town, Zigui County at the bank of Qinggan River, a tributary of the Yangtze River, occurred at the beginning of impoundment in 2003. Although a landslide warning was noticed and the most of the people lived on the failed slope was transferred, houses on the slope was ruined and the asset value of Shaxi Town was reduced by 40%. The boats in the river were damaged and 24 persons were killed.

Therefore, it is very important and urgent to study the deformation characteristics and model of the slope in Three Gorges Dam, which is the premise to forecast the landslide occurrence. In this paper, the Tanjiawan landslide in Badong County was chosen, its deformation characteristics were analyzed through field investigation, exploration and monitoring, the deformation model and mechanism were studied. The conclusions are of use for landslide forecasting and prevention in Three Gorges Reservoir area and other parts of world having the similar geological settings[11-16].

FEATURES OF TANJIAWAN LANDSLIDE

Tanjiawan landslide is situated at the left bank of Yangtze River, Dongxiangkou village, Maoping Town, Zigui County, Hubei Province. The sliding direction of the landslide is 215°. The landslide distributes between 145m and 350m in elevation, vertical height of the landslide is 205 m (Figure 1). The average angle of the slope is about 35°. The plane of the landslide is a rectangular shape, the length is 423 m, the width is between 60 m and 125 m, the average thickness of the sliding mass is about 25m. The landslide is about 100.4×10^4 m^3 in volume.

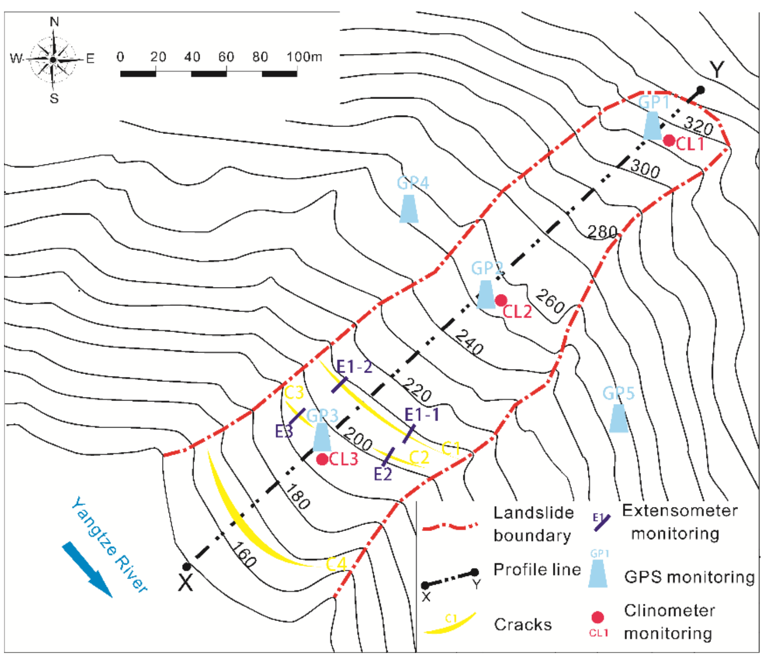

Figure 1. Plane of the Tanjiawan landslide and location of monitoring works

37 families about 137 people lived on the Tanjiawan landslide, Bazi highroad (from Badong County to Zigui County), one of the main highroads in Badong County, traverses across the landslide. The failure of Tanjiawan landslide is a huge threat for the people and highroad on it.

Through field investigation and exploration, the landslide structure was analyzed. The result suggests that the failure occurred along the contact surface between the superficial deposits and the bedrock. The geological units mainly contain superficial deposits, sliding zone soil and bedrock.

The superficial deposits mainly contain three parts: arable soil at the surface, colluvial deposit in the middle and residual deposit at the bottom of the sliding mass. The arable soil is between 1 and 2 m in thickness. Some non-irrigated fields distribute on the landslide, which are the main income of people living on the landslide. The colluvial deposit is between 5 m and 10 m in thickness and isabelline in color. It is in a loose state. The composition is gravel soil. The gravels are the weathered quartz sandstone and argillaceous siltstone, which are also the composition of the bedrock. The gravels are mainly between 0.2 m and 2 m in diameter. The content of gravels could reach as much as about 60% in weight. The residual deposit at the bottom of the sliding mass, is between 10m and 15m in thickness and fuchsia in color. It is also the gravel soil in composition, while the diameter of the gravels is between 0.1m and 0.5m, much smaller than that in the colluvial deposit. An exploratory trench was dug to investigate the composition of the sliding mass, from the trench, the boundary between colluvial and residual deposits is clear.

