Study on the mechanism of Xiajiang Hydraulic Project landslide reactivation based on long-term in situ monitoring techniques

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Abstract. Landslide reactivation is a progressive process that takes a long time and is influenced by various factors. Studies that focus on short periods or limited factors may fall short of revealing the complicated reactivation mechanism. In this study, the mechanism of Xiajiang Hydraulic Project landslide reactivation is investigated using long-term in situ monitoring techniques. The slope’s long-term reactions were monitored using different sensors installed since the initial landslide. The reactivation process is analyzed based on the obtained monitoring data, revealing the reactivation mechanism. The results show the following: (1) Heavy rainfall and poor drainage conditions are direct trigger factors for landslide reactivation. (2) The reactivation process is promoted by multiple factors such as the slope deformation, rainfall infiltration, and the strength of geomaterials, which are mutually coupled. Further, suggestions are proposed to improve safety management based on the aforementioned results.

1. Introduction
Landslide reactivation is a challenging problem in hydraulic engineering due to its complex developing mechanisms [1, 2]. The changes in its geomaterial properties and hydraulic boundary conditions are the fundamental reasons for the slope instability [3, 4]. Therefore, an essential research approach for landslide reactivation is investigating the geomaterial properties and boundary conditions’ deteriorative process, which usually takes a long period and can be influenced by various factors. Different loading, infiltration, and water-level conditions can be easily imposed on the computational model using numerical simulation. However, the simulation results highly depend on the constitutive model, mesh density, and the loading process that the researchers choose. Moreover, numerical methods continue to face significant challenges in simulating long-term slope movements coping with multiple-factor interactions. In situ monitoring techniques, unlike analytical and numerical approaches, are good at measuring the true responses of the relevant factors throughout the reactivation process. Thus in situ monitoring technique is critical in studying landslide reactivation.

In this study, the landslide reactivation in Xiajiang Hydraulic Project in 2019 is investigated using long-term in situ monitoring techniques. Different kinds of in situ monitoring sensors were installed since the initial landslide in 2011. The long-term monitoring data of the internal deformation, crack
development, and underground water-level distribution are analyzed to provide a comprehensive picture of the reactivation process. Further, the reactivation mechanisms are revealed and suggestions about slope stability are proposed.

2. Engineering background

2.1 Landslide development
Xiajiang Hydraulic Project is an important hydraulic junction located in the middle reaches of the Ganjiang River. This project’s right bank is a manually excavated high rock slope with several weak planes and rock mass joints. The right bank slope lost stability in 2010 at an altitude from 71.0–105.0 m mainly due to the excavation disturbance. Measures such as slope cutting and reinforced supports were observed in 2011, and deep drainage holes were also set up in 2014, then the slope tended to stabilize again [5]. However, following an intense period of heavy rainfall in early July 2019, the slope lost its stability again. Field investigation revealed an obvious crack deformation increase in the landslide’s trailing edge. Intense shearing cracks were also observed in the downstream direction as the landslide’s leading edge reached an altitude of 51.2–61.0 m.

2.2 Monitoring system design
The in situ monitoring system was set up after the initial landslide in 2011 to record the slope’s responses. Different sensors, including jointmeters (K), inclinometers (CL), and piezometers (P), are employed to measure the development of surface crack deformations, internal horizontal movement trend, and underground water distribution, respectively. Figure 1 shows the locations of some typical sensors.

![Figure 1](image)

Figure 1. Location of slope cracks and monitoring sensors

3. Data analysis

3.1 Slope response after the initial landslide
3.1.1 The development of surface crack deformations
Figures 2(a–c) show the development of surface crack deformations measured using jointmeters; different regions exhibit different deformation features.

The crack deformation near the trailing edge (measured using K1 and K2) shows a constant increase. The distortion surpassed the sensors’ full size (30 mm) at the end of 2014, causing the sensors to collapse. The deformation near the crack’s middle (measured using K3 and K4) shows a moderate increase, whereas the deformation near the leading edge (measured using K5 and K6) exhibits no significant increment. K5 data even dips below 0 mm, indicating a crack-sealing tendency.

K1, K2, and K3 were replaced with new sensors in 2016, which were designated K1’, K2’, and K3’. The crack deformation measured using K1’ and K2’, significantly increases after their installation. The deformation measured using K3’ first decreases slightly, then moderately increases, indicating a persistent slope deformation development.

The aforementioned data reveal that the crack deformation can still develop even after reinforcement and deformation occur at the trailing edge. Figure 2(a) shows that the development process exhibits a stepwise increment. The monthly deformation increment and rainfall are reorganized in figure 2(d) to conduct further increment analysis. The monthly deformation increment is observed to be positively correlated with the monthly rainfall with a slight hysteresis. The maximum monthly rainfall during the monitoring period is 347.50 mm (May 2014), whereas the maximum monthly increment is 5.06 mm and 5.52 mm for K1 and K2, respectively (July 2014). The aforementioned analysis suggests that rainfall is a direct cause of crack development.

![Figure 2](image_url)

**Figure 2.** The development of crack-expanding deformation after the reinforcement

### 3.1.2 Underground water-level distribution

A time window (from April 2014 to July 2014) when the crack increased significantly is selected to analyze underground water-level response to rainfall. Figure 3 shows the distribution of underground water levels and rainfall. Sensor P5-2 reveals a slight increase in underground water level after rainfall, whereas stable water levels are observed using other sensors. The data indicate that the drainage facilities were in good condition and the underground water level remained stable at that time.
3.1.3 Internal horizontal deformation

Figure 4 shows the internal horizontal displacement distribution measured using inclinometers. Localized deformation was observed between the inflection points in the deformation distribution curves. This phenomenon indicates a slip zone in the slope. Thus, the geomaterial strength in the slip zone becomes the dominant factor for slope stability [6]. Table 1 presents the characteristics of the slip zone at different monitoring points. The displacement near the leading edge (CL1-1, CL4-1) mainly concentrates on a thick slip zone near the shallow region of the slope. The deformation exhibits continuous growth and the maximum displacement reached 72.28 mm at the end of 2015. The horizontal displacement near the middle of the slip body (CL3-2) is also significant, whereas the slip zone is relatively narrow (about 2.0 m) and deep.

