Analysis of the Hydraulic Characteristics of the Debris Flow Disaster Chain in Baozhuping Gully and Analysis of the Conditions for Debris Flow Initiation

Hai Yue[1,2,3](✉), Dingde Wu[1,2,3], Lifeng Hou[1,2,3], and Mingliang Zhang[1,2,3]

1 Sichuan Geological Environment Survey and Research Center, Chengdu 610081, Sichuan, China
114721535@qq.com

2 Sichuan Province Engineering Technology Research Center of Geohazard Prevention, Chengdu 610081, Sichuan, China

3 Sichuan 915 Construction Engineering Co., Ltd., Meishan 620010, Sichuan, China

Abstract. Taking the Baozhuping gully landslide-debris flow disaster chain in Ya'an City as an example, through field investigation and on-site measurement, this study analyzed the characteristics of the collapse and breakthrough during the "7.16" debris flow outbreak, and provided the types of dam break and its hydraulic characteristics after the landslide slide. The results show that the instability of the dam body of the pond is mainly due to the damage caused by the overflow of the top, and the maximum flow rate of the dam break reaches 30.12 m^3/s, which triggers the initiation of debris flow downstream, providing reference for the prevention and control of similar debris flows.

Keyword: Debris Flow · Disaster Chain · Dam Break · Baozhuping Gully

1 Introduction

On July 16, 2022, heavy rainfall occurred in Yucheng District, Ya'an City. A landslide occurred on the upstream slope of Baozhuping gully, a right-bank tributary of Zhougong River, on the right bank of Qingyi River. The slope soil rapidly slid to the foot of the slope, and the water in the pond quickly rushed into Baozhuping gully, triggering a debris flow that lasted for about 15 min. It burst out of the channel at Nanba East Street, damaging three vehicles. The debris flow accumulated on the surface of Nanwai Ring Road and Nanba East Street, blocking the roads and causing damage to houses on both sides of Baozhuping gully. This resulted in road interruption, vehicle destruction, injuries to people, and property losses. People's Daily, China News Network, and other media outlets reported on this incident promptly, generating strong social response [1]. The dam break played an important role in triggering the debris flow in Baozhuping gully.

Currently, extensive research has been conducted both domestically and internationally on the formation of blockage and failure points in channel sedimentary dams.

G. Feng (Ed.): ICCE 2023, LNCE 526, pp. 728–736, 2024.
https://doi.org/10.1007/978-981-97-4355-1_73

Takahashi [2] identified three main causes of debris flow: 1) Infiltration of water into the deposited material in the channel bed, which forms surface flow and destabilizes the material, leading to debris flow. 2) Soil blocks that collapse from the slope break apart and mix with water during movement, transforming into debris flow. 3) Slope collapse material blocking the channel bed, which becomes unstable due to the accumulation of upstream water and subsequently forms debris flow as a large amount of water flows out. Wu [3] discussed the generation of flow from blockage and failure of landslides, debris flows, and glacial deposits in channels. David and Froehlich [4] analyzed a large amount of data on failed sedimentary dams and used multiple regression to derive a new empirical formula for predicting peak outflow during dam failure. Xiang [5] analyzed the hydraulic characteristics and initiation conditions of debris flows within the Qipanguo dam failure in Wenchuan County. Yucheng District in Ya'an City is known for its frequent occurrence of geological hazards due to rainfall [6]. This article takes the "7·16" debris flow in Baozhuping gully, Yucheng District, Ya'an City as an example to analyze the characteristics of hydraulic conditions and initiation conditions after the landslide sliding and pond failure. The results have certain representativeness and can serve as a reference for the prevention and control of similar geological hazard chains.

2 Basic Situation of Baozhuping Gully

Baizhuping Gully is located in Chengqing Village, Dongcheng Street, Yucheng District, Ya'an City. Its geographical coordinates are 103°01′28.13" E and 29°59′12.13" N. It is approximately 4 km away from the Yucheng District People's Government. There is a rural cement road leading to the exploration point, and the gully mouth is connected to the South Outer Ring Road, providing good transportation conditions.

