Dynamic analyses of high-position long-runout landslide in Shuicheng, Guizhou, China: perspectives from overloading erosion effect

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Abstract. On July 23, 2019, a large-scale, high-position landslide was triggered by heavy rainfall at Pingdi Village, Jichang Town, Shuicheng County, Guizhou, China. Based on a field investigation, multi-temporal remote sensing images, and topographic maps, the elevation of the crown of the landslide and the front edge was approximately 1700 m and 1233 m, respectively. The height difference of the landslide was 467 m, and the horizontal distance was approximately 1332 m with a main sliding direction of NE20°. Its volume was up to 1.81 million m³. The landslide buried 21 houses, leading to the death of 51 people. The landslide first exited from the upper part of the steep slope in the Emeishan Formation with a basaltic lithology, which accumulated continuously at the back of a previous residual landslide and triggered the slope instability under the exit. The erosion volume due to the “overloading effect” was up to 1.44 million m³, and the landslide then transferred to a long-runout double-channeled debris flow. The landslide then converted to diffused flow and finally accumulated to the east side of the Jichang reservoir because the terrain was wide and the slope angle decreased gradually. Based on the above investigation, the entire movement process of the Jichang landslide was retrieved using dynamic numerical simulation technology. In contrast to the previous erosion model, the overloading erosion effect was proven, which added loads and drove the deposit below to move downward together.
1. Introduction

High-position and long-runout rockslide-debris avalanches have occurred frequently in the mountainous areas of southwestern China, resulting in huge losses of human life and property. They often suddenly slide from the ridge crest or high positions on steep slopes, impact and scrape a large volume of surface materials, and produce high-speed debris avalanches, which are then transformed into debris flows that accumulate and even block the frontal river valley (Xing et al., 2014; Zhang et al., 2014; Fan et al., 2020; Ouyang et al., 2019). Research on the dynamic processes of the landslide evolution is of great significance for the early identification, early warning, risk assessment, and prevention of landslide hazards. The strong entrainment (also called dynamic erosion) often increases the accumulation volume of the debris avalanche. On June 24, 2017, a catastrophic high-position, long-runout landslide debris avalanche occurred in Xinmo, Maoxian, Sichuan Province. The initial landslide volume was only 3.90 million m$^3$, but the final volume was 16.4 million m$^3$, which was more than four times the original volume. In 2019, successive rockslides and repeated damming occurred along the Jinsha River over a very short time. In particular, the second rockslide, which had a slide volume of approximately 1.6 million m$^3$, slid rapidly and applied an impact load to the upper part of the residual mass of the first landslide, leading to an entrainment volume of approximately 6.6 million m$^3$. On February 7, 2021, a massive rock and ice avalanche occurred at Chamoli, Indian Himalaya, in which initial volume of the landslide was approximately 19.1 million m$^3$, and the estimated total accumulation volume was 63 million m$^3$ (Fan et al., 2020; Ouyang et al., 2019; Xu et al., 2018; Wang et al., 2019; Mazoomdaar, 2021).

Liquefied models, rheological models, grain flow models, sled models, and discrete element models are generally used to simulate the dynamic erosion process during landslide evolution (Hungr et al., 1995; Sassa et al., 2014; Xing et al., 2014). More recently, 3D discrete element packages, i.e., the Engineering Discrete Element Method (EDEM) and the Particle Flow Code, are being used increasingly to simulate the granular nature of the flow of landslide material. In particular, a new overloading erosion model was proposed based on the impact-sliding process of the lower-old landslide due to accumulated loading effects that could explain the huge entrainment volume in southwestern China (Yin et al., 2017).

In this paper, based on field investigation and numerical analysis, the high-position and long-runout landslide that occurred in Jichang Town, Guizhou Province, was used as an example to analyze the overloading entrainment processes and the related dynamic characteristics, which included the following: (1) providing the basic characteristics and failure mechanism of the Jichang landslide based on the investigation; (2) analyzing the dynamic processes through numerical analysis; (3) conducting numerical analysis of the overloading erosion effect as an important cause of the scale-up of the landslide.

