A Multiple Method of Monitoring for Rainfall Induced Landslide

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Abstract. Landslide induced by rainfall is very common in the world, which seriously threatens the safety and construction. Taking the landslide on the right bank of the Xiajiang Water Control Project as an example, this paper carried out comprehensive monitoring of groundwater level, earth pressure, and surface deformation of the landslide analyzed the landslide formation mechanism and predicted the stability of the landslide. The results show that the rainfall infiltration caused fluctuations in the groundwater level of the slope, which caused the instability of liquefaction in the shallow surface layer, fluctuations in the reservoir reduced the stability of the slope. Groundwater activity between the bedrock and the soil-rock mixture controls the slope stability to a large extent. Based on the comprehensive impact analysis of these triggering events, it is considered that the slope is undergoing continuous deformation and needs to be landslide management.

1. Introduction

Rainfall induced landslides are geological phenomena in which the slope’s cohesion decreases and the weight of the rock and soil increases, when the sliding force is greater than the anti-sliding force, the downward movement of the shallow rock and soil will eventually develop to deformation and failure. Landslides induced by rainfall are highly concealed, have complex mechanisms, are highly sudden, and cause great harm. For example: In December 2018, 35 people were killed by the West Java Sirnaresmi landslide in Indonesia; in April 2017, 316 people died in Mocoa, Colombia, and 103 people were missing; in September 2016, 28 people died in the Su village landslide, Suichang, Zhejiang province, China; In May 2015 a rainfall induced landslide occurred in the granite area of Ganzhou, Jiangxi Province, killing 8 people. Therefore, monitoring and early warning of these rainfall-induced landslides is of great significance [1].

The research on landslide monitoring and forecasting has mainly gone through three stages: using empirical-statistical forecasting, displacement-time statistical analysis and forecasting, comprehensive forecasting model and forecasting criteria. Frattini P (2009) has been used the empirical statistical model to defining thresholds and forecasting the rainfall induced landslide [2]. Bozzano et al (2014) have been used the field experiment for calibrating landslide time-of-failure prediction functions, and they found that events occurring on slopes modified by human interventions could be effectively predicted using the Voight function if suitable parameters are used [3]. Wang F (2013) established a
comprehensive model of phreatic surface prediction based on GM (Grey model) and SVM (Support Vector machine).

Landslide forecasting is not only a pure method. To achieve accurate forecasting, the analysis of the slope deformation failure mechanism must be combined with quantitative forecasting. Factors closely related to landslides must be studied and analyzed. Therefore, people have begun to attach importance to the research of macro-precursors and macro-criteria of landslides and start to explore the landslide prediction from the analysis of physical phenomena and physical models [4].

The slope on the right bank of the Xiajiang River is a loose accumulation landslide with a volume of 3 million cubic meters. It is located on the right bank of the dam of the Xiajiang Water Conservancy Project in Jiangxi Province, China. The slope develops to a landslide induced by an excavated artificial slope. The height of the excavated slope is 51.2 m to 105.4 m, and it is a high slope with a height of more than 54 meters. In March 2009, the slope formed an empty surface due to the excavation of the water conservancy hub, and the slope began to deformation and failure. To study the formation mechanism of the landslide and ensure the safety of the Xiajiang Water Conservancy Project, the slope monitoring was started in October 2010 and ended in July 2016. Since the landslide is only 6 kilometers downstream of Baqiu Town and has more than 30,000 residents, its stability is a major safety issue. Therefore, we must analyze the landslide deformation characteristics and their potential damage.

2. Monitoring Method

We mainly carry out groundwater level monitoring, slope internal deformation monitoring, slope surface deformation monitoring, and crack deformation monitoring of the slope. A plane deformation control network in the landslide-prone area of the water conservancy hub was established, to further determine the areas where the slope is more affected and the areas that are prone to instability, and improve their monitoring utilization [5].

2.1. Monitoring Point Layout

There are 5 measurement points in the north-south direction of the slope plane deformation control network, numbered TB1 to TB5. Eight monitoring sections are arranged in the east direction of the slope, and two to three displacement marks are set on each section. Each section has 11 groundwater level holes (11 piezometers) and 11 inclinometer holes at different elevations. Three sets of anchor dynamometers are distributed on the anchor cables supported by the slope. Six crack gauges are arranged at the rear trailing edge of the high slope (Figure 1).