Baizhuping Gully is a right-bank tributary of Zhougong River, a tributary of Qingyi River. It has a drainage area of 0.26 km^2 and flows from southeast to northwest. The upstream area has a funnel-shaped topography, while the middle and downstream areas have a strip-shaped topography. The main gully is 1.4 km long with a gradient of 313‰ and a relative elevation difference of 430 m.

2.1 Geological Conditions

The main geological structure in the area of Baizhuping Gully is folding structure, with no regional faults observed. The internal structure of the area exhibits a north-south orientation, forming part of the north-south tectonic belt of Sichuan and Yunnan. The basin's geological formations mainly consist of sandstone and mudstone of the Cretaceous Guankou Formation, with additional exposures of loose deposits from the Quaternary period. These loose deposits are primarily found in the sedimentary areas of the middle and lower reaches of the gully and on the surface of the gully slopes.

The main gully has a narrow valley, typically with a width of 10–20 m, and often exhibits a "U" shape. According to the Comprehensive Vulnerability Score based on the "Technical Code for Investigation of Debris Flow Disaster Prevention and Control Engineering (Trial)" (TCAGHP 006–2018), Baizhuping Gully has a score of 74, indicating a mild susceptibility to debris flows. The completeness coefficient of the Baizhuping

Gully basin is relatively small (0.133), indicating poor convergence conditions and a relatively gentle flood process. Therefore, the likelihood of debris flows occurring is low in the absence of rapid changes in hydraulic conditions [7–9].

Considering the surrounding environment, there are several tributaries with similar geological conditions to Baizhuping Gully (see Figs. 1 and 2). These tributaries share similarities in terms of basin area, main gully length, terrain slope, and lithology. No debris flows were reported in any of these tributaries on July 16, 2022. From the video footage taken by Chuan Guan News after the debris flow event in Baizhuping Gully, it can be seen that there was still a large amount of floodwater in the gully, while the left tributary remained clear (see Figs. 3 and 4). This indicates that the debris flow in Baizhuping Gully was likely caused by rapid sliding of slope soil and rock from the upstream slope into the foot pond, resulting in a significant change in hydraulic conditions due to the rapid influx of water [10–12].

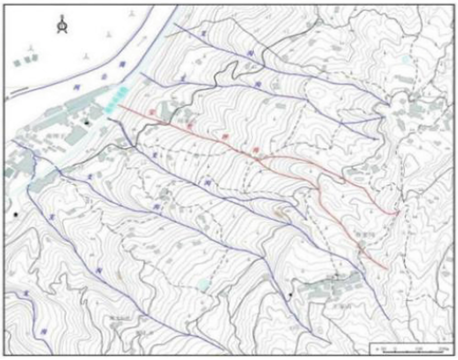

Fig.1. Distribution map of Baozhuping gully and surrounding branch gully

Fig. 2. Image of Baozhuping gully and surrounding branch gully

2.2 Hydrometeorological Conditions

The average annual rainfall in Yucheng District, Ya'an City is 1614 mm. The largest annual rainfall in 50 years was 2367.2 mm in 1966, and the largest daily rainfall in 50 years was 339.7 mm in 1959. The maximum hourly rainfall was 86 mm, and the maximum 10-min rainfall was 30.1 mm.

According to the measured data from Zhougongshan Meteorological Station (the nearest meteorological station to Baizhuping Gully), which is located upstream of the gully, there were a total of 18 times with daily maximum rainfall greater than 100 mm in the past five years, ranging from 103.1—179.2 mm. The maximum hourly rainfall during these 18 heavy rainfalls ranged from 15.7—85.6 mm. The debris flow in Baizhuping Gully occurred on July 16, 2022, with a rainfall of 159.1 mm and a maximum hourly rainfall of 48 mm. In mountainous areas of Sichuan Province, the rainfall that usually triggers debris flows is around 48—50 mm for a single rainfall or 8.0—12.2 mm for a 10-min rainfall, with a rainfall intensity of about 0.8—1.2 mm per minute (Wu et al., 1993). Before July 16, 2022, there were 13 heavy rainfalls, and after that, there were four heavy rainfalls, but none of them triggered debris flows. Therefore, it is unlikely that Baizhuping Gully was directly triggered by rainfall to cause large-scale debris flows. The main cause is the fast sliding of slope soil and rocks from the upstream slope into the foot pond, causing a significant change in hydraulic conditions due to the rapid influx of water into Baizhuping Gully in Table 1.