The sliding zone is between the superficial deposit and the bed rock. From the drilling data, the thickness of the sliding zone soil varies mainly between 10cm and 20cm. The composition is mainly the silty clay and small gravels, diameter of which is smaller than 1cm. The composition of the gravels is quartz sandstone and argillaceous sandstone, which are also the weathered bedrock. The content of silty clay could reach as much as 90%.

The bedrock mainly consists of fuchsia argillaceous siltstone of Badong Formation of Triassic period. It is the monoclinal stratum, the dip direction is 20°, which is reverse to the dip direction of the slope and sliding direction of the landslide. The dip angle is 16°. Stata of Badong Form is called one of the “easiest sliding strata” (which means that landslide occurs most frequently) in China due to its special geological settings and weak strength, while in Tanjiawan landslide, the bedrock did not fail.

DEFORMATION CHARACTERISTICS

Crack Distribution

The investigation of crack distribution and monitoring on deformation were conducted to analyze the deformation characteristics of Tanjiawan landslide.There are mainly four large cracks in the slope, they are numbered as C1, C2, C3 and C4 from the front to the back. They distributes in the front and middle part of the sliding mass, between 175 m and 210 m in elevation, which suggests that the deformation mainly occurred in the front and middle part of the slope.

The Crack C1 was first found in Mar., 2010, the initial length was about 7m and width was between 5mm and 10mm. The extension direction is approximately parallel to the river and perpendicular to the sliding direction of the landslide. The monitoring on the Crack C1 was conducted from Apr. 1 to Dec. 3, 2011. The result shows the deformation of the crack increased rapidly as the rainfall reached more than 20 mm,

The Crack C2 was first found in Jun. 18, 2011after a heavy rain, the initial length was 150 m, the width was between 10 mm and 65 mm, the visible depth was about 370 mm, and has completely gone across both lateral sides of the landslide. After Jun. 24, 2011, the depth of crack C2 increased to 100 mm and visible depth increased to 700 mm. The monitoring on Crack C2 was conducted on Jun. 25, 2011.

Monitoring of on the slope

Clinometer monitoring

Clinometer monitoring and GPS monitoring were conducted analyze the deformation distribution of Tanjiawan landslide. Three Clinometers were installed in the slope, they are located at 170m, 200m and 210m in elevation and along the line of section X-Y. They are numbered as Clinometer 1, 2 and 3 respectively from the front to the back. The details of the clinometers are shown in Table 1. The data of each clinometer are decomposed along two directions, which are labeled as A and B. The directions of A (SW215^0) and B (SE125^0) are along and perpendicular to the major sliding direction, respectively.

Table 1: Elevation and depth of the clinometers, depth of the slip band.

Clinometer No.	Elevation/(m)	Depth/(m)	Depth of the slip band/(m)
B1	318.18	31.1	22.6
B2	251.96	55.3	34.9
B3	195.68	39.4	26.5

The deformation of Tanjiawan landslide was first found in 2007, obvious deformation appeared at the front part of the landslide. Therefore, on Jan. 9, 2008, Clinometer 1 was installed at the front part to monitor the displacement. It suggests that the deformation occurred severely at 7m in depth, where the deformation reached as much as 8.5cm on May 11, 2009. On Jun. 9, 2011, the detector of the Clinometer cannot be put into the monitoring hole and the Clinometer could not work anymore, which means that the deformation at the location was too large to be monitored with clinometer. While the depth of the sliding mass in the location is about 30m, therefore, the deformation just occurred at the surface layer of the landslide.

In order to monitor the deformation at the middle and back of the landslide, clinometers 2 and 3 were installed on Dec. 10, 2010. The result suggests that the deformation at the middle and back of the landslide is not obvious.

GPS monitoring

Mainly 5 GPS monitoring points were conducted from Mar., 2007 to Dec., 2011. Two reference stations were located in the stable areas: GP4 at the west of the landslide, at a height of 270 m, and GP5 on the east side, at a height of 260 m. Three monitoring points (GP1 to GP3) were approximately situated along the main sliding direction between the reference stations (see Figure. 1). GP1 was situated at the head of the landslide; GP2 and GP3 were located at the middle and the front part of the slope, respectively. The data were obtained once per month. The frequency increased only in the rain season.

The data observed by GPS have shown a rather nonuniform movement of the whole landslide. In other words, the displacements in the front zones of the slope change a lot, but those in other zones change little. The total landslide movements were 12.0 mm at the head and 5.3 mm in the middle part, while the accumulated displacement in the front zone was up to 886.8 mm. Fig.2 illustrates the correlation between the landslide movements and water fluctuation. The top plot shows accumulated landslide movements measured at the three GPS benchmarks. The bottom plot illustrates reservoir water level recorded in the capital of Badong County, about 5.3 km west of the landslide site. There were four significant rapid slides at the front of the landslide, which coincided with abruptly falling of water level. The average sliding rates of the front zones were 0.057 mm/d, 0.054 mm/d, 0.178 mm/d, and 0.144 mm/d during the falling of the reservoir level and were 1.193 mm/d, 5.320 mm/d, 9.617 mm/d, and 10.533 mm/d shortly after the descent of the water table.