![Figure 1](image-url)  
**Figure 1.** Plan layout of monitoring points on the right bank slope of the dam of Xiajiang Water Conservancy Project.
2.2. Monitoring Device

2.2.1. Osmometer and Earth Pressure Gauge. The working principle of the steel string type pore water pressure gauge is: a vibrating steel string is connected to a sensitive pressure diaphragm. When the pore water pressure is transmitted to the inner cavity of the instrument through the water permeable plate and acts on the pressure-bearing membrane, the pressure-bearing membrane is deformed together with the steel string. By measuring the change of the frequency of the natural vibration of the steel string, the liquid pressure can be converted into an equivalent frequency signal and measured. Its pressure calculation formula is:

\[ P = G(R_0 - R_i) + K(T - T_0) \]  

(1)

Where, \( P \) is the pore water pressure (kPa), \( R_0 \) denotes the initial frequency modulus value of the instrument (digit), \( R_i \) is the measured frequency modulus value of the instrument at the \( i \)-th moment (digit), \( G \) is instrument calibration coefficient (KPa/digit), \( T \) denotes the initial temperature value of the instrument (℃), \( T_i \) denote the measured temperature value of the instrument at time \( i \) (℃), \( K \) is temperature correction coefficient (kPa/℃).

The observation principle and calculation formula of the earth pressure gauge is the same as those of the osmometer, and the earth pressure acts on the pressure-bearing membrane through the liquid. Because the buried heights of the various measuring points are different, usually for comparison purposes, the measured pore water pressure is converted into the lifting pressure water level, and the calculation formula is:

\[ h_i = h_0 + \frac{P}{\gamma} \]  

(2)

Where, \( h_i \) is the lift pressure water level at the measurement point (m); \( h_0 \) is the buried elevation of measuring point (m), \( P \) is the pore water pressure at the measuring point (kPa), \( \gamma \) is the density of water (usually 9.8 kN/m³).

2.2.2. Strain Gauge and Non-Stress Gauge. The working principle of the differential resistance type strain gauge and the non-stress gauge is that two sets of differential resistance steel wires are connected at both ends of the instrument. When the temperature, axial strain or displacement of the instrument changes, the resistance ratio of the differential wire will change accordingly. Accounting to this principle, the corresponding concrete strain or joint displacement can be calculated. The strain calculation formula is:

\[ \varepsilon = f \times \Delta Z + b \times \Delta T \]  

(3)

Where \( \varepsilon \) is the strain (10⁻⁶), \( f \) is the minimum reading of the strain gage (10⁻⁶ / 0.01%), \( Z \) is variation of resistance ratio (0.01%), \( Z = Z - Z_0 \), \( b \) is temperature correction coefficient of strain gauge (10⁻⁶ / ℃), \( T \) is the temperature change (℃), \( T = T - T_0 \).

Where the temperature is

\[ T = \alpha' \Delta R, \quad T \geq 0^\circ C \]  

(4)

\[ T = \alpha'' \Delta R, \quad T < 0^\circ C \]  

(5)

In the formula (4) and (5), \( T \) is the temperature (℃); \( R \) is the resistance change (Ω), \( R = R - R_0 \); \( R_0 \) is measured instrument resistance (Ω); \( R_0 \) is the calculated resistance value of the instrument at 0 ℃ (Ω); \( \alpha' \), \( \alpha'' \) denote the temperature constant (℃ /Ω).

2.2.3 Joint Gauge, Crack Gauge and Bedrock Deformation Gauge. The crack gauge, crack gauge, and bedrock deformation gauge are all CF differential resistance type instruments. The principle of the instrument is that when the seam gauge is subjected to external deformation, most of the deformation
will be borne by the bellows of the casing and the suspension spring in the sensing part, and a small part of the deformation will cause the change of the wire resistance. And the change of the resistance of the two steel wires during the deformation is differential, and the change of the resistance is proportional to the change. According to the above principles, the displacement of the corresponding seam can be calculated.

