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Scraping Effect of Dam-Overtopping Debris Flow—A Case Study of Chutou Gully ‘8.20’ in Miansi Town, Wenchuan County

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ABSTRACT

After the May 12 earthquake in Wenchuan, numerous debris flow disasters occurred due to heavy rainfall. After the earthquake, disaster prevention and mitigation projects, such as the sand dam, played an essential role in safety. However, when the outflow of solid material exceeds the designed storage capacity of the sand dam, the debris flow overtopping the dam intensifies the scraping effect on the source material of the gully channel. This paper takes the “8.20” debris flow in the Chutou gully as the research object. A transport mode of the debris flow after dam overtopping is studied through comprehensive field investigation, theoretical analysis, and indoor model tests. A quantitative evaluation model is established for the scraping depth and scraping volume of dam-overtopping debris flow. The study results showed that once the debris flow overtops a dam, the loose source carried by the channel is involved in the entire migration process, enlarging the fluid scale and intensifying the damage along the channel. The results agree with the measurements and observations, with maximum relative errors of 5.81% and 14.70%, respectively. This shows model validity. Furthermore, the test results show that the debris flow scarping phenomenon in the $\gamma=[1.4 \text{ t/m}^3, 1.6 \text{ t/m}^3]$ interval is the most significant. Overall, this study will help improve future engineering decisions, design strategies, and finding the best design solutions to minimize the risk of dam-overtopping debris flow disasters.

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KEYWORDS

Chutou gully; dam-overtopping debris flow; scraping effect; section flow method; model test

1. Introduction

After the Wenchuan earthquake on May 21, 2008, loose material on the slope surface gathered in the gullies and bank slopes on both sides of the gully, creating ideal conditions for debris flow with the onset of heavy regional rainfall (Cui et al. 2018; Liu et al. 2020; Pei et al. 2017). There have been several large-scale debris flows, such as on August 12, 2010, in Qingping Township, Mianzhu, Sichuan Province (M. Zhang, Yin, and M 2016), the large-scale debris flow on July 10, 2013, in Wulipo, Dujiangyan City, Sichuan Province (X. Z. Chen and Cui 2017), and the large-scale debris flow on August 20, 2019, in Banzi gully, Wenchuan County (D. W. Wang et al. 2022). Debris flows tend to have tremendous destructive power because of the potential for high capacity, high velocity, and high discharge characteristics. Sand dams following the “5.12” earthquake played an essential role in the comprehensive debris flow disaster reduction, as they are the principal disaster prevention and mitigation engineering strategy, and, to a certain extent, it has curbed the development speed of geological disasters such as debris flows.

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With the siltation of the reservoir area accompanying the sand dam, once the debris flow breaks, it overtops the dam and rushes out, eroding the loose source materials of the channel, thus amplifying its one-time rush-out volume and resulting in more damage to the existing infrastructure and posing severe threats to human life and properties. For instance, after the “8.8” debris flow outbreak in Zhouqu, Gansu Province, in 2010, under the full storage capacity cascade blockage effect formed by the blocking dam, the flow velocity and flow rate after the debris flow overtops the dam increased, thereby increasing the destructive force during the debris flow movement process (Chong et al. 2021; M. Zhang, Yin, and M 2016). During the Wenjia gully catastrophic debris flow disaster on August 13, 2010 (J. Huang et al. 2019; Kang et al. 2021), the strong scraping impact eroded and scraped a deep groove of more than 700 meters downstream, transporting about $310 \times 10^4 \text{ m}^3$. On July 4, 2013, a large-scale debris flow occurred in the Shimian Hou gully, Sichuan Province (Chang et al. 2020; Dai et al. 2021). After the overtopping of the dam by the debris, the gully channel source materials were constantly supplemented, which gradually expanded the scope of the replenishment area and enhanced the hazard capacity. The total volume of solid substance washed out exceeded $15 \times 10^4 \text{ m}^3$. On August 8, 2017, there was a catastrophic debris flow in Tongzilin gully, Puge County, Sichuan Province (L. Wei, Hu, and Liu 2022; Zhong et al. 2021). The bottom of the gully channel and bank slope side were eroded after the fluid overtopped the dam through several stages of erosion, scraping, impact flight, accumulation, and burial, increasing the damaged area and size of the disaster.

Most studies focus on landslide-debris flow and the high-speed remote landslide scraping effect (Perrone et al. 2021; Qi, Yu, and Ren 2016; Y. F. Wang, Dong, and Cheng 2017). In addition, some studies have focused on the formation mechanism and scraping depth of erosion pits under dams that are overtopped due to debris flow. Pan et al. (2013; 2013b) studied the shape of the erosion pit beneath the dam under various working conditions through flume experiments and obtained the law that the position of the maximum depth point moves downstream with the increase in slope angle. The theoretical formula for calculating the erosion pit depth downstream of the flood discharge dam is typically derived from physical model experiments. Previous studies have found that the scraping depth mainly depends on the bulk density, flow rate, flow depth, particle gradation of the movable bed, and longitudinal gradient of the channel (H. Y. Chen et al. 2019). Yang et al. (2018) conducted a scaled physical model test (1:2000) of the Wenjia gully debris flow. By changing the initial scale and kinetic energy, they obtained the variation law of scraping depth under the dam, gully bed thickness, and entrainment depth. Furthermore, they qualitatively analyzed the scraping characteristics during debris flow movement over the dam.

Several studies utilized digital elevation models (DEM) data generated by UAV aerial remote sensing images to obtain the erosion changes along the overtopping dams due to debris flow (T. Huang et al. 2021; Liu et al. 2021). Studies in some countries and regions show that using the real-time monitoring system can track the debris flow scraping phenomenon and study the velocity, flow, and erosion of debris flow in the process of migration by analyzing dynamic image data (Imaizumi, Tsuchiya, and Ohsaka 2016; D. W. Wang et al. 2022). The model test results of Haas and Woerkom (2016) showed that the scraping depth gradually transits to the downstream gully bed and finally forms a relatively uniform erosion morphology. The scraping depth increases with the rise in the river slope, flow velocity, flow depth, flow, and shear stress.

With the development of computing technologies, many started to study the dynamic characteristics of dam overtopping debris flow migration evolution and erosion through numerical simulation analysis methods. They used the fluid-solid coupling model to simulate the debris flow overtopping migration process. The fact that soil layer scraping increases the fluid volume of the debris flow was confirmed by modeling the erosion and entrainment of the erodible soil base (Lee and Jeong 2018, 2022). Han et al. (2019) adopted the smoothed particle hydrodynamics method based on the Bingham model to conduct back analysis and simulate the dynamic characteristics of dam overtopping debris flow. Generally, the simulation results are in good agreement with the field measurements.

The current research on the debris flow scraping effect mainly focuses on the scraping characteristics and morphology of erosion pits under the dam and the scraping mechanism of the original gully

bed after the debris flow outbreak. There are few studies on the influence of the sand dam itself after engineering treatment on the dynamic characteristics of debris flow erosion and migration in dam overtopping. More specifically, there is no quantitative evaluation method for the scraping depth, scraping volume, and other indicators of debris flow. Based on this, there is an urgent need to study the scraping effect of dam overtopping debris flow.