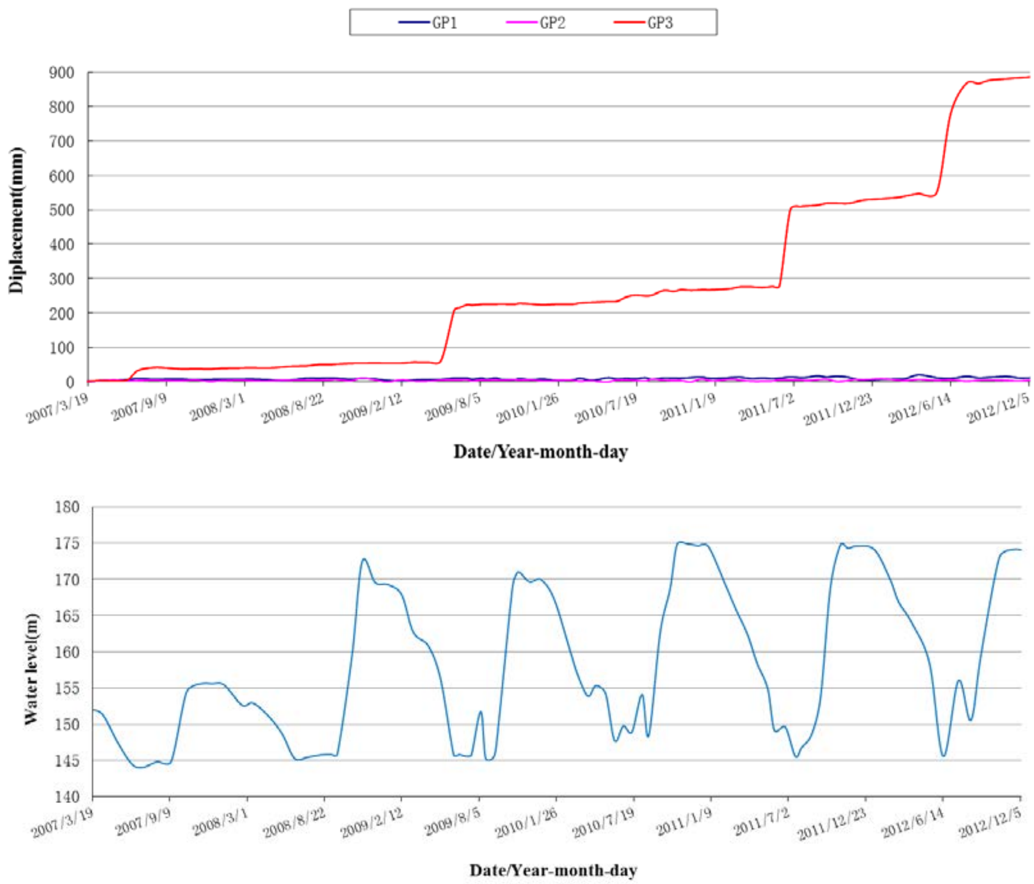

Figure 2. Monitoring result of GPS and records of the reservoir level

CONCLUSIONS

Field investigations were conducted to determine the structure of the Tanjiawan landslide. An integrated monitoring system, including extensometers, GPS stations, and inclinometers, was used to monitor the cracks, surface displacement, and internal displacement. Using the results obtained, it was possible to analyze the deformation characteristics and failure mode of the landslide. Finally, an evaluation of the risk from a water surge was conducted by calculating the maximum wave height that could propagate to the opposite side of the river.

1. The Tanjiawan landslide is a multi-rotational landslide that contains three rotational sub-landslides. Deformation and failure have developed progressively from the front part to the back parts. At present, the failure has reached the middle part, and further failure will occur if the landslide is not reinforced.

2. The coupled actions of the rainfall and the reservoir water are considered to be the reasons for the deformation and failure of the Tanjiawan landslide. However, more detailed and quantitative

works are needed to quantify the failure mechanism and the exact influences of rainfall and the reservoir water.

3. The authors suggest that people living on the landslide and the opposite side of the river at elevations from 185 to 190.7 m should be temporarily evacuated to a safe place before the sliding body of the Tanjiawan landslide is reinforced in order to reduce the risk from a water surge, and the Bazi highroad should be closed to ensure the safety of the people who are currently transiting the landslide.

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