Table 1. Statistical table of heavy rainfall in the past 5 years at Zhougongshan Meteorological Station in Yucheng District, Ya'an City

Number	Data	Maximum daily rainfall (mm)	Maximum hourly rainfall (mm)	Note	Number	Data	Maximum daily rainfall (mm)	Maximum hourly rainfall (mm)	Note
1	2019.8.6	141	20.1		10	2021.8.22	150.1	80.4	
2	2019.8.22	112.1	22.9		11	2022.5.9	162.2	26.9	
3	2019.9.13	134.5	20.6		12	2022.5.13	121.2	27.5	
4	2020.8.11	179.2	85.6		13	2022.7.12	194	74.2	
5	2020.8.16	147.8	15.7		14	2022.7.16	159.1	48	Debris flow occurred in Baozhuping Gully
6	2020.8.18	155	47.2		15	2023.7.11	103.1	41.1	
7	2020.8.30	185	50.8		16	2023.7.16	137.5	24.2	
8	2021.8.18	139.8	24.1		17	2023.8.10	108.3	21.1	
9	2021.8.20	123.1	43.5		18	2023.8.12	106.0	46.2	

3 Hydrodynamic Characteristics After Dam Failure

3.1 Basic Characteristics of Ponds

The main cause of the mudslide in Baizhuping Gully on "7·16" was the significant change in hydraulic conditions due to the failure of the upstream reservoir. The reservoir is located on the right bank tributary of Baizhuping Gully, about 300 m from the watershed, with a drainage area of approximately 0.05 km^2.

According to the investigation and analysis of pre-and post-failure images (Fig. 3), the reservoir was excavated by local residents as a slope foot, with a front section built as a dam primarily for aquaculture. It has an elongated rectangular shape, with a length of about 85m and a width of 50—20 m. The depth of the reservoir is approximately 4m, with a storage capacity of about 11,900 m^3.

Based on the data from Zhougongshan Meteorological Station on the Rain City Natural Resources and Planning Bureau's meteorological information service platform, there was continuous rainfall from July 12th to July 16th, 2022, with a total accumulated rainfall of 402.3 mm. The reservoir was already at full capacity before the occurrence of the mudslide.

Due to the heavy rainfall over several days, the slope formed by excavating and constructing the fish pond at the front edge became saturated. The strength and stability of the soil and rock decreased continuously, eventually resulting in a rapid sliding along the mudstone layer towards the reservoir. The sliding distance was approximately 30 m, with a volume of 9,600 m^3. The soil and rock mass squeezed the water in the reservoir, causing it to rapidly overflow into Baizhuping Gully.

Fig. 3. Aerial images on August 11, 2022

3.2 Types of Reservoir Dam Breach

By using the slope stability calculation formula, the stability safety factor of the reservoir dam at half and full capacity was calculated. The overall stability factor of the most dangerous surface under both conditions was greater than 1, indicating that the reservoir dam would not experience overall movement instability. The damage to the dam was due to the erosion caused by a large amount of water overflowing to the outside of the dam after the reservoir was full. The failure mode was an overflow erosion and collapse type (Kuang, 1993). This calculation result is consistent with the on-site investigation.

3.3 Hydrodynamic Characteristics After Dam Failure

Regarding the overflow erosion and collapse type dam, according to the peak flow formula proposed by David C. Froehlich (1996), the peak flow during the collapse was calculated to be 30.12 m^3/s (Table 2), causing significant damage downstream.

$$Q_p = 0.607 V_w^{0.295} H_w^{1.24} \tag{1}$$

Here, VW represents the capacity of the reservoir at the time of the incident (m^3), and HW represents the depth from the bottom of the final breach to the surface of the reservoir when the dam fails (m).

Table 2. Calculation table for peak flow when the reservoir bursts

Dam location	The capacity of the pond at the time of the accident (m^3)	The depth of the pond from the bottom of the final breach to the surface of the reservoir when the dam failed (m)	Peak discharge flow (m^3/s)	Note
Baozhuping gully upper reaches reservoir dam	11900	2.5	30.12	

4 Conditions for Triggering Debris Flow After Reservoir Dam Failure

Based on the morphology of the on-site investigation, the Baizhuping Gully debris flow is a dilute debris flow (water and sediment flow) containing certain fine particles. According to the research results of Fei (2004), it is assumed that the fine particles are uniformly distributed along the vertical line.