2. Environmental geologic setting

At 8:40 p.m., on July 23, 2019, a landslide with a volume of approximately 1,810,000 m$^3$ occurred in Jichang Town, Shuicheng County, Guizhou Province, China (104°40’02.52”E, 26°15’19.62”N, see Fig. 1–2). After the landslide, the sliding material shoveled along the slope and two gullies and then evolved into a high-position and long-runout debris flow. Finally, it destroyed the houses along the slope by the tremendous impact and accumulated on
the east side of the Jichang Reservoir, which blocked the reservoir, leading to the death of 51 people.

**Figure 1.** Location of the Jichang landslide in Shuicheng County, Guizhou Province.

The landslide occurred in the southwest margin of the Yangzi platform, which also belongs to the watershed zone of the Beipanjiang River, and the main regional tectonics of the landslide area is mainly the Faer vortex structure, which is accompanied by many small faults and folds. Deep V-shaped gullies often develop along the slope surfaces, and the landscape morphology is relatively steep in this area. The surface strata observed at the landslide comprises mainly the Upper Permian Emeishan basalt group (P$_2^\beta$2-3) and Upper Permian Longtan–Dalong Formation (P$_2^l$d) sandstone (Fig. 1) (Zheng et al. 2020; Xu et al. 2010). Many catastrophic landslides developed in Permian Emeishan basalt, such as the 1965 Lannigou landslide in Luquan County, Yunnan Province, with a volume of 390 million m$^3$, which buried 444 people, and the 1991 Touzhai landslide in Zhaotong City, Yunnan Province, with a volume of 9 million m$^3$, which killed 216 people (Xu et al. 2010).
Figure 2. Comparison of the images before and after the Jichang landslide, Guizhou. (a) Google Earth image adopted before the landslide. The alluvial platform was entrained by the landslide above it; (b) UAV image after the landslide.

The surface lithology of basalt weathers strongly and forms a thick loose surface layer, approximately 12~25 m, whose shallow surface is clay-like. The middle part has many small broken blocks and open weathering fissures. It is rich in fissure water, with a flow that can reach up to 1.0 L/s. Multiple small landslides can be found on both sides of the sliding source area (Fig. 3).

Figure 3. Small landslides can be found near the sliding source: (a) strongly weathering basalt, and (b) broken formation.

According to the rainfall data provided by the nearest weather station in Pingdi Village (Jichang Town station served as a trend comparison analysis), the average annual precipitation in the landslide area is 1137 mm (From 2007 to 2017). After the beginning of the flood season in 2019, the maximum daily rainfall was 98 mm, which was close to that during the same period in previous years, 103.6 mm. Between June 24, 2019, and the onset of the first landslide (June 23, 2019), the cumulative rainfall at the station was 323.5 mm (Fig. 3). The abundant rainfall finally triggered the landslide. During the three-day period before the landslide (July 22 to 24), there was a heavy rainfall event of 98 mm, starting at 8:00 PM on July 22 and ending at 4:00 AM on July 23, with a maximum hourly rainfall of 58 mm (Fig. 4).
3. Post-landslide characteristics

Based on multi-period remote sensing images, the post-landslide UAV image and actual ground survey, the landslide had a rear edge elevation of approximately 1700 m and a front edge elevation of 1233 m, with a maximum horizontal distance of 1332 m long and 207 m wide. The area was approximately 1.55 million m$^2$, and the average sliding depth was approximately 10 m. According to the above estimation, the volume of the landslide was approximately 1.81 million m$^3$.

The entire landslide area was roughly rectangular, trending NE20°, and it can be divided into four zones: the sliding source area, entrainment area, debris flow area, and accumulation area (Figs. 5 and 6).

In the sliding source area, the outlet of the slip surface was located below the Jichang–Longchang road, where approximately 40 thousand residual sliding mass remained (Fig. 5a). Fissure water seeped in streams from bedrock fissures in the prominent scarp of the landslide. According to the multi-period remote sensing images, there were no apparent signs...
of slope construction on the Jichang–Longchang road before April 2019. By April 2019, the road widened through slope excavation and filling behind the retaining wall (Fig. 5b–5d).