Thus, this paper constructs a quantitative statistical model of the scraping effect in the dam overtopping debris flow erosion migration process and puts forward the migration evolution mode, scraping morphology, and the laws governing dam overtopping debris flows. The “8.20” debris flow in the Chutou gully in 2019 is used as a case study. Preliminary field investigations (high-resolution remote sensing image, UAV shooting, satellite positioning technology, field particle screening test, etc.) combined with the cross-sectional flow method and the scale physical model test were conducted. This study provides a scientific basis for analyzing scraping mechanisms after debris flow overtopping and the structural design of a sand dam.

2. Study Area

The Chutou gully is situated in Qiangfeng Village, Mian’si Town, Wenchuan County, Sichuan Province, roughly 2.5 km from Mian’si Town (Fig. 1). The Gully is bounded by longitude 103° 27’ E –103° 28’ E and latitude 30° 20’ N–31° 21’ N, with ~21.7 km² basin catchment area. The debris flow gully mouth is near the Duwen Expressway and national highway G213. The current repaired tractor

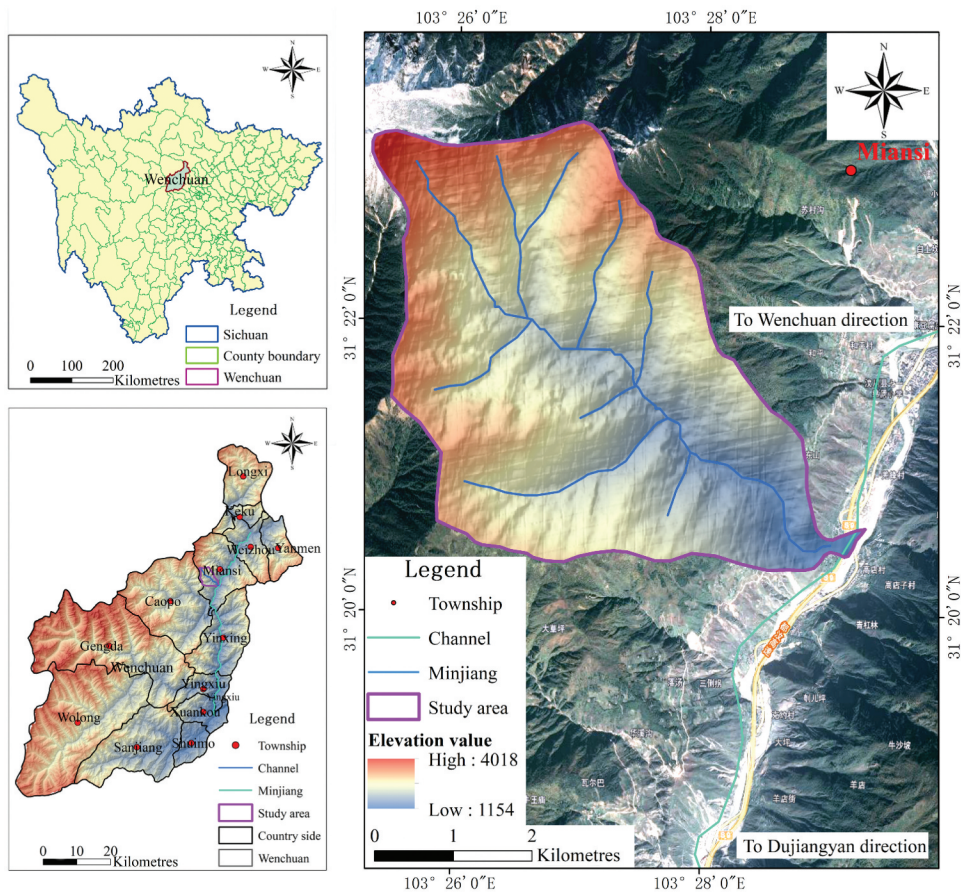


Figure 1. Location and elevation of the Chutou gully and study area (purple outline). Modified from the water injection vector map.

road in the gully connects directly to the residential section of Qiangfeng Village in the gully mouth, making local transportation extremely convenient.

The Chutou gully catchment is located at the junction of erosion-denudation low mountains and deep-cut middle mountains. The overall bank slope in the catchment is steep, and the cutting depth is significant. The free space surface is strongly developed, resulting in adverse geological phenomena such as landslides and collapses. This situation provides advantageous topographic conditions for transporting the loose source materials and initiating and developing debris flows. The overall drainage basin is fan-shaped, with many branch gullies. It has an elevation of 1154–4130 m, and the longitudinal gradient of the main channel is 110‰–702‰. The gully is narrow with a steep longitudinal gradient, and the undercutting erosion of the gully bed is significant. The study area is located downstream of the Chutou gully, with a length of about 2 km. The longitudinal gradient of the channel is relatively gentle, and most debris flow erosion, scraping, and deceleration accumulation zones are located along its length.

Over the past 25 years, the annual average rainfall in the area has been 716 mm, with the annual maximum rainfall of 834 mm (2014) and the highest monthly rainfall in July of 92 mm (July). The annual rainy season is from May to August. The maximum rainfall is 326 mm or 62.2% of the annual total, and the average number of rainfall days is 150.6 days. The rainfall distribution in the Chutou gully catchment is irregular throughout the year, with a significant difference between annual and interannual rainfall and a phenomenon of intense rainfall in summer. The rainfall in the study area is rich and concentrated, which can meet the hydrodynamic conditions required to stimulate debris flows.

The Chutou gully is an old debris flow gully. Historically, there have been six debris flow disasters, including two small-scale flows in 1976 and 1999 and four large-scale flows on July 10 July 15, 2013 August 20, 2014, 2019, and August 17, 2020. After the large-scale debris flow outbreak in the Chutou gully area on August 20, 2019, two sand dams built in the catchment have blocked fluid and debris flows. The number of solid substances in a debris flow at the gully mouth is about $75 \times 10^4 \text{ m}^3$, as the scale of this debris flow outbreak exceeds the design working condition. Accordingly, in the siltation of the existing 1 and 2 # sand dam reservoir area in the Chutou gully basin, the apron of 1 # sand dam was seriously damaged. The front edge was eroded (Fig. 2A), and the revetment wall and the unilateral protective embankment on the left bank were eroded and washed away. The impact scraped and destroyed the drainage canal at the gully mouth, and the middle and lower sections of the gully were silted up and raised by 5–10 meters. More than 10 households in groups 2, 3, and 4 of the Qiangfeng Village were damaged at the mouth of the gully. The Duwen expressway was buried under ~200 meters of sediment. The solid source material of debris flow overflowed the bridge deck of the expressway and rushed into the Minjiang River, and the Gaodian bridge on line G213 was destroyed (Fig. 2B).

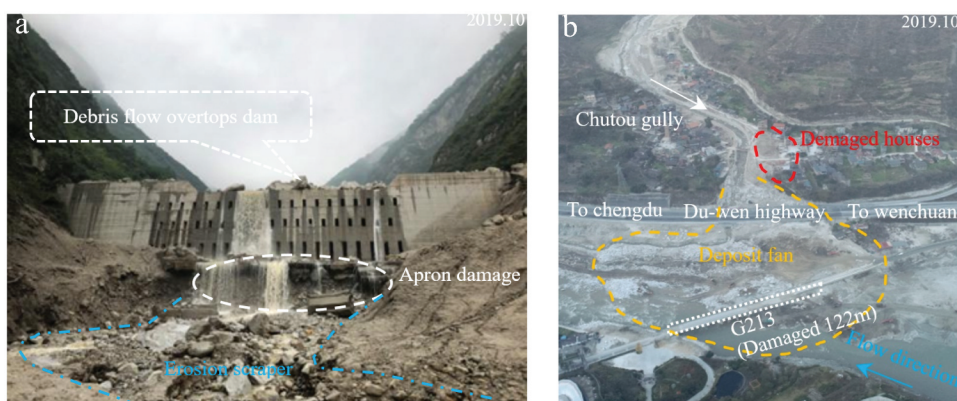


Figure 2. Damage caused by “8.20” debris flow overflowing dam.

