Triggering mechanism and possible evolution process of the ancient Qingshi landslide in the Three Gorges Reservoir

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ABSTRACT
The Qingshi landslide in the Three Gorges Reservoir was selected as a case study of ancient landslides. The detailed on-site surveys and long-term monitoring data were analysed to classify the triggering mechanism and possible evolution process of the Qingshi landslide. The results show that the ancient Qingshi landslide was triggered by the water storage in 2010. The leading edge slipped first, and the trailing edge underwent large-scale deformation after losing the resistance provided by the leading edge. In early 2011, the compaction of the leading edge of the landslide provided a certain resisting force, which controlled the overall downward movement of the landslide. In 2014, the integrity of the landslide was strengthened by emergency treatment measures, which caused the stabilization of the landslide and further reduced the displacement rate of the landslide. The local strengthening of the leading edge may act as a locking segment that could provide direct support to the sections in the middle and upper parts of the landslide. However, abnormal water-level regulation and heavy rainfall may cause the landslide to collapse again. The entire evolution process of the Qingshi landslide can provide an important reference for ancient landslides located on reservoir banks.

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Introduction
Ancient landslides have the characteristics of concealment and sensitivity (Sassa 2013; Yashar et al. 2013; Zhang et al. 2018). These landslides may react to human engineering activities and extreme weather events (Zhao et al. 2019). Because of the involvement of hydrodynamics, the reactivation and evolution of ancient landslides in reservoir areas are complex and challenging to understand (Zangerl et al. 2010;
In addition to the water-level fluctuations (Wang et al. 2020a; Wang et al., 2020b), a periodic rainy season is also a key factor to induce the phased deformation of landslides (Pour and Hashim 2017; Hashim et al. 2018; Wang et al. 2019; Xiao et al. 2020). Moreover, once a bank slope slips into the reservoir, the impulse waves generated by the landslide would expand the range of the threat greatly, causing more serious casualties and property losses (Crosta et al. 2016; Bao et al. 2018; Huang et al. 2019; Zheng et al. 2021).

The Three Gorges Reservoir (TGR) has been identified as an area with frequent geological disasters. Since 2008, the reservoir water level has increased from 75 to 175 m, the hydrogeological environment in the TGR has changed dramatically, and several ancient landslides have been reactivated (Gong et al., 2021; Yin et al. 2016). These landslides include the Qianjiangping landslide (Yin et al. 2015), the Huagtupo landslide (Tang et al. 2015; Wang et al. 2021), the Shuping landslide (Song et al. 2018), and the Quchi landslide (Gu et al. 2017; Huang et al. 2018). However, the existing researches cannot effectively reveal the entire evolution process of ancient landslides on reservoir banks, especially the stabilization of ancient landslides after reactivation.

Taking the Qingshi landslide in the TGR as an example, the entire evolution process of ancient landslides was analysed based on on-site surveys and long-term monitoring data. During the monitoring process, we carried out emergency treatment of the landslide, involving the creation of drainage channels, sealing the crack and covering it with a tarpaulin, removing dangerous stones, reinforcing the leading area with an anchor, and small-scale slope-cutting. The integrity of the landslide was strengthened and the failure mechanism of the landslide can be further clarified by comparing monitoring data before and after the emergency treatment. The entire evolution process of the Qingshi landslide can provide an important reference for ancient landslides on reservoir banks.

**Study area**

The Qingshi landslide is located in Qingshi Village, Wushan County, Chongqing City (109°58′50″ E, 31°00′53″ N; Figure 1). It is distributed on the steep slope of the right bank of the Goddess River that is an important tributary of the Yangtze River. The study area is a U-shaped valley. The height of the trailing edge of the Qingshi landslide is about 580 m, and the leading edge is located at 110 m, resulting in a relative height difference of 470 m.

The average width of the Qingshi landslide is about 600 m, the average length is about 825 m, and the main sliding direction is 30°. The average thickness is about 80 m, and the sliding surface angle is 20°–30°. The study area is 0.495 km², and the volume of the landslide is about 40 million m³, which can be classified as a giant landslide.

The sliding mass was the Quaternary collapse deposits (Q₄coln). According to the drilling results, the thickness of the deposits in the middle-front area of the landslide was relatively large, and those of the two sides and the trailing edge were relatively thin. The sliding zone was developed along with the interface between the ancient...
landslide deposits and the underlying bedrock, forming a fold-type slip surface. The slip bed of the Qingshi landslide was the thick layer of limestone and dolomite in the Lower Triassic Jialingjiang Formation (T1j1).