In the entrainment area, based on the occurrence of two locations with a slightly raised microtopography in the terrain, the landslide mass appeared to have collided directly with and entrained the alluvial platform, with the maximum erosion depth reaching more than 10 m (Fig. 2, 5a). This erosion process gave it the dynamic characteristics of overloading erosion. Furthermore, this area was also the upstream of two gullies, the retrogressive erosion of which made the platform base looser and easier to slide. The landslide converted to a debris avalanche because of the considerable impact force.

![Figure 6. Zoning map of the Jichang landslide in Guizhou. The yellow dotted lines represent the Jichang–Longchang road. The yellow circle denotes the observation points. The purple region denotes the area of destroyed houses.](image)

The sloping terrain had slowed down in the debris flow area, changing from 20° to 5–10°. The sliding mass was divided into two parts and continued to move along two gullies, which then transformed into two pipe-type debris flows because of the high moisture content in the material. Destroyed houses were found mainly in this area (Figs. 5 and 6). The unaffected area formed a safety island, which is very much like a cone insert that could affect the speed of debris flows.
In the accumulation area, the pipe-type debris flows came together and transformed into fan-like debris flow due to the open and concave terrain in the front. The debris flow formed a surging impact that caused mud splashing, which affected the road below, as well as an air surge that pushed down the trees on the opposite slope.

![Diagram of geological section](image)

**Figure 7.** Engineering geological section along the profile line A-A' in Figure 4.

The grain-size distribution on the surface of the deposit (Fig. 5) was estimated at three sample points (Fig. 7). The sample points were mainly at the debris avalanche and debris flow areas. Each of the grain-size distributions was divided into four grain-size groups: >100 cm, 50 ~ 100 cm, 10 ~ 50 cm, and <10 cm. The sample point from the source area (S1) contained the coarsest material. The portion of boulders larger than 10 cm was approximately 40%. The sample point from the accumulation area (S3) had the finest material, containing grains mainly smaller than 10 cm, comprising more than 90% (Fig. 7). This suggests that the landslide body had fragmented in the runout process, particularly in the entrainment and debris flow phases.

![Grain-size distribution](image)

**Figure 8.** Grain-size distribution at the observation points on the surface in Figure 4.

4. Runout analysis

The prevailing international easy formula for estimating the speed of the large landslide on the base of the sled theory was as follows (Scheidegger 1973):

\[ v = P_1 \beta^2 \]
\[ V = \sqrt{2g(H - f \times L)} \]  \hspace{1cm} (1)

where \( g \) is the gravitational acceleration; \( H \) is the height difference from the starting point to the estimating point; \( L \) is the horizontal distance from the starting point to the estimating point; \( f \) is the tangent of effective friction angle, which is the angle of a line from the avalanche starting point to the most distant end of the debris from the longest-running avalanche.

The geometric relationship can be obtained based on the above formula (Fig. 8). The deduced moving velocity of the landslide reached 35.19 m/s at the exit (point A), then 35.19 m/s in the bottom of the entrainment area, and a maximum of 54.62 m/s in the debris flow area (point C). When it reached 50.43 m/s, (point D), the velocity decreased rapidly to zero (Fig. 8). The velocity values based on the sled model are always larger than those in realistic processes. Therefore, further analysis is needed to compare with other methods, e.g., the Discrete Element Method model (Wang et al., 2019).

5. Erosion effect analysis

For the entrainment area, the erosion effect was tested using many models mentioned before. Of these, Kang et al. (2018) used a Discrete Element Method model to understand the entrainment process between moving and stationary particles because entrainment begins when the moving particles reach the erodible bed (Fig. 9). Erosion occurs when the front edge of flowing particles arrives at the stationary particles in the flow channel, including the impact, then plow (i.e., a form of dynamic shear) and low-angle shear across the channel boundary.

![Figure 9. Velocity at the various stage of sliding downward.](image)

![Figure 10. Dynamic erosion process of flowing particles at different times (Kang et al., 2018).](image)

This process above is an ideal erosion model considering that the below particles are confined to a concave terrain. Below the old deposit, there are many types, among which, the
main one is a stable or almost-stable accumulation body or talus or young cover. In this paper, the alluvial platform can be seen as a stable accumulation body without boundary confinement.