Table 1. Image and terrain data of the study area.

Type	Image source	Acquisition time	Spatial resolution (m)	Scale	Effect
High-resolution remote sensing image	GF1	2018.05	0.6	/	Comparison of Migration Characteristics and Scraping Effect Before and After Debris Flow Outbreak
	GF1, ZY3	2019.10	2	/	
Topographic map	UAV geographic information mapping	2018.06	/	1:500	
		2019.09	/	1:500	
Digital elevation model (DEM)	ALOS	2019.05	12.5	/	Generation of slope, elevation, contour, and hillshade

The Chutou gully catchment was selected as the research object of this paper mainly because this region belongs to the “5.12” Wenchuan earthquake extreme seismic area, with strong geological structure and frequent geological disasters in the catchment. Therefore, research on the scraping effect of debris flow after dam overtopping in this region (1# the section from the existing sand dam to the gully mouth) has significant representativeness and is significant for engineering management of geological disasters in seismic areas.

3. Data and Methods

This study collected high-resolution remote sensing images, topographic maps with a scale of 1:500, and digital elevation models (DEM) from the two periods before and after the Chutou gully debris flow outbreak on August 20, 2019, as detailed in Table 1. It analyzes the migration and evolution characteristics, scraping trends, and scraping mechanisms of debris flows after dam overtopping. The evaluation method between scraping characteristic indicators and various influencing factors is quantified using the acquisition of early topographic and geomorphic data, combined with field investigation methods, cross-sectional flow method, and dynamic comparison of an indoor model test.

3.1. Section Flow Method

The cross-section flow method investigates the change of debris flow energy before and after the overtopping of the dam and the energy exchange with the gully source after entering the gully channel, determining the scraping depth of the debris flow erosion pit after the dam overtopping.

In the stage of flat throwing motion after the debris flow overtops the dam, the air resistance is ignored, and the energy is composed of two parts: kinetic energy and potential energy. The debris flow must have sufficient energy to overcome the erosion resistance of the gully bed accumulation source to generate an erosion pit once the dam overtopping (Fig. 3).

Debris flow movement is a dynamic process. The following assumptions were adopted before analysis: Firstly, without considering the effect of rainfall, the debris flow directly acts on the dry gully bed after overtopping the dam; Secondly, the particle size composition of debris flow before and after dam overtopping is identical. The bulk density of debris flow remains constant during the whole migration phase.

In the local amplification area in Fig. 3, the flow through an upstream element is:

$$dq = v_h dx dh \tag{1}$$

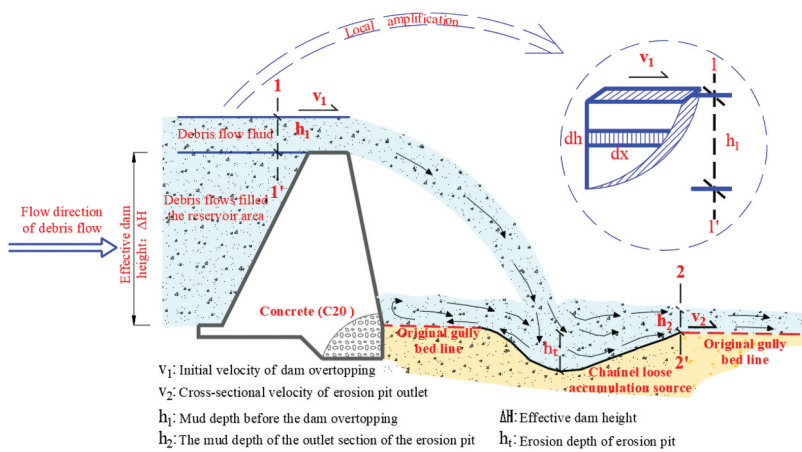


Figure 3. Schematic diagram of erosion pit formed by debris flow overtopping.

where v_h is the debris flow velocity, m/s; dx is the length of the element, m; dh is the element thickness, m.

3.2. Indoor Test Model Construction

According to the on-site investigation, the gully behind the Chutou gully 1# dam has a “U” shape. The overall slope of the gully bed is gentle, and the average thickness of the accumulation covering layer exceeds 10 m. Other parameters are shown in Table 2.

Due to the original channel being blocked by the landslide accumulation body, the gully channel changes and swings strongly under flood action. Therefore, this section is the primary source area of debris flow scraping.

According to the principle of similarity theory, following the similarity of various physical quantities such as debris flow fluids, a scaled test with a similarity ratio of 50 was ultimately conducted. Based on the on-site survey results, the average longitudinal gradient between the 1# dam of the Chutou gully debris flow and the gully mouth is 93‰ (5.5°). The slope of the acceleration section of the model groove movement is 8.0°, and the scraping (stacking) section is set as 5.5° in agreement with the calculation of 0.5–0.7 times the longitudinal slope of back siltation. Figure 4 illustrates the size of the test model groove with a total length of 6.2 m, and its acceleration section measured 2.0 m in length, 0.5 m in width, and 0.35 m in height. The scraping (stacking) section length was 4.2 m, the width was 0.5 m, the height was 0.5 (0.35) m, and the thickness was 0.2 m. The bottom was a steel plate, and the baffles on both sides were made of tempered glass and strengthened with angle steel.

Due to the significant influence of the upper limit particle size of solid particles in debris flows on the transport characteristics and dynamic characteristics of debris flows, the nonuniformity coefficients C_u of the solid particle grading curve (Fig. 5) before and after scaling were 18.33 and 18.24 based on the field screening test combined with the debris flow bulk density and solid-liquid separation tests.

Table 2. Calculated values of parameters for each section.

Position	Section peak flow rate $q(\text{m}^3/\text{s})$	Cross section mean velocity $v_c(\text{m/s})$	Average mud depth h/m	Exploratory trench position
Existing drainage canal inlet	691.13	5.41	3.5	TC01
Existing protective embankment entrance	627.87	4.94	3.1	TC02
Existing 1 # sand dam	613.61	4.21	2.5	TC03

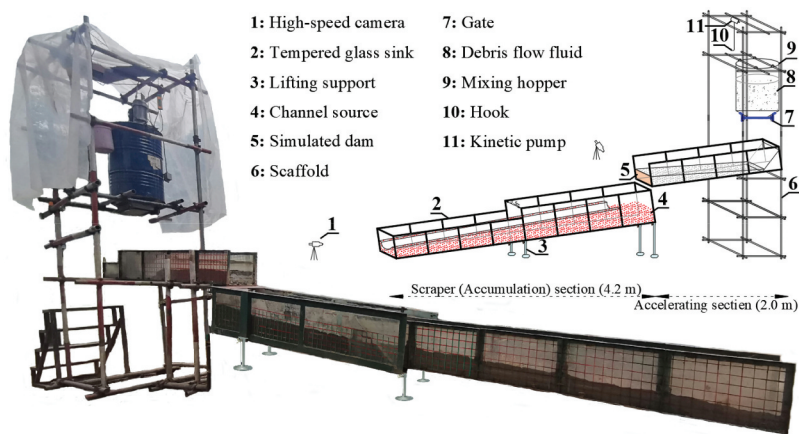


Figure 4. Schematic diagram of the indoor test model tank.