In 2009, the water storage level in the TGR reached 156 m. At that time, a collapse of about 1500 m³ occurred on the eastern side of the leading edge of the Qingshi landslide. At an elevation of 530–550 m on the trailing edge of the landslide, a 1–2 cm wide crack was formed with a length of 120 m. In addition, three collapse pits were formed, with diameters of about 0.7–1.8 m and depths of about 0.35–0.7 m. On 11 October 2010, because of the 175 m water-level impoundments of the TGR, the leading edge of the landslide (the submerged bank slope) collapsed. On 18 October 2010, a 1–20 cm wide tension crack appeared with a length of 487 m. By 23 November 2010, the cumulative width of the crack had reached 3.5 m, and the total amount of sinking was 4.2 m. More than nine cracks spreading in different directions appeared near the displaced material, and a secondary slump began to form. The leading edge of the Qingshi landslide gradually disintegrated, and the Goddess River channel was closed.

According to the deformation characteristics of the landslide, we divided the landslide into a strong deformation area and a weak deformation area (Figure 2). The strong deformation area had an average width of about 325 m, a longitudinal length of about 225 m, an average thickness of about 70 m, an area of about 0.108 km², a volume of about 7 million m³, and a sliding direction of 26°. The trailing edge and the two sides in the strong deformation area were bounded by the deformation cracks. According to the spatial distribution, the strong deformation zone was further
divided into subareas A, B, and C; and the weak deformation zone was labelled as subarea D.

Area A was the bank slope section that experienced the most obvious deformations and landslide collapse. Its area and volume were about 0.022 km² and about 0.15 million m³, respectively. It collapsed into the Goddess River, with a slope of 35°–40°. Area B was located on the southern side of area A. The terrain slope was about 30°–35°, and the area was about 0.072 km². Area C was located on the eastern side of area B. The slope of the leading edge was 60°–80°, and the area was about 0.036 km².

The main sliding direction of the weak deformation area of the landslide (area D) was 30°. The average thickness was about 80 m, the area was 0.387 km², and the volume was about 33 million m³. Its sliding surface was in a fold line.

**Monitoring system and emergency treatment**

A monitoring system was established to obtain the deformation trend of Qingshi landslide. This system included surface displacement monitoring, rainfall monitoring, reservoir water-level monitoring, and macroscopic geological inspection. The layout of the surface displacement monitoring system in the three main sections and the location of the drilling holes emplaced during the on-site surveys are shown in Figure 3. Note that the displacement monitoring data were recorded manually before 2017 (JCD in Figures 3 and 4) and were recorded automatically after 2017 (GPS in Figures 3 and 4). In addition, the rainfall monitoring device was arranged in the dense distribution of houses in area D. The real-time monitoring of the reservoir water level was realized through the automatic surface water monitoring station. The boreholes (such as B5 in Figure 4) were used to obtain the real-time trend of the groundwater level.
During the monitoring period from May 2014 to November 2014, we conducted emergency treatment measures on the landslide (Figure 4). The specific construction measures were as follows:

- **Create drainage channels.** We created a first-stage drainage channel in the rear of the landslide and a second-stage drainage channel in the rear edge of the strong deformation area.
- **Seal the crack and cover the area with a tarpaulin.** We filled and tamped the 19 trailing edge cracks with clay and used a tarpaulin to cover the cracking area.
- **Remove dangerous stones.** We removed the unstable stones on the surface of the leading edge, and the volume of the dangerous stones was 22,771 m$^3$.
- **Reinforce area A with an anchor and small-scale slope-cutting.** The slope was cut according to the actual situation in area A. After small-scale slope-cutting, we installed an active protection net and reinforcement anchor in area A. We

![Figure 3. The layout of the surface displacement monitoring system in the three main sections and the locations of the drilling holes emplaced during the field investigations. Note that the displacement monitoring data were recorded manually before 2017 (JCD) and were recorded automatically after 2017 (GPS).](image)
arranged six rows of anchors in the upper part, and the length of each anchor was 12 m. The middle and lower anchors from top to bottom was arranged every 13.5 m in the horizontal direction, with a length of 8.0 m.

Results and discussion

Comprehensive analysis of monitoring data for different areas

After the obvious deformation of the Qingshi landslide, the rainfall, the reservoir water level, and the displacement in the study area were continuously monitored in November 2010. The monitoring results are shown in Figure 5. We divided the monitoring process into three parts: accelerated deformation (Part 1), uniform deformation (Part 2), and creep deformation (Part 3). By analysing the monitoring data, we obtained the deformation trends of the different areas. Notably, the reservoir water has been adjusted periodically and each storage cycle is determined as a hydrological year in the following text.

