The reactivated mechanism of Aniangzhai ancient landslide in Danba County, China

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Abstract. This study presents a catastrophic landslide that occurred on June 17, 2020, on the left bank of the Xiaojinchuan River in Danba County, Sichuan Province of China. This landslide was a large-scale reactivation of the Aniangzhai ancient landslide. The failure event blocked the Xiaojinchuan River, induced a landslide-outburst flood disaster chain, destroying a 6.6 km-long section of national road G350 and causing significant economic losses. Based on field investigations, unmanned aerial vehicle surveys, and geophysical prospecting, this study unravels the causing factors and reactivates the landslide mechanism. The results suggest that the topography and unconsolidated rock-soil mass are predisposing factors for reactivation. The hourly precipitation within three hours reached 61.80 mm and induced the Meilong debris flow. The debris flow rushed into the Xiaojinchuan River and converted it to flow along the foot of the Aniangzhai ancient landslide. The intense scouring of slope toe caused by the rise of river level is the inducing factor of the landslide. Based on the geometry and geomorphic parameters, the landslide can be divided into four areas: leading edge collapse area, middle bulging area, upstream cracking area, and downstream cracking area. The reactivated Aniangzhai landslide could be determined as a compound landslide involving incipient retrogressive failure and latter progressive slide. Several cracks had developed in the upper part of the slope due to the movement of the landslide, and the four areas of the reactivated landslide mass were still creeping. A detailed monitoring and mitigation measure should be paid to this reactivated deposit.

1. Introduction

Landslides are a common geohazard in mountainous areas with active tectonic activities, especially in Southwestern China[1]. Ancient landslides refer to the landslides that occurred in geological history and remained stable or metastable for a long time afterward. An ancient landslide is probably reactivated by events, such as seismic activity, rainfall, or other exogenic factors, which often results in enormous casualty and property loss[2-3].

With the increasingly ubiquitous and intense human activities, the instability of considerable landslides is initially caused by the destruction of the slope toe[4]. Several factors can induce slope toe damage. For instance, road-induced reactivation of ancient landslides is frequently encountered during excavating operations in the western mountainous areas in China[5-6]. Additionally, landslide reactivated by reservoir impoundment is common in reservoir areas due to slope foot’s intense scouring and erosion[7-8]. In Southwestern China, rainfall is also a primary triggering factor for landslides[9-11]. In extreme rainstorm events, the occurrence of some landslides is not independent, but as part of the disaster chain, accompanied by other natural disasters, such as flood and debris flow[12-13].
In mountainous areas, large-scale debris flow often blocks the river channel; it raises the water level, leading to intense fluvial erosion in the leading edge of landslide and even drives entire slope failure\cite{15}.

On June 17, 2020, after the Meilong debris flow, the Aniangzhai (ANZ) ancient landslide on the left bank of the Xiaojinchuan (XJC) River in Danba County, Sichuan Province of China, was reactivated, with a volume of $4 \times 10^7$ m$^3$. The failure event blocked the XJC River, raised the water level, and induced a landslide-outburst flood disaster chain, destroying a 6.6 km-long section of national road G350 and causing considerable economic losses. Several cracks had developed in the upper part of the slope due to the movement of the landslide, and the reactivated landslide deposits were still creeping.

In this study, field investigations, unmanned aerial vehicle surveys, and geophysical prospecting were conducted to examine the characteristics, contributing factors, and reactivated mechanisms of the ANZ landslide. The results can allow a reference for prevention and mitigation of the reactivated landslides induced by fluvial erosion.

2. Regional geological setting

The reactivated ANZ landslide is located on the left bank of the XJC River in Banshanmen Town, Danba County, Sichuan Province of China (Fig. 1). The study area is in the high mountain area of Minshan and Qionglai. It is a part of the transition zone from the Qinghai-Tibet Plateau to the Sichuan Basin and is characterized by a typical alpine canyon landform. Due to the phased uplift of the crust with the deep-cutting and lateral erosion of the river, the plateau surface has been damaged in various degrees. The valleys are mostly V-shaped in the eastern, middle, and northern parts. The northwest and southern valleys are relatively gentle and mostly U-shaped. The neotectonic movement in this area shows the east-west horizontal compression, among which the Xianshuihe fault zone is the most active and frequent area of modern seismic activities. The lithology of the outcrops in the study area consists of quartzite and phyllite of the Weiguan Group belonging to the Devonian.