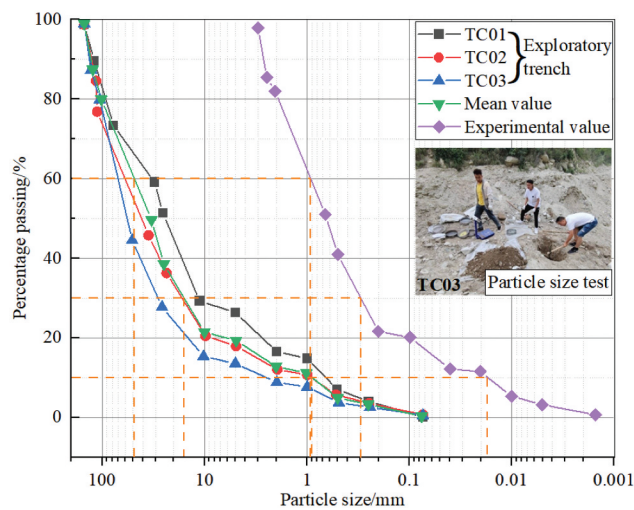


Figure 5. Particle grading curve.

The curvature coefficients CC were 6.30 and 6.21, consistent before and after scaling. This ensured the fluidity of debris flow fluid and showed no solid-liquid separation.

Three suitable test points were determined during the field screening test at equal intervals in the scraping accumulation area behind Dam 1#, represented by TC01, TC02, and TC03, as shown in Fig. 12. The sampling pit was $1.0\text{ m} \times 1.0\text{ m} \times 1.0\text{ m}$. In laboratory model tests, the mixture of gravel, sand, and silt was used as the test material, in which the source Grading ratio of the gully bed was 1:4:8:0.9, respectively. The bedrock material was compacted with clay.

This experiment was designed as 75 groups, a three-factor, five-level experiment. In order to better distinguish between debris flow fluids and gully bed source materials, an appropriate amount of red pigment slurry was added to the gully bed source materials during the experiment, making it easy to clearly observe the scraping phenomenon of the dam-overtopping debris flow during the gully transport process. Before the experiment, a glass graduated tube (with a diameter of 50 mm) was used to drill holes and take samples every 20 cm in the gully channel of the scraping section model groove and every 50 cm on both bank slopes. The covering layer and rock depth of the gully channel and both bank slopes were recorded, and the hole was restored to its original state after recording.

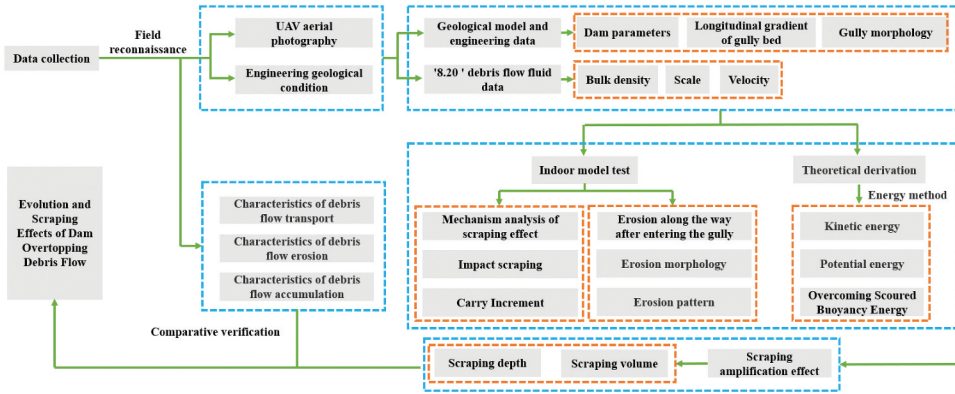


Figure 6. Technology framework.

After the discharge of debris flow materials in the hopper was completed and the overall flow stopped, the camera was turned off. New holes were drilled at 5 cm intervals upstream of the existing holes in the gully channel and both bank slopes. The thickness of debris flow fluid deposition, cover layer, and rock layer depth after the test were recorded and compared with those before the test.

Combining theoretical research and field investigations, the motion characteristics of the dam-overtopping debris flow under different parameter conditions were explored. A quantitative analysis model for the depth and volume of debris flow scraping was created. The mechanism of scraping effect of debris flow after turning over dam is discussed. Figure 6 is the technical framework.

4. Results and Discussion

4.1. Theoretical Analysis of Scraping Depth of Dam Overtopping Debris Flow

Debris flow fluid constantly changes throughout the migration process. The velocity distribution along the vertical section also varies. Numerous studies have proposed velocity distribution formulas based on theoretical analysis or field statistical methods (Takahashi 1993; F. Q. Yu 2009). However, the scraping effects of debris flows with various properties also differ throughout the process. In this paper, the empirical formula for the flow velocity of rarefied and viscous debris flows recommended in Southwest China is utilized (Jiang 2014):

$$v_C = \frac{1}{\sqrt{\gamma_H \Phi_C + 1}} \frac{1}{n} h^{\frac{2}{3}} I^{\frac{1}{2}} (\Phi_C = \frac{\gamma_C - \gamma_W}{\gamma_H - \gamma_C}; K = \frac{1}{\sqrt{\gamma_H \Phi_C + 1}}) \quad (2)$$

$$v_C = \frac{1}{n} h^{\frac{2}{3}} I^{\frac{1}{2}} \quad (3)$$

where v_C is the average velocity of debris flow section (m/s), γ_H is the bulk density of debris flow solid matter (t/m^3), Φ_C is the sediment correction coefficient of debris flow, γ_C is the bulk density of debris flow (t/m^3), γ_W is the bulk density of clean water (t/m^3), $1/n$ is the roughness coefficient (2.5–8.9), h is the average mud depth of the gully (m), and I is the longitudinal gradient of debris flow gully bed.

Substituting Eqs. (2) and (3) into (1) and integrating at the mud depth h_y , equations (2) and (3) are substituted into (1) and integrated at the mud depth h_y . The flow rates per unit width of diluted and viscous debris flows are:

$$q_1 = \frac{3}{5} \cdot \frac{k}{n} h_1^{\frac{5}{3}} I^{\frac{1}{2}} \quad (4)$$

$$q_2 = \frac{3}{5} \cdot \frac{1}{n} h_1^{\frac{5}{3}} I^{\frac{1}{2}} \quad (5)$$

The 2–2' section in Fig. 3 is considered the reference plane, where the debris flow consists primarily of kinetic and potential energy, represented by E_1 and E_2 , after overtopping the dam and before entering the gully channel. Assuming that the elevation before and after the formation of the erosion pit remains unchanged, the debris flow energy can be expressed as:

$$E_1 = \frac{1}{2} \gamma_C q v_1^2 \quad (6)$$

$$E_2 = \gamma_C q \Delta H \quad (7)$$

where γ_C is the bulk density of debris flow fluid (t/m^3), q is the unit width flow of debris flow, (m^3/s), v_1 is the initial velocity of debris flow overtopping the dam (m/s), and ΔH is the dam height (m).