The formula for calculating the displacement of the seam is:

\[ J = f \times \Delta Z + b \times \Delta T \]  \hspace{1cm} (6)

In the formula (6), \( J \) is the seam opening and closing degree (mm); \( f \) denote the minimum reading of seam gauge (mm/0.01%); \( Z \) denote the variation of resistance ratio (0.01%), \( Z = Z - Z_0 \); \( b \) is the temperature correction coefficient (mm/℃) of the seam gauge, \( T \) denotes the temperature change (℃), \( T = T - T_0 \). The remaining parameters have the same meaning as in formulas (4) and (5).

3. Monitoring Results

3.1. Groundwater Level Monitoring Results

The change of the groundwater level process line at the 8# measuring points on the right bank 81m and 71m elevation stable at the road has been relatively stable. Its small fluctuations are mainly related to factors such as rainfall. However, even during rainfall, the changes are small, and there are no sudden rises and falls of excessive groundwater levels. The measured values of the two measurement points on the right bank 96m elevation at horse track are fluctuating, and the slight fluctuations are mainly related to factors such as rainfall (Figure 2).

The measured value of the P2,1 measurement point on the right bank 61m Elevation at the Road is somewhat fluctuating. The height is about 50 m at low water level, and the height is about 54 m at high water level. The water level changes by about 4 m, and the water level changes little. The groundwater level at each measurement point is relatively stable on sunny days, the water level changes are small, and the groundwater level is normal. However, some of the measurement points are high on rainy days, and observations should be continued.

![Figure 2. Groundwater level measured the curve of right bank slope.](image)

3.2. Deformation of Slope Cracks

The crack deformation process curve measured at each measuring point on the right bank slope is shown in Figure 3. It can be seen from the figure that the deformation range of K3, K4, K5, K6, and each measuring point is from 0.5 mm to 2 mm, and the total amount of crack deformation at each
measuring point within a smaller range. Only the K1 and K2 measurement points gradually increased the crack deformation in March 2012, and it was relatively stable after July 2012. However, since March 2013, the crack deformation increased again, and by May 30, 2015, the maximum crack deformation was 29.00 mm and 35.33 mm, respectively.

![Crack deformation curve of right bank slope.](image)

It can be known from the results that basically, the measured values of cracks in the rainy season are greatly deformed by the influence of rainfall. However, with the end of the rainy season, the fracture measurements have converged. The rate of change in measured values has decreased since 2014. Since the seam deformation of some seam gauges is close to the instrument range, from April 2016 to November 30, 2017, the K1, K2, and K3 seam gauges were replaced. It can be seen from the measured deformation process lines of the three newly installed crack gauges that from April 2016 to October 2017, the crack deformation process lines at the K1 and K2 measurement points have changed smoothly. The maximum deformation increment of the above two monitoring points is less than 4mm, and the landslide deformation has stabilized.

### 3.3. Horizontal Displacement Inside Slope

The cumulative horizontal displacement process line of the oblique hole measured at each measuring point of the right bank slope is shown in Figure 4. As can be seen from the figure, each oblique hole has a certain measured horizontal displacement. The maximum horizontal displacement of most measuring points is only a few millimeters or dozens of millimeters, and gradually accumulates from the bottom of the hole to the orifice. Considering that the measured values of the mobile inclinometer need to be accumulated one by one, which leads to a certain observation error, these measured value changes are normal. Therefore, it can be said that the horizontal displacement of these measuring points is small.

However, the displacement of the CL4-1 measuring point began to increase from 2.5 m above the hole depth, and the deformation was always small below 2.5 m. That is, the displacement mainly occurs in the surface soil below the orifice, and the displacement has been gradually increasing. The maximum measured value of this measuring point reached about 20mm in 2016, but it has returned to about 10 mm in 2017. Considering the observation error of the inclinometer, the actual deformation can be regarded as no obvious change, indicating that the slope has stabilized, which is consistent with the conditions monitored by the crack meters K1 and K2.