The study area has a subtropical plateau monsoon climate, with obvious vertical zoning; the annual average temperature is about 14.6°C. The annual average precipitation is 532.7–823.3 mm, which is mainly concentrated from May to September, accounting for over 80% of the annual rainfall. From June 1 to June 17, the accumulated rainfall in Danba County reached 107 mm, and the maximum rainfall intensity reached 34.1 mm/h.
3. Characteristics of the Aniangzhai reactivated landslide

3.1. Geometric characteristics
The ANZ ancient landslide has a fan-shaped morphological characteristic, with an area of 1.2 km² and a volume of $8 \times 10^7$ m³. According to the field surveys, the most recent revival of the landslide was approximately 120 years ago. The reactivated area presents a trapezoid in the platform morphology, with a length along the sliding direction of 650–950 m, a lateral width of 600–850 m, covering a total area of 0.62 km² (Fig. 2). The results of geophysical prospecting indicate that the resurrection body has deep-seated sliding characteristics; the sliding mass is more than 10 m deep at the leading edge and 60–80 m deep at the middle and trailing edge (Fig. 3). The average thickness of the landslide is about 65 m, and the volume is $4 \times 10^7$ m³, which is determined as a huge-scale landslide\cite{16-17}. The slope gradient is within the range of 26°–35°. The maximum and minimum elevations at the trailing and leading edges are 2480 and 2030 m, respectively. The boundary of the reactivated area is visible because of the 450-m relative difference in height. The remnants of the suspended subgrade are observed on the landslide scarps, with a height of 10–15 m formed in the trailing edge. Multiple slumping blocks and steep scarps are formed in the leading edge, affected by the intense scouring of the XJC River.

3.2. Detailed characteristics
Based on the resurrection time sequence revealed by field investigation and deposit characteristics, the reactivated ANZ landslide can be divided into four areas: area I—leading edge collapse area; area II—middle bulging area II; area III—upstream side-cracking area; and area IV—downstream cracking area. The following sections will describe the detailed deformation characteristics of each area (Fig. 4c).

3.2.1. Leading edge collapse area I
Leading edge collapse area I is located in the front section of the reactivated area, with a sliding direction of 296°. The area is about 220 m long and 520 m wide, covering an area of $1.4 \times 10^6$ m². The
slope topography is gentle, with an original gradient of about 10–15°. The leading edge was scoured by the XJC River to form multiple slumping blocks, forming a high and steep free face, with a slope height of about 70–80 m and a gradient of 35–45°. The geomaterial of the downstream side has a low cohesion; the tensile fractures are densely developed in parallel, with a strike of 85° (Fig. 4d). The cracks are distributed in an arc shape, extending and penetrating to the free-face direction.

3.2.2. Middle bulging area II
Middle bulging area II is located in the middle part of the slope, with a length along the sliding direction of 550–600 m and a lateral width of 400–460 m, covering an area of $2.2 \times 10^5$ m², which is the largest area. Area II is characterized by the most intense deformation, manifested as bulging, tensile, and shear cracks. The bulging cracks, basically formed by extrusion, are distributed in areas adjacent to areas III and IV, where the local collapse of rock-soil mass occurred under compression (Fig. 4e). The tensile cracks are distributed in the trailing edge and the middle of the landslide in an arc-shaped transverse direction. The trailing edge cracks in area II are connected with those in areas III and IV, and a scarp with a height of about 15–20 m is formed in the trailing edge. Shear cracks, arranged in echelon, are found in the right boundary of the reactivated area, extending from the trailing edge to the surface of the slumping area in the leading edge.

3.2.3. Upstream cracking area III
Upstream cracking area III is located on the upstream side, with a relative elevation difference of 420–450 m. The area is 900–950 m long and 140–280 m wide, covering an area of $2 \times 10^5$ m². The deformation in area III is manifested as penetrating tensile cracks in the trailing edge and shear cracks. The trailing edge cracks are connected with those in areas II and IV. The penetrating shear cracks on the right side extend from the trailing edge of the upper slope to the surface of the slumping area near the XJC River in the leading edge, where the tensile cracks are locally developed (Fig. 4a).