The debris flow overtops the dam and impacts the downstream gully bed. After overcoming the erosion resistance of the gully bed material source, the surface material source is removed, forming an erosion pit. The energy consumed in this process is denoted by E_3 , while the energy of the debris flow fluid rushing out of the erosion pit (section 2–2') is E_4 :

$$E_3 = \frac{1}{2} h_t W_s \quad (8)$$

$$W_s = \frac{1}{2} (\gamma_s - \gamma_0) h_t g$$

$$E_4 = \frac{1}{2} \gamma_C q_1 v_2^2 \quad (9)$$

where W_s is the erosion resistance of the gully source (t), h_t is the scraping depth of the erosion pit (m), γ_s is the bulk density of the gully source (t/m^3), γ_0 is the bulk density of clean water (t/m^3), g is the acceleration of gravity (m/s^2).

Based on the law of conservation of energy, the energy consumed by collision and entrainment between fluid particles during migration, and the energy consumed by collision and entrainment between fluid particles and trench bed can be ignored. The energy balance relationship is as follows:

$$E_1 + E_2 = E_3 + E_4 \quad (10)$$

$$\frac{1}{2} \gamma_C q v_1^2 + \gamma_C q \Delta H = \frac{1}{2} (\gamma_s - \gamma_0) h_t g + \frac{1}{2} \gamma_C q_1 v_2^2$$

The maximum scraping depth of the erosion pit of a diluted debris flow and viscous debris flow can be determined as follows:

$$h_t = \sqrt{\frac{3 \gamma_C \frac{k}{n} I^{\frac{1}{2}} \left[\left(\frac{k}{n} \right)^2 I (h_1^3 - h_2^3) + 2 h_1^{\frac{5}{3}} \Delta H \right]}{5 (\gamma_s - \gamma_0) g}} \quad (11)$$

$$h_t = \sqrt{\frac{3\gamma_C \frac{1}{n} I^{\frac{1}{2}} \left[\left(\frac{1}{n} \right)^2 I (h_1^3 - h_2^3) + 2h_1^{\frac{5}{2}} \Delta H \right]}{5(\gamma_s - \gamma_0)g}} \quad (12)$$

4.2. Migration Evolution and Scraping Mechanism of Dam Overtopping Debris Flow

The mechanical characteristics, movement law, and scraping characteristics of dam overtopping debris flow differ from a general debris flow (Pan et al. 2012). The test results indicate that the debris flow over the dam has a noticeable amplification effect on the scraping depth and volume. This paper analyzes the evolution mechanism and scraping characteristics of different stages: stagnation acceleration, scraping (bottom deceleration, surge acceleration, undercut scraping), and deceleration accumulation. High-speed cameras record the migration mode of debris flow after the dam has been overtopped under different working conditions (Fig. 7).

Figure 7A shows that the fluid in the stagnation stage mainly performs horizontal projectile motion. After entering the channel, the kinetic energy rapidly decreases and is converted into energy for scraping the channel material source, resulting in fluid splashing and ejection (Fig. 7B). The observations of test phenomena in Fig. 7C, D show that the surge of dam overtopping debris flow usually includes an initial isolated surge and the formation of a series of subsequent surges. When each surge travels downstream along the gully, the depth and cycle continue to be superimposed and augmented, and scraping carries the gully source materials and expands the size of dredging along the way.

In succeeding fluid migration, the scraping process is characterized primarily by undercutting and grooving. The scraping of the entire mode is gradually intensified. Debris flow fluid runs through the gully from sections with good hydraulic conditions, continuously intensifying the extent of traceability scraping and forming prominent gullies on the accumulated overburden (Fig. 7E). With the ongoing migration of debris flow, the shape of the erosion pit progressively stabilizes. With the decrease in debris flow discharge, most debris and sand particles in the debris flow gradually settled out of the fluid into the erosion pit, eventually filling the pit (Fig. 7F). This phenomenon is consistent with the actual situation of the field investigation. A vast surge pushes the earlier fluid out of the groove mouth

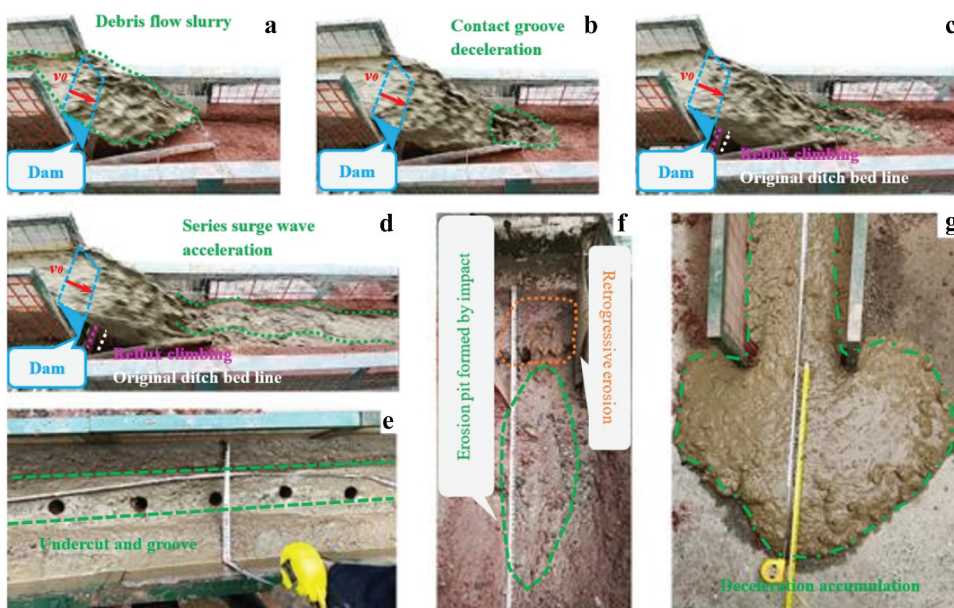


Figure 7. Evolution diagram of debris flow movement over the dam.

to form an accumulation body, and new material increases from the distal to the proximal end, gradually expanding the scope of the accumulation body (Fig. 7G).

The formation of erosion pits behind the dam, especially the traceability scraping of diluted debris flow, accelerates the damage scope of the apron behind the dam and seriously affects the sand dam stability. Once the sand dam is damaged, the material source in the reservoir area is instantly released, further enhancing the scraping of the channel material source and posing a severe threat to downstream residents and property. The “8.20” debris flow event also showed that the apron behind the dam is the most seriously damaged. Due to the failure of the apron, the debris flow directly acts on the gully bed after overtopping the dam, and the scraping effect on the gully bed is further amplified. Overall, the model established in this paper provides critical parameters for designing the apron behind the dam. Furthermore, the downstream gully bed scraping, longitudinal profile, and other changes caused by debris flow overtopping provide a more realistic and optimal cost-benefit evaluation for the design and maintenance of the sand dam apron.