### 3.4. Horizontal Displacement of Slope Surface

The measured of the horizontal displacement of the right bank slope surface is shown in figure 5. As can be seen from the figure, the deformation of each measurement point is relatively stable, and the continuous fluctuations of the measurement values are in a small range. The measured values of most measuring points change within the range of ± 20 mm, and the maximum deformation is about 30mm.

Considering that the total station observation distance is long and the artificial observation has certain observation errors, the actual total slope displacement is small, and the slope surface displacement is currently stable.
Figure 4. Horizontal displacement curve insight slope.

4. Analysis of Monitoring Results
When rainfall occurs, the rainwater will infiltrate into the deep slope body through the loose deposits. Then encountered water blockages such as bedrock, a large amount of rainwater accumulated in the slope of the accumulation body. Eventually, the groundwater level was raised to 82 m (the maximum elevation was about 10m) (May 29, 2015). The maximum deformation of the crack at the trailing edge of the slope exceeds 35 mm (May 30, 2015), indicating that there is a certain lag effect between the slope deformation and the groundwater level, and the delay time is about 1 day. The maximum displacement in the deep part of the slope body reached a maximum of 20 mm (April 23, 2016), indicating that the deformation lag time in the deep part of the slope was longer. Besides, the ground surface displacement of the leading edge of the slope more than 20 mm (April 23, 2016), indicating that the slope is mainly a rainfall-induced sliding landslide.
The monitoring results are in line with the ground deformation observed on site. This indicates that the slope has been deformed by rainfall infiltration in the study area. Especially at the trailing edge of the slope, obvious cracks and fissures appeared. And the deformation will continue to develop under the action of rainfall, and it is very likely to cause a landslide disaster of a sliding type. Once the landslide occurs, it will directly threaten the construction and operation of the Xiajiang Water Control.
Project. Even the Baqi Town, which blocks the Gan River and affects more than 30,000 people 6 kilometers downstream, has affected the lives and property of the people. Therefore, the results obtained from the analysis must be strengthened.

Table 1. Groundwater level, cracks width and horizontal displacements.

| Time          | Maximum Displacement                                                                 |
|---------------|---------------------------------------------------------------------------------------|
| Groundwater of the slope | 2015-5-29 | The groundwater level raised to 82m (the maximum elevation was about 10m) at P1-2 monitor point and P2-2 point. |
| Cracks width at the back of the slope | 2015-5-30 | The maximum deformation of the crack at the trailing edge of the slope exceeds 35mm (May 30, 2015) at K3 monitor point. |
| Horizontal displacement inside the slope | 2016-4-23 | The maximum displacement in the deep part of the slope body reached a maximum of 20 mm at CL4 bore hole. |
| Horizontal displacement of the slope Ground surface | 2016-4-23 | The maximum horizontal displacement in the deep part of the slope body over 20 mm at section 1. |

5. Conclusion
This study presents a case study on rainfall-type landslide monitoring. The focus is on the analysis of the deformation and failure process of the reservoir bank landslide caused by precipitation infiltration. In summary, we draw the following conclusions:

1. The slope on the right bank of the Xiajiang Water Conservancy Project is a large rainfall landslide. A large number of cracks have formed at the trailing edge of the landslide. Observed cracks and fissures indicate that the landslide formed a sliding landslide due to rainfall infiltration and added sliding force.

2. Rainfall infiltration affects water level changes and deformation of the slope to varying degrees. In the upper part of the slope with high permeability, water easily penetrates the slope, which raises the groundwater level and reduces the strength of geological materials. Hence, after the rainfall infiltration, the trailing edge of the slope will deform, and the cracks will gradually widen. In the lower part of the slope with poor permeability, rainfall accumulates in the slope body, which makes the front edge of the slope deform relatively slowly. After rainfall, the deformation of the trailing edge is accelerated faster than that of the leading edge.

3. The monitoring results show that the slope will be in the process of deformation. When rainfall continues to occur or encounters extreme rainfall, the slip first appears at the trailing edge of the slope, and the deep horizontal displacement of the slope body will continue to increase, eventually reaching the overall landslide, or even blocking the Ganjiang River, seriously threatening the highway at the leading edge of the slope and building safety.

4. Based on the above monitoring results, it is recommended to immediately strengthen the comprehensive management of landslides.

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