3.2.4. Downstream cracking area IV
Downstream cracking area IV is located on the downstream side, with a relative elevation difference of 80–140 m. The area is 230–250 m long and 200–210 m wide, covering an area of $4.8 \times 10^4$ m². The deformation in area IV is manifested as penetrating tensile cracks in the trailing edge, which are connected with cracks in the trailing edge of area II. The dislocation of the head scarp was 15–30 m in the vertical direction (Fig. 4b). The bulging cracks are distributed in the fan-shaped radially, near the trailing edge of the upper slope in area IV.
Figure 2. Topographical map of the reactivated ANZ landslide

Figure 3. Geological longitudinal profile A-A’ of the reactivated ANZ landslide along the main sliding direction
Figure 4. Typical reactivation characteristics of Aniangzhai (ANZ) landslide; (a) tensile cracks in area III; (b) head scarp in area IV; (c) overview of reactivated ANZ landslide; (d) tensile crack in area I; (e) bulging cracks in area II

4. Triggering mechanism
Based on field investigation, unmanned aerial vehicle surveys and geophysical prospecting, the factors causing reactivation and failure process are discussed.

4.1. Factors contributed to reactivation

4.1.1. Topography and geomorphology
The geomorphologic type of study area is an erosional mid-alpine canyon landform. The gradient of the original slope is steep and gentle in the upper and lower parts, respectively. The terrain on the left side is steep, with a bedrock outcrop, and the right side is adjacent to a small ridge. A steep slope with a height of 50–100 m forms in the trailing edge. The soil mass in the leading edge collapses to form a
steep slope with a relative height difference of 50–80 m, and the gradient is 35°–45°; thus, providing superior free-face conditions for the slope failure. Due to the sliding of an ancient landslide, the landslide area shows a round-backed armchair terrain, with a high elevation of lateral boundaries, which is conducive to the catchment and infiltration of rainwater.

4.1.2. Lithology
The sliding mass consists of gravel soil that experienced the ANZ ancient landslide. Collision and disintegration occurred during the formation and movement of the early ancient landslide. Additionally, the free accumulation of fragments maintained a relatively unconsolidated structure, demonstrating that the ancient landslide accumulation layer had high porosity and water-rich nature[11]. The following findings arise from geophysical prospecting results. First, the apparent resistivity is 80–500 Ω·m ranging from 0 to 80 m below the surface, which is speculated to be gravel soil. Second, the apparent resistivity gradient between 80 and 120 m is relatively large, suggesting a weak interlayer sliding surface. Third, below 120 m is supposed to be relatively complete bedrock. Finally, there is a concave low resistance area at a depth of 0–120 m in the middle of the landslide, with overall apparent resistance of 50–300 Ω·m, speculating that the area is extremely rich in water (Fig. 5). Therefore, the ancient landslide deposits allow rapid infiltration of precipitation and surface water.

4.1.3. Heavy rainfall
According to the data from the Danba Meteorological Bureau, from 23:40 on June 16 to 02:30 on June 17, heavy rain fell in most towns and villages in Danba County, with the maximum hourly precipitation within three hours reaching 61.80 mm. The maximum rainfall intensity was 34.1 mm/h, equivalent to a 50-year return period rainfall intensity in Danba County (Fig. 6). For one thing, the cumulative rainfall in the early stage weakened the physical and mechanical properties of the ANZ ancient landslide; thus, reducing the anti-sliding force of the slope. The results of the laboratory direct shear test show that the cohesion (c) and internal friction angle (φ) of slip zone soil in the natural state are 11.5 kPa and 25°, respectively. In a saturated state, these two values decrease to 10.8 kPa and 23.8°, respectively. For another sliding force of the slope increased due to an increase in sliding mass density from 21.0 to 23.0 kN/m³. Furthermore, short-term rainstorm on June 17 induced the Meilong debris flow, resulting in scouring and erosion of the slope toe of the ANZ ancient landslide.