Deformation analysis of area A

Because the slope of area A was steep and the deformation was mainly surface collapse, we used macroscopic geological inspections to monitor this area instead of arranging monitoring points. The water storage in the TGR reached 156 m in 2009, and area A began to collapse. From 2009 to early 2011, several large-scale collapses occurred in area A, with a total volume of more than 100,000 m$^3$. After 2011, the deformation rate in area A decreased, but dozens to hundreds of square meters of collapse still occurred after rainfall events. After the emergency treatment measures
Figure 5. Displacement–time curves of the reservoir water level and rainfall in different areas: (1) accelerated deformation, (2) uniform deformation, and (3) creep deformation.
were implemented in area A, additional large-scale collapse did not occur, and we did not observe any new signs of deformation.

**Deformation analysis of area B**
During Part 1 of the monitoring process, the monitoring curves for area B rose steeply, and the surface displacement was large. Notably, the deformation trends of areas C and D were consistent with that of area B during Part 1. The maximum accumulated horizontal displacement was 1827.1 mm, and the maximum vertical displacement was 2864.3 mm. During this period, we observed obvious tensional deformation of the slope’s surface. After entering Part 2 of the monitoring, the landslide deformation immediately slowed down. During hydrological years 2011 and 2012, the annual variations in the horizontal and vertical displacement were 24.6–35.0 mm and 17.0–70.6 mm, respectively. After entering Part 3 of the monitoring, the deformation of the landslide continued to slow down, and the annual variation in the surface displacement at each monitoring point remained within 20 mm. As of 2018, we noted that the annual changes in the vertical and horizontal displacements at each monitoring point were less than 10 mm.

**Deformation analysis of area C**
During Part 1, the horizontal and the vertical displacements were 93.6–101.9 and 35.3–56.5 mm, respectively. Moreover, the number of cracks continued to increase. In 2012, the deformation rate decreased significantly. Except for individual monitoring points, the annual horizontal displacement and vertical displacement were less than 20 mm in 2018. During the implementation of the emergency treatment measures, the curves of the monitoring points increased abnormally because of the vibrations generated by the construction. After the emergency treatment measures were completed, the monitoring curve gradually became gentler, and the deformation rate was less.

**Deformation analysis of area D**
The annual horizontal displacement and vertical displacements were 65.3–196.5 and 17.6–45.3 mm during Part 1. At this time, the tensile cracks in the slope’s surface were observed. After 2011, the deformation slowed down significantly. By the end of 2016, the annual horizontal displacement was <30 mm, while the annual vertical displacement was <20 mm. During Part 2 and Part 3 of the monitoring process, the deformation in area D was significantly larger than that in areas B and C. In 2018, the surface displacements were <10 mm, indicating that the deformation in area D was very slow.

**Analysis of monitoring data for the longitudinal profile of the landslide**
Through the analysis of the monitoring data for cross-section 1-1’, we studied the deformation characteristics and evolution process of the Qingshi landslide. The annual cumulative displacements during Part 2 and Part 3 are shown in Figure 6. A comparison of the monitoring curves of the surface displacement before and after the emergency treatment measures (Figure 7). Notably, because GPS01 was affected by the emergency treatment in 2014, the related monitoring data were ignored when carrying out the comparison analysis.
Through monitoring the reactivation of the Qingshi landslide in 2010, the results showed that the deformation rate continued to decrease at the beginning. In the same section, over time, the cumulative displacement of the trailing edge (GPS04) was larger than that of the leading edge (GPS01), which indicates that the leading edge tended to be stable and provided a certain resisting force after the previous compaction. Moreover, the trailing edge continuously pushed the leading edge of the landslide under the influence of gravity, thus causing its cumulative displacement to be larger. Because of the stabilization of the leading edge, the deformation of the leading edge caused by the water-level fluctuations was no longer the main cause of the overall deformation. In other words, if the water-level fluctuations were the primary reason for the overall deformation, the deformation of the leading edge would be larger than that of the trailing edge. Only in this way could the leading edge provide enough space for the trailing edge to slip. However, the monitoring results are contrary to this scenario. This indicates that the landslide has entered a stage of stabilization. As previously mentioned, the deformation rate continued to decrease and the deformation of the trailing edge was greater than that of the leading edge, which provides direct evidence of the stabilization of the leading edge.