EDEM software was used to perform the overloading erosion process of the Jichang landslide, which was written by Discrete Element Method (DEM) Solutions. EDEM® is a Computer-Aided Engineering software that simulates particle movement and the interaction of particles based on the DEM (Cundall et al., 1979). The Hertz–Mindlin (no-slip) contact model is the default model used in EDEM because it is an accurate and efficient force calculation. Table 1 lists the physical and mechanical parameters, and Table 2 presents the properties governing the particle-particle and particle-path interactions used in the numerical simulations.

**Table 1. Physical and mechanical parameters**

| Parameter                                      | Value  | Remarks                      |
|-----------------------------------------------|--------|------------------------------|
| Young’s modulus (GPa)                         | SR=43 / DAF=2.5 | Xu et al. (2010); Li et al. (2020) |
| Poisson’s ratio                                | SR=0.21 / DAF=0.38 | Liu et al. (2005) |
| Density (kg/m³)                                | SR=2460 / DAF=1960 |                             |
| Cohesion (kPa)                                 | SR=65 / DAF=21.01 | Li et al. (2020); Guo et al. (2020) |
| Friction angle (°)                             | SR=30 / DAF=21.8 |                             |
| Tensile strength (kPa)                         | 0      |                              |

**Table 2. Properties governing the particle-particle and particle-path interactions**

|                  | Particle-particle | Particle-path |
|------------------|-------------------|---------------|
|                  | SR-SR             | SR-DAF | DAF-DAF | SR-path | DAF-path |
| Coefficient of restitution | 0.49  | 0.35   | 0.35   | 0.3     | 0.35     |
| Coefficient of static friction               | 0.57  | 0.40   | 0.40   | 0.57    | 0.42     |
| Coefficient of rolling friction               | 0.035 | 0.04   | 0.05   | 0.07    | 0.05     |

**6. Results and discussion**

Figure 10 shows the EDEM simulation results of the Jichang long-runout landslide reconstructed using the Hertz–Mindlin (no-slip) contact model and the overloading erosion process. The sliding processes of the landslide are shown at different times. The blue and red particles represent the moving landslide materials and the platform formed by the alluvial cover, respectively.

At 16 seconds, the above landslide mass fell gradually onto below the alluvial cover on a
small scale. At 12 seconds, the above landslide mass impacted the alluvial cover and pushed it forward, with the characteristics of low-angle shear on the surface of the alluvial cover. At 16 seconds, the above landslide mass continued to push the alluvial cover with the obvious characteristics of low-angle shear on the surface of the alluvial cover. At 20 seconds, the landslide mass and the alluvial cover flowed downward at the same time. At 90 seconds, the landslide mass and the alluvial cover accumulated at the bottom, and the landslide mass was still on the surface of the alluvial cover.

The debris flow formed by the overloading effect simulated by DEM showed an obvious velocity dropping process in the entrainment zone (Figure 8) and then increased to the peak velocity in the debris flow zone, promoting a rapid and simultaneous increase in velocity. In addition, the velocity reached its peak value of 44 m/s in the debris flow area due to factors, such as the steepening of the terrain.

The above motion analysis showed that the upper landslide scrapes the surface rock and soil mass of the lower accumulation body and drives the accumulation body to move downward together, which is different from the erosion model along the depth proposed previously.

Figure 11. EDEM simulation results for the landslide and overloading-erosion process.

7. Conclusions

On July 23, 2019, a large-scale high-position landslide was triggered by heavy rainfall at Pingdi Village, Jichang Town, Shuicheng County, Guizhou, China. The present study introduced the dynamic behavior of the landslide based on field investigations and simulations. The following summarizes the main findings:

(a) The landslide developed in Permian Emeishan basalt, where landslides occur easily, particularly during the heavy rain on July 22–23, 2019.

(b) The platform formed by the alluvial was impacted and entrained by the above sliding mass from the sliding source area. The landslide then converted to a debris avalanche, and the
debris then flowed in the two gullies. Finally, it transformed into a fan-like debris flow and accumulated in the accumulation area.

(c) This erosion process had the dynamic characteristics of overloading erosion, which was further proven by the DEM simulation, which added loads and drove the accumulation body to move downward together. This is different from the erosion model along the depth proposed previously.

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