4.3. Scraping Pattern and Rule of Overtopping Debris Flow

Figure 8 indicates that the smaller the bulk density of debris flow, the larger the dam's height and scale, and the deeper the scraping depth of the trench bed after the debris flow turns over the dam. There are three types of erosion and siltation: bed surface silting, formation of punching pits, and undercutting and grooving. When the scraping condition is intense, traceable erosion occurs. The experiments show that the erosion and deposition morphology under various working conditions are related to the following properties of debris flow. A diluted debris flow has the following pattern: traceable erosion, erosion pit formed by impact, surge wave erosion again, and gully undercutting and grooving. Viscous debris flows have the following pattern: Full cross-section deposition, erosion pit formed by impact, gully undercutting and grooving, and silting accumulation in front of the gully.

Based on a summary of the scraping pattern of the gully bed caused by overtopping debris flow, the impact of the bulk density, dam height, and debris flow scale on the scraping depth and scraping volume were further analyzed. The above-obtained scraping depth data was imported into CATIA software. After 3D positioning with the function of Sketch Tracer, 3D modeling was performed with the function of multi-section geometry (Fig. 9). Combined with the high-speed camera video recording, the equal-proportion overtop dam route map, and the CATIA 3D modeling results, it can be concluded that the scraping depth of debris flow and the scraping volume of the overtop dam under different working conditions, as shown in Figs. 10–12.

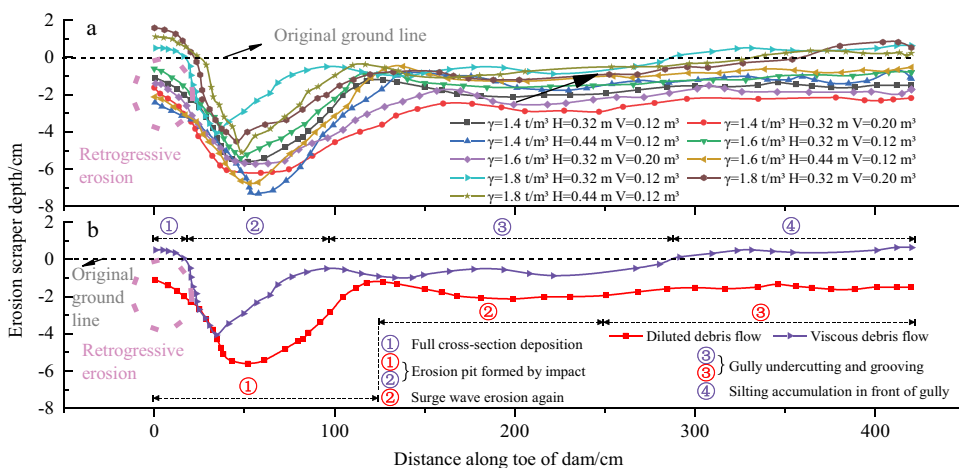


Figure 8. Scraping pattern under different working conditions.

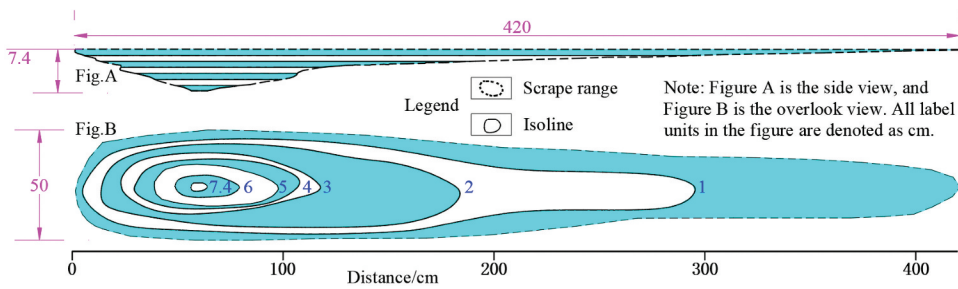


Figure 9. Model diagram of debris flow scraping volume of dam overtopping.

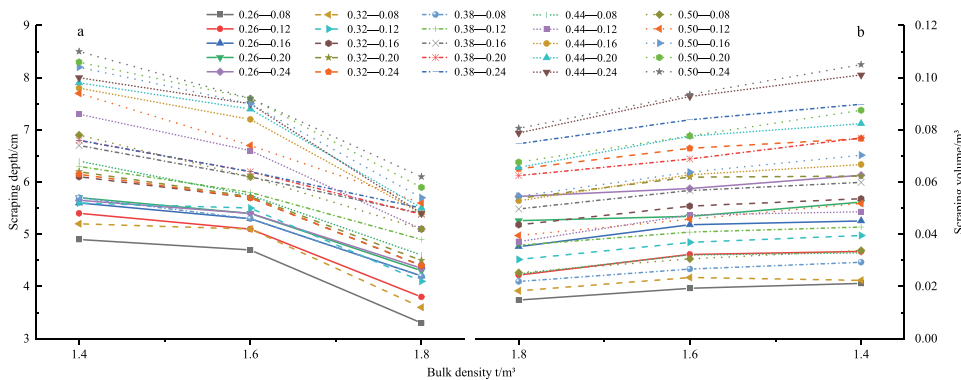


Figure 10. Scraping depth, scraping volume, and the bulk density of debris flow.

With a constant bulk density (Fig. 10), due to the increase in dam height and scale, the impact force of the debris flow on the source material of the gully channel increases. Therefore, the depth and volume of scraping increase with the height and scale of the debris flow dam. Taking $H = 0.32$ m, $V = 0.16$ m³, $H = 0.32$ m, $V = 0.20$ m³, $H = 0.38$ m, $V = 0.16$ m³ as an example ($\gamma = 1.6$ t/m³), the depth of scraping was 5.7 cm, 5.8 cm, 6.1 cm, respectively. The scraping volume was 0.0508 m³, 0.0619 m³, and 0.0568 m³, respectively. The experimental results show that the depth and volume of scraping are positively correlated with the change of debris flow scale and dam height, but the influence of debris flow scale is significantly greater than dam height. Primarily because of the size of the debris flow, which ensures continuous inflow, the fluid scraping capacity gradually exceeds the anti-scraping capacity of the gully bed material downstream of the gully channel. The continuous strong downward cutting erodes the gully bed. At the same time, the turbulence formed by multiple surges continues to undercut and carries the gully source material along the way, increasing the scraping effect.

As shown in Fig. 10, the scraping depth and scraping volume decrease as the debris flow bulk density increases for a given dam height and debris flow scale. Based on the experimental phenomenon, the reasons are primarily twofold: with the increase of debris flow bulk density, the erosion energy dissipation form of gully matter sources changes from collision to friction. Therefore, the dynamic force acting on the movable bed matter sources is relatively weakened after the debris flow overtops the dam. Second, after the erosion pit or undercutting and grooving is formed during the migration of dilute debris flow, the scour continues to expand along the initial scour channel due to the strong dynamic action. During the bed-laying process of the viscous debris flow, the scraping effect is minimal, and a relatively smooth sliding surface is formed on the bed surface. Consequently, debris flows can flow directly along the bed surface behind the bed without causing scraping.