By carefully analysing Figure 7, the following findings could be obtained. Since 2011, none of the typical characteristics of step-type deformation were observed (Gu et al. 2017; Huang et al. 2018; Du et al. 2020), which indicates that the water-level fluctuations had little effect on the deformation of the entire landslide. After the emergency treatment measures, the displacement rate and cumulative displacements were significantly reduced. Filling the cracks and the reinforcement treatment in area A actually improved the integrity of the landslide and accelerated the rate of stabilization. Meanwhile, the arrangement of the tarpaulin and the drainage channels further reduced the influence of rainfall infiltration on the landslide deformation. As a result, the cumulative displacement and displacement velocity after the treatment (Period AT) remained smaller than that before the treatment (Period BT) even though the rainfall during Period AT was greater than that during Period BT (Figures 7(a,b)). Furthermore, regarding the oscillations shown in Figure 7, we found that the oscillating amplitude during period AT became smaller despite the similar rainfall intensity and reservoir water-level fluctuations. After confirming the monitoring devices were still working well, it is considered that this oscillation of the monitoring data could provide indirect evidence of small deformations.
Figure 7. Comparison of the monitoring curves before and after the emergency treatment measures were implemented: (a) the reservoir water and rainfall during Period BT; (b) the reservoir water and rainfall during Period AT; (c) the monitoring data for GPS02 during Period BT; (d) the monitoring data for GPS02 during Period AT; (e) the monitoring data for GPS03 during Period BT; (f) the monitoring data for GPS03 during Period AT; (g) the monitoring data for GPS04 during Period BT; and (h) the monitoring data for GPS04 during Period AT.
Factors influencing the landslide

Hydrogeological conditions
After the impoundment of the TGR, the water level of the Goddess River increased significantly, which enhanced the erosion of the river, increased the groundwater level, and changed the hydrogeological conditions. And the water-level fluctuations induced the reactivation of the ancient landslide. When the water level rose, the pore water pressure increased, the strengths of the rock and soil decreased, and the widths of the cracks increased. When the water level dropped, the pore water pressure decreased, which caused the bank slope to deform. The original collapsed deposits in the leading edge were unstable because of the erosion of the foot of the slope, resulting in the cracking of the trailing edge of the landslide.

Geological structure
During the slope’s geological history, it was subjected to shearing and large-scale sliding. The sliding zone was mainly composed of plastic clay or sand crushed stone that could not provide a sufficient resisting force (referred to the Qingshi landslide survey report).

Topographical conditions
The study area is located in a U-shaped valley. The relative height difference between the trailing edge and leading edge of the landslide was about 470 m. Moreover, the slope of the submerged foot was about 50°–60°. This landform could provide the potential space for slip.

Karstification
The caves, depressions, and sinkholes were distributed in the study area (referred to in the Qingshi landslide survey report). These Karst phenomena could provide seepage space for precipitation, surface water infiltration, and groundwater migration. And the long-term erosion caused by the groundwater further decreased the mechanical properties of the discontinuities. Therefore, it is considered to be detrimental to the stability of the Qingshi landslide.

Rainfall
The average annual rainfall in Wushan County is 1049.3 mm. The primary rainfall is concentrated from May to September, accounting for about 70% of the annual rainfall. This rainfall season coincides with the drop of reservoir water level (Figure 5). The landslide deformation under the coupling effect of rainfall and reservoir water level has been analysed in detail based on the monitoring data.

The evolution process of the Qingshi landslide
The failure process of the Qingshi landslide can be divided into three stages: slip of the ancient landslide, reactivation of the ancient landslide, and stabilization after reactivation.
Slip of the ancient landslide