The increasing displacement implies that the internal horizontal deformation undergoes a period of development even after the reinforcement.

![Figure 4. Distribution of internal horizontal displacement at different monitoring points](image)
### Table 1. Characteristics of the slip zone

| Monitoring point | Altitude range (m) | Depth from the surface (m) | Thickness (m) | Maximum deformation (mm) |
|------------------|-------------------|----------------------------|---------------|-------------------------|
| CL1-1            | 65.17-68.67       | 2.5                        | 3.50          | 72.28                   |
| CL4-1            | 77.43-79.93       | 2.0                        | 2.50          | 21.09                   |
| CL3-2            | 78.36-79.86       | 16.5                       | 1.50          | 53.26                   |

### 3.2 Slope response during the landslide reactivation.

Since 2018, strong lightning strikes have damaged several sensors and collection units, resulting in the loss of associated data. Fortunately, some piezometers were unaffected and data on the underground water level were obtained. Figure 5 and Table 2 show the underground water-level change during the landslide reactivation process. The measuring points outside the slip body (P2-1 & P5-1) remain at a stable water level as the increment is below 2.0 m. The underground water level of the measuring points, P4-1 & P5-2, increases significantly after heavy rainfall. The maximum water level of P4-1 & P5-2 are 79.55 and 83.93 m, respectively. The measured data in Table 1 indicate that the underground water infiltrates the slip zone where the geomaterials were previously unsaturated.

The management staff observed that the drainage holes were clogged after landslide reactivation. Emergency drainage holes were drilled at the end of July 2019 and enough water was drained. Figure 5 shows that the underground water level dropped significantly, with a maximum reduction of above 5.0 m.

### Table 2. Characteristics of underground water levels before and after landslide reactivation

| Monitoring point | P2-1 | P4-1 | P5-1 | P5-2 |
|------------------|------|------|------|------|
| Maximum water level | 55.67 m | 79.55 m | 63.01 m | 83.93 m |
| Minimum water level | 54.51 m | 74.49 m | 61.15 m | 78.84 m |
| Maximum difference | 1.16 m | 5.06 m | 1.86 m | 5.09 m |

![Figure 5. The distribution of underground water level](image-url)

### 4 Landslide reactivation mechanism analysis

The landslide reactivation mechanisms for Xiajiang Hydraulic Project can be concluded as follows based on the aforementioned data analysis:

1. The weak planes and joints in the rock mass provide intrinsic geological conditions for the initial landslide and its reactivation.
2. The reinforcement temporarily hinders the slip body from moving as a whole, as observed from the slight crack deformation measured near the leading edge. However, the development of internal horizontal displacements is still observed. The displacements are localized in a slip zone where the geomaterial strength becomes the dominant factor for slope stability.
3. Factors such as slope deformation, seepage effects, and geomaterial strength are combined and mutually related. Particularly, the existence of surface cracks provides infiltration passages, then the
rainfall infiltration increases the slope weight and decreases the material strength, promoting further slope deformation. Meanwhile, developing crack deformation can create better passages for rainfall infiltration. The seepage process can accelerate the migration of fine particles due to the increasing infiltration, leading to the gradual clogging of the drainage system. The drainage system’s deficiency temporarily raises the underground water level and amplifies the adverse effects of rainfall infiltration.

(4) The cumulative effect of the aforementioned factors results in an increasing risk of slope safety. Large volumes of rain infiltrated the slope during the heavy rainfall in 2019, and the underground water level increased rapidly due to the slope’s poor drainage. Thus, the underground water infiltrated the slip zone where the geomaterial lost its strength due to wetting effects. Further, the slope lost its stability and the landslide reactivated along the former slip surface.

5 Conclusion

In this study, the landslide reactivation mechanism is investigated considering landslide reactivation in Xiajiang Hydraulic Project in 2019. Long-term in situ monitoring techniques are used to evaluate slope responses, and monitoring data are used to analyze the reactivation mechanism. The main conclusions can be drawn as follows:

(1) Long-term in situ monitoring techniques are essential research approaches that are capable of providing the slope’s true response.

(2) The landslide reactivation process is complex and progressive. The influencing factors such as deformation, rainfall infiltration, and geomaterial strength are combined and mutually related.

(3) Heavy rainfall and poor drainage are direct triggers for landslide reactivation, whereas poor geological features, slope deformation development, and seepage passages create essential reactivation conditions.

(4) Because the underground water level is critical in the reactivation process, measures such as sealing the surface crack and enhancing the drainage system are essential for slope stability throughout the operating period.

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References

[1] Huang R 2016 Chinese Journal of Rock Mechanics & Engineering 26(03) 433-454.
[2] Zheng Y, Zhao S and Deng W 2003 Chinese Journal of Rock Mechanics & Engineering 22(12) 1943-1943.
[3] Ren S, Zhang Y, Xu N, Wu R and Liu X 2021 Rock and Soil Mechanics 42(3) 863-881.
[4] Zhang Y, Wu R and Ren S 2021 Chinese Journal of Rock Mechanics and Engineering 40(4) 777-789.
[5] Liu Z 2011 Yangtze River 042(0z2) 71-73.
[6] Hu F, Li Z, Hu R, Zhou Y and Yue R 2018 Chinese Journal of Rock Mechanics and Engineering 37(3) 766–778.