Under the condition of constant dam height (Fig. 11), the scraping depth and the scraping volume are larger with the increase in the scale and the reduction of bulk density. Three

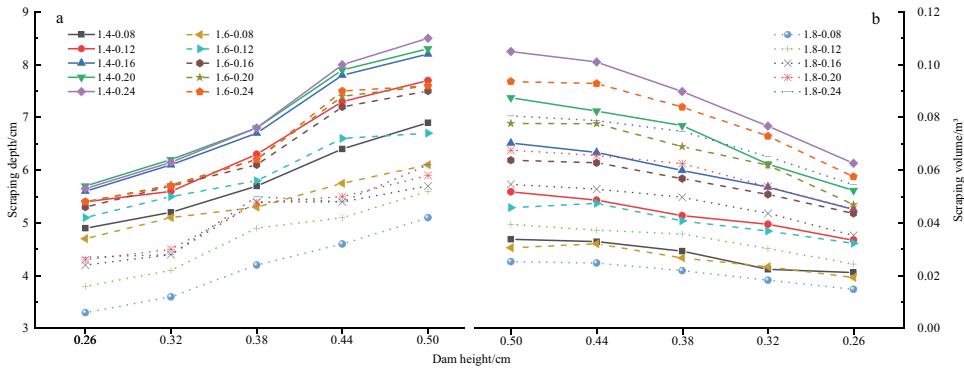


Figure 11. Scraping depth compared to dam height with variable scraping volume.

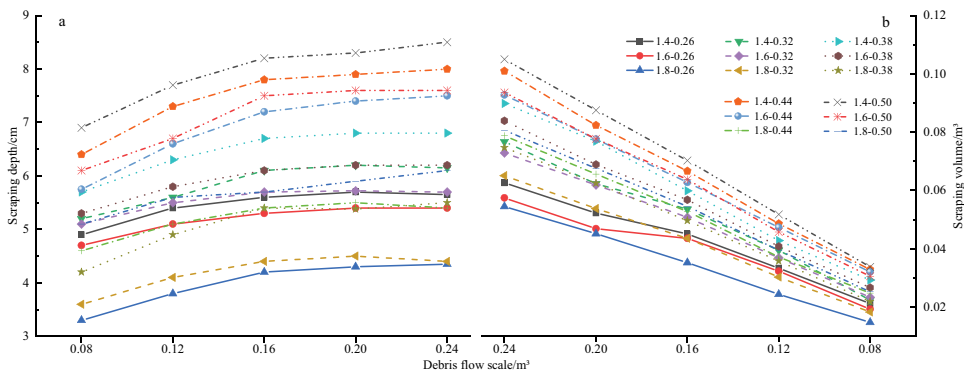


Figure 12. Scraping depth, scraping volume, and debris flow scale.

experimental conditions of $\gamma = 1.6 \text{ t/m}^3$, $V = 0.16 \text{ m}^3$, $\gamma = 1.6 \text{ t/m}^3$, $V = 0.20 \text{ m}^3$, $\gamma = 1.8 \text{ t/m}^3$, $V = 0.16 \text{ m}^3$ were taken as examples ($H = 0.38 \text{ m}$). The scraping depth was 6.1 cm, 6.2 cm, and 5.4 cm, respectively. The scraping volume was 0.0568 m^3 , 0.0689 m^3 , and 0.0497 m^3 , respectively. The results show a positive correlation between the depth and the volume of scraping and the change of debris flow scale, but it is far less than the effect of bulk density on the depth and volume of scraping. The smaller bulk density and the coarse particles are easier to separate in the movement process. The solid matter composed of coarse particles continues to flow and jump in the form of moving and strongly interacts with the channel source, increasing the scraping effect.

Figure 11 demonstrates that under constant debris flow bulk density and debris flow scale, the depth and volume of scraping rise as the height of a dam increases. The reasons are as follows: the dam height increase directly causes debris flow velocity, which enhances the debris flow scour dynamic effect. Second, as the dam height increases, the strong impact force reduces the stability of the movable bed source itself, making it easier to begin scraping under the influence of debris flow.

Under a constant scale (Fig. 12), the depth and volume of scraping are mainly related to the bulk density of debris flow. The volume of scraping increases with the bulk density of debris flow after the dam overtopping of dilute debris flow, while the volume of scraping after the dam overtopping of viscous debris flow is the opposite. The content of solid matter in the fluid of dilute debris flow is related; the higher the content is, the larger the bulk density, the stronger the capacity of sand carrying erosion during the fluid migration process, and the more obvious the amplification effect. The bulk density of viscous debris flow is large, and after entering the

gully, it mostly migrates in the form of full cross-section sedimentation with poor fluidity, and the ability to scrape to entrain gully sources is reduced. Three experimental conditions of $\gamma = 1.6 \text{ t/m}^3$, $H = 0.32 \text{ m}$, $\gamma = 1.8 \text{ t/m}^3$, $H = 0.32 \text{ m}$, $\gamma = 1.8 \text{ t/m}^3$, $H = 0.38 \text{ m}$ were taken as examples ($V = 0.16 \text{ m}^3$). The scraping depth was 5.7 cm, 4.4 cm, and 5.4 cm, respectively. The scraping volume is 0.0508 m^3 , 0.0436 m^3 , and 0.0497 m^3 respectively. The experimental results show that the depth and volume of scraping are positively correlated with the change of the bulk density of debris flow and dam height, but the influence of the bulk density of debris flow is significantly greater than dam height.

Figure 12 shows that the depth and volume of scraping increase with the debris flow scale under a specific bulk density and dam height of debris flow. With an increase in debris flow scale, the drag force of debris flow passing through the bed also increases, enhancing the dynamic scraping effect of debris flow on the gully bed. At the same time, when debris flow flows through the movable bed, the thickness of the smooth layer formed after the laying process is limited, and the slurry gradually penetrates during the continuous migration. As a result, the surface of the movable bed cannot remain continuous after the laying process, and the roughness decreases compared to that before bed-laying. This impact diminishes as the debris flow scale increases.

In conclusion, within the range of experimental conditions, the lower the bulk density of debris flow, the larger the dam height and debris flow scale, the greater the scarping depth of debris flow on the matter sources of the gully after overtopping, and the larger the scraping volume. Especially for dilute debris flows, the roughness of the bed continues to increase after the formation of the initial crater, resulting in continuous development and even traceable erosion. In addition, the experiment showed that if the total volume of debris flow and the gully source materials reserves are sufficient, the scour pit and the undercutting and grooving continue to expand.