Discontinuities, including tectonic fissures, layers, and unloading fissures, were developed in the study area (Figures 8(a,b)). The high-steep gully at the leading edge was formed by the erosion of the river, which provided the slip space for the overlying rock mass. When the sliding force of the overlying rock mass exceeded the shear resistance, a layered tension area was generated in the trailing edge. After this tension area slipped down, the leading edge bulged significantly and was accompanied by the local collapse. The unloading around the foot of the slope further promoted the deep deformation of the slope. After the sliding surface was gradually penetrated, the rock mass slid along the underlying weak structural surface toward the river, causing the sliding mass to disintegrate. Obvious scratches appeared on the back wall and the right side of the landslide, attaching with subangular to rounded stones with calcium cement. The sliding zone is the boundary between the slip bed and the sliding mass. And the thickness of the sliding zone is varied with the specific geological conditions. For example, the Vajont rockslide’s sliding zone is considered to be 1.4 mm (Crosta et al. 2016). As for the Outang landslide in the TGR, the broken zone affected by the shearing deformation can reach 4 m (Huang et al. 2020). In this paper, a broken zone with a thickness of about 10 m was revealed by the drilling results (Figure 4). The stone particles in the broken zone were rounded as a result of abrasion and fragmentation during the landslide’s evolution process. Researchers have found that, during the landslide movement, the particle crushing on the sliding surface can create excess pore water pressure as well as weaken the friction coefficient, resulting in reduced frictional resistance (Gerolymos and Gazetas 2007; Sadrekarimi and Olson 2010; Chen and He 2020). Furthermore, after the reactivation of the ancient landslide, the broken zone caused by shearing deformation expanded significantly. These characteristics could provide evidence for the failure mode of the ancient landslide.

![Figure 8](https://example.com/figure8.png)

**Figure 8.** The possible evolution process of the Qingshi landslide. (a, b) Slip of the ancient landslide; (c) Reactivation of the ancient landslide; (d) Stabilization after reactivation.
Reactivation of the ancient landslide

After the impoundment of the TGR, the hydrogeological conditions of the study area changed significantly (Figure 8(c)). The infiltration, the softening of rock and soil, uplift and seepage pressure caused the steep bank slope (ancient collapsed deposits) to experience intense transformation. The leading edge of the landslide was then unloaded, which broke the original equilibrium state of the bank slope. Under the action of self-weight, the tensile cracks in the trailing edge and shear cracks in the side edges were generated. When the sliding force exceeded the resisting force, the bank slope underwent significant shear sliding. Furthermore, the sliding surface was formed gradually, and the rear part of the ancient collapse deposits was reactivated. This evolution stage could be reflected by monitoring Part 1 obviously.

Stabilization after reactivation

After the ancient landslide was reactivated, it gradually entered a stage of stabilization (Figure 8(d)). Each adjustment of reservoir water will last for a year (shown as Figure 5). Thus, it is believed that sufficient time was provided for the consolidation of the leading edge during the periodic rise and fall of the reservoir water level. Moreover, the loose deformation part of the leading edge was gradually compacted under the effects of its own weight. The consolidation of the submerged leading edge was accompanied by drainage of the landslide soil, which was similar to the consolidation drainage process of a specimen under a load in geotechnical tests (Bhat et al. 2014). This consolidation phenomenon can be defined as the deformation adaptive of reservoir-type landslides (Gu et al. 2017). Through the compression deformation of the slope and the drainage consolidation, the strengths of the rocks and soil were improved, and the stabilization of the landslide was further enhanced (Doglioni and Simeone 2013; Wang et al. 2018). In addition, the loose deposits in the trailing edge gradually compacted the leading part of the rock mass. The stress imbalance caused by the reactivation was gradually stabilized by the multiple small deformations.

Conclusions

Through on-site investigations and analysis of monitoring data, we studied the triggering mechanism and possible evolution process of the Qingshi landslide.

After the water storage, the river erosion elevation and groundwater level were uplifted significantly. The original equilibrium state was broken, which caused the leading edge of the landslide to slide first. As a result, the middle and upper parts of the landslide gradually slid downward, and the ancient landslide was reactivated.

In early 2011, the deformation of the Qingshi landslide gradually slowed down and entered a stage of stabilization. In this stage, the landslide began to stabilize with small deformations, which was represented by the oscillation of the displacement rate. Moreover, the compaction of the leading edge provided a certain resisting force to control the overall downward movement of the landslide. Because of the continuous compaction of the submerged leading edge, the periodic fluctuations of the reservoir water had little effect on the deformation of the landslide. The periodic short-term heavy rainfall became the primary factor affecting the landslide’s deformation.
In 2014, we implemented emergency treatment measures in the Qingshi landslide. By filling the cracks and reinforcing the bank slope section, the integrity of the landslide was strengthened, which caused the stabilization of the landslide. The addition of a tarpaulin and drainage channels reduced the impact of the rainfall on the landslide deformation. Therefore, after the emergency treatment measures, the displacement rate of the landslide further decreased.

The leading edge was the key to the overall stability of the Qingshi landslide. The local strengthening of the leading edge may act as a locking segment, which provides direct support to the middle and upper parts of the landslide. Abnormal water-level regulation and heavy rainfall may cause the landslide to collapse again, and thus, long-term monitoring and inspection remain necessary.

Disclosure statement

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