4.1.4. Fluvial erosion
On June 17, the Meilong debris flow broke out with a volume of about $4 \times 10^5$ m³. Then, it rushed into the XJC River, raising the riverbed by 8–12 m, and the backwater formed a dammed lake. Afterward, the river overflowed the front section of the deposit with a new river channel formed at the foot of the ancient ANZ landslide. The intense fluvial erosion collapsed the leading edge abruptly and enlarged the free-face continuously, leading to the reactivation of the ancient ANZ landslide. On July 17, the water level of the XJC River rose again, and the river discharge was 680 m³/s. The slope toe of the area I was eroded and then collapsed, increasing the landslide deformation rate sharply. The deformation rate gradually decreased with the subsidence of the water level. Therefore, fluvial erosion is the main driving factor for reactivation.

4.2. Evolution process of reactivation
Combined with geological, geomorphological and meteorological factors contributed to the reactivated ANZ landslide. It can be inferred that the slope geomaterials and topography provide the precondition for reactivation. While the external factors, such as rainfall and fluvial erosion, are offered, the mechanical parameters of rock-soil mass and surface morphological characteristics gradually deteriorate, leading to the occurrence of the activated landslide. Based on the above analysis, the possible evolution of the reactivated landslide is represented in Fig. 7. It proposes three stages of the reactivation mechanism: leading edge collapse, traction deformation, and compound sliding with incipient retrogressive failure and latter progressive slide. Continuous rainfall in the early stage made
the reactivated area in a critical state, and the soil mass on the left bank of the XJC River was saturated, reducing the shear strength (Fig. 7a). The Meilong debris flow rushed into the XJC River and raised the water level. The intense scouring of the river on the slope toe directly induced multiple collapses in area I and formed a free face beneficial to landslide (Fig. 7b). Under the traction of area I in the leading edge, the sliding mass in the area II started slipping, and the cracks on the slope gradually expanded and penetrated from the leading edge to the rear, collapsing the trailing edge (Fig. 7c). The bulging deformation occurred in the middle and front of the area II, with radial bulging cracks on the road and tensile deformation on the local scarp section, and the landslide entered the stage of compound sliding (Fig. 7d). Afterward, the trailing edge cracks in the area II extended to area IV. Additionally, the sliding mass in the area IV deformed toward the free-face gully continuously and squeezed the soil mass in the area II due to resistance by the bedrock in the left boundary. Since the upstream boundary of area II penetrated and fell, favorable free-face conditions were provided for area III. Thus, tensile deformation occurred in area III toward the downstream of the XJC River, squeezing the soil mass in area II (Fig. 7e).
Meteorological Bureau

Figure 7. Reactivation mechanism of the ANZ landslide; (a) deformation in early stage; (b) collapse in leading edge; (c) traction deformation; (d) compound sliding with incipient retrogressive failure; (e) compound sliding with latter progressive failure

5. Conclusion
This study presents a detailed analysis of the mechanism of the reactivated ANZ landslide. Field investigations, unmanned aerial vehicle surveys, and geophysical prospecting were performed to analyze its characteristics and contributing factors and deduce the reactivation evolution process. The main conclusions are listed as follows:

1. The ANZ ancient landslide is located on the left bank of the XJC River in Danba County, Sichuan Province, with an area and volume of 1.2 km$^2$ and $8 \times 10^7$ m$^3$, respectively. The reactivation in 2020 occurred within the reactivated sliding mass of $4 \times 10^7$ m$^3$, with an average thickness of about 65 m, covering an area of 0.62 km$^2$.
2. Based on the resurrection time sequence revealed by field investigation and deposit characteristics, the reactivated ANZ landslide can be divided into four areas: area I—leading edge collapse area; area II—middle bulging area II; area III—upstream cracking area; area IV—downstream cracking area.
3. The ANZ ancient landslide reactivated after a short-term rainstorm; it was induced by several factors. The topography and unconsolidated rock-soil mass were predisposing factors for reactivation, conducive to free-face conditions and rainfall infiltration. The combination of rainfall and fluvial...
erosion of the slope toe triggered the landslide. The fluvial erosion played a dominant role, closely related to the Meilong debris flow and river discharge.

4. The deformation and failure of the slope mainly experienced three stages: leading edge collapse, traction deformation, and compound sliding. The intense scouring of the slope toe caused multiple collapses in the leading edge of area I, and the area II started slipping under traction of area I. Affected by the deformation of areas II, III, and IV deformed and squeezed area II to generate bulging cracks. The overall development of failure could be determined as a compound sliding with incipient retrogressive failure and a latter progressive slide.

6. References

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