SPSS was used for multivariate nonlinear regression analysis and the establishment of empirical expression between the scraping depth (Y_1), volume (Y_2), and the control factors (bulk density, dam height, and debris flow scale) of the overtopping dam debris flow:

$$\begin{aligned} \text{Diluted debris flow } Y_1 = & 5.559 - 6.099\gamma + 0.169H + 0.065V \\ & + 2.796\gamma^2 + 0.003H^2 - 0.001V^2 - 0.077\gamma H - 0.008\gamma V \\ & + 0.002HV, R^2 = 0.972 \end{aligned} \quad (13)$$

$$\begin{aligned} Y_2 = & 29.32 - 71.87\gamma + 1.887H + 0.396V + 28.66\gamma^2 - 0.04H^2 - 0.001V^2 - 0.203\gamma H - 0.173\gamma V \\ & + 0.002HV, R^2 = 0.994 \end{aligned} \quad (14)$$

$$\begin{aligned} \text{Viscous debris flow } Y_1 = & -0.396 + 5.318\gamma + 0.218H + 0.078V - 2.946\gamma^2 - 0.001V^2 \\ & - 0.04\gamma H - 0.011\gamma V + 0.001HV, R^2 = 0.965 \end{aligned} \quad (15)$$

$$\begin{aligned} Y_2 = & -48.34 + 31.34\gamma + 2.241H + 0.359V - 7.811\gamma^2 - 0.045H^2 - 0.001V^2 - 0.184\gamma H \\ & - 0.106\gamma V + 0.011HV, R^2 = 0.988 \end{aligned} \quad (16)$$

4.4. Comparison Verification and Error Analysis

Through the field investigation (Fig. 13), it was found that the apron under the dam is the most seriously damaged part, where the scraping depth of the foundation is 3.5 m, and the length of the scraping area after the debris flow overtopped the dam is about 1.55 km. The total area is about $3.37 \times 10^4 \text{ m}^2$. In addition, the average undercut scraping depth is about 5 m, and the total scraping volume is

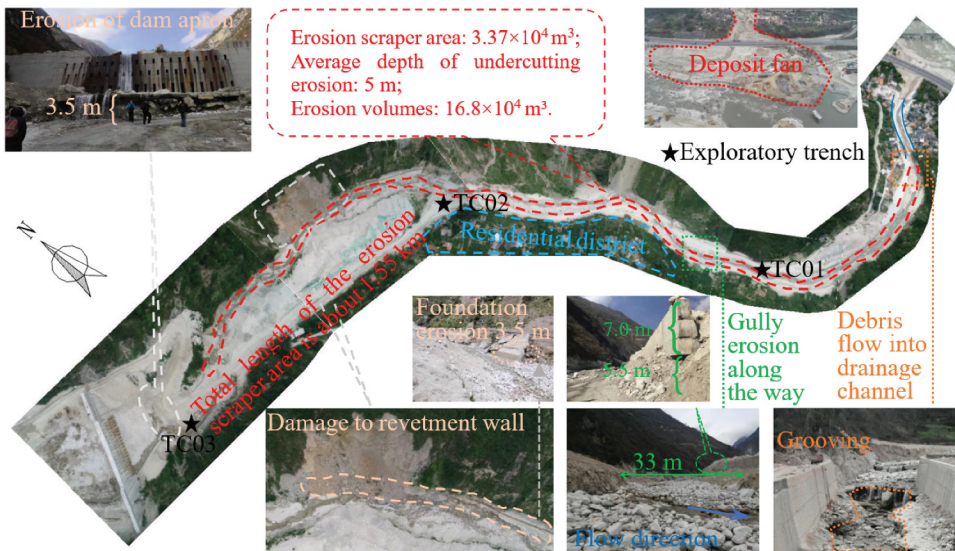


Figure 13. Field investigation of “8.20” debris flow scraping effect.

about $16.8 \times 10^4 \text{ m}^3$. The gully mouth is 457 m wide, and 193 m long, and the alluvial fan comprises an area of $32 \times 10^4 \text{ m}^3$ (Xiong et al. 2021). The field investigation shows that the “8.20” debris flow was mainly caused by gully scraping. The scraping effect after the debris flow overtopped the dam enlarged the debris flow and scale and intensified the destructiveness of the Chutou gully debris flow along the way. Based on the field calculation, after the debris flow was swept out of the gully mouth by scraping, the debris flow scale grew by about 32.3%.

This paper compared and verified the data obtained from the field investigation with the theoretical analysis and test results (Tables 3 and 4). The study outcomes show that the theoretical derivation and experimental calculation values of the scraping depth of the erosion pit behind the dam are 5.56 m and 5.31 m, respectively. The errors with the field values are 6.66% and 5.81%, respectively. The experimental calculation value of the scraping volume is $19.7 \times 10^4 \text{ m}^3$, and the error with the field value is 14.7%.

The findings indicated that the calculated values of the theoretical approach and the indoor model test results are higher than the actual values of field measurements. The main reason is that the apron’s energy dissipation and scraping prevention effect after debris flow overtopping and the friction and collision impact of debris flow and gully source are not considered in the theoretical research derivation process. The gully source is properly hardened within 0.5 m below the dam to minimize the test error. Therefore, the calculated value obtained from the theoretical approach is slightly larger than that of the indoor model test.

Due to the limitations of the test equipment and site, a small volume of debris flow fluid is left in the mixing hopper and the model groove of the acceleration section during the test, resulting in a drop in the initial scale of debris flow dam overtopping and a corresponding reduction in the scraping of gully sources. This issue explains why the calculated value of theoretical research is slightly larger than the indoor model test results.

5. Conclusions

To explore the scraping effect and evolution model of debris flow over the dam, this paper used the 2019 ‘8.20’ debris flow in the Chutou gully, Miansi Town, Wenchuan County, as a case study to prove the usefulness of the proposed model. The analysis mechanism of the combination of the cross-sectional flow method, indoor model test, and field investigation method was constructed. The scraper

Table 3. Comparative verification analysis on the scraper depth of dam-overtopping debris flow.

Model	Parameter								Scraping depth H/m		
	Mud depth h_1/m	Mud depth h_2/m	Dam height H/m	Longitudinal gradient of channel % ₀	Gravitational acceleration $g/(m/s^2)$	Clear water bulk density $\gamma/(t/m^3)$	Volume weight of channel source $\gamma_s/(t/m^3)$	Volume density of debris flow $\gamma_C/(t/m^3)$	Calculated value	Measured value	Error
Theory	2.5	2.0	19	93	9.8	1.0	2.5	1.8	3.75	3.5	6.66%

Table 4. Comparative verification analysis of scraping volume of dam-overtopping debris flow.

Model	Parameter			Scraping volume $V_1/10^4 \text{ m}^3$		
	Bulk density $\gamma_c/t\cdot m^{-3}$	Scale V/m^3	Dam height H/m	Calculated value	Measured value	Error
Test	1.8	52	19	19.7	16.8	14.7%

amplification effect of dam overflow debris flow was quantitatively analyzed, and the scraper mechanism and mode along the dam overtopping debris flow were explored. The conclusions are as follows:

- (1) A theoretical expression for predicting scraping depth in the dam is proposed based on the energy conservation principle. Generally, the developed model results agree with the field measurements, and its relative error is 6.66%.
- (2) The movement mode of debris flow after dam overtopping is recorded under different test conditions using a high-speed camera, CAD, and CATIA. After that, the scraping mechanism, morphology, and debris flow law at different dam overtopping stages are obtained.
- (3) Multivariate nonlinear regression analysis establishes a quantitative statistical model of scraping depth, scraping volume, debris flow bulk density, dam height, and scale. Moreover, comparing the “8.20” debris flow data in the Chutou gully indicates that the two errors are 5.81% and 14.70%, respectively.
- (4) The quantitative evaluation of the scraping effect in dam overtopping debris flow and its mitigation measures proposed in this paper helps improve the understanding of such issues and slow down the destructive capacity of dam overtopping debris flow in earthquake-prone countries. In the subsequent work, the support apron can be included, and the damage mechanism of the support apron after the debris flow overtops the dam can be further analyzed to provide some reference for the actual engineering treatment.

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Author Contribution

Chen Huang: Writing-original draft, Methodology, Software, Data curation. Qijun Hu: Conceptualization, Supervision. Mingyang Li: Visualization, Investigation.

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