In the Fig., θ is start critical inclination angle for channel, h is the deep flow; h' is the thickness of the channel coarse-grained layer, driving shear stress in fixed loose materials (τ) and starting resistance (τ_L) are:

$$\tau = \left[S'_{vm}(\gamma_s - \gamma_f)h' + \gamma_f h\right]\sin\theta \tag{2}$$

$$\tau_L = \left[S'_{vm}(\gamma_s - \gamma_f)h'\right]\cos\theta\tan\alpha' + \tau_f \tag{3}$$

In the equation γ_f is the bulk density of a suspension composed of fine particles and water, $\tan\alpha'$ is the friction coefficient in the presence of fine particles, γ_s is the solid bulk density, $s_{vm'}$ is the channel activation layer concentration, the suspension shear stress τ_f is very small, can be ignored, In this way, the starting condition is

$$\tau = \tau_L \tag{4}$$

or

$$\tan\theta = \frac{S'_{vm}(\gamma_s - \gamma_f)\tan\alpha'}{S'_{vm}(\gamma_s - \gamma_f) + \gamma_f(h/h')} \tag{5}$$

When the channel slope is greater than or equal to θ, debris flow starts. Select the location of the pond and dam for starting condition analysis, and calculate the peak flow rate at this location in 50 years to be 1.99 m^3/s based on the inference formula. The peak flow rate after the collapse is 30.12 m^3/s (Table 3), Compared with normal conditions, the flow rate is enlarged by 15.1 times (table). Based on experience, it is judged that the possibility of debris flow under this flow rate is greater.

Table 3. Calculation table of cross-section flood peak flow at the location of the dam

Calculate position	catchment area km^2	Main groove length km	Main ditch longitudinal slope‰	peak flow (m^3/s)(p = 1%)	peak flow (m^3/s)(p = 2%)	peak flow (m^3/s)(p = 5%)	peak flow (m^3/s)(p = 10%)
Section at the location of the dam	0.05	0.4	249	2.20	1.99	1.69	1.46

Using Formula (5), the determination of whether a debris flow will be triggered after the Baizhuping Gully reservoir dam failure is conducted. The calculation parameters are based on field measurements and empirical data, and the calculation results are shown in Table 4. From Table 4, it can be observed that the slope of the channel is greater than the initiation slope of the debris flow. Therefore, when the reservoir overflows and erodes, it will trigger the scouring of sediment at the bottom of the channel, initiating a debris flow (Zhao et al., 2021).

Table 4. Summary of calculation parameters and results

$s_{vm'}$	γ_s	γ_f	h	$h\prime$	$\tan\alpha'$	θ	Channel slope
0.9	2.4	1.1	3	1	0.75	11.1	12.0

5 Conclusion

The fact that multiple tributaries with similar engineering geological conditions on both sides of Baizhuping Gully have never experienced debris flow indicates a lower integrity coefficient and poor convergence conditions in the Baizhuping Gully watershed. The likelihood of debris flow occurrence is lower in the absence of rapid changes in hydraulic conditions.

In the past five years, the region has experienced 18 heavy rainfall events (daily rainfall ranging from 103.1 to 179.2 mm, maximum hourly rainfall ranging from 15.7 to 85.6 mm). Except for the event on "7·16", no debris flow occurred, suggesting that rainfall is not the main triggering factor for debris flow in Baizhuping Gully.

Through stability calculations and on-site investigations, the failure mode of the upstream reservoir in Baizhuping Gully is identified as overflow erosion and collapse type.

The peak flow rate during the failure of the upstream reservoir in Baizhuping Gully is 30.12 m^3/s, with an initiation slope of 11.1°. The downstream channel slope of the dam is 12.0°. The failure flood triggers scouring of sediment at the bottom of the downstream channel, initiating a debris flow and causing significant damage downstream.

References

1. Zhang, X., et al.: Fine investigation project report on geological hazards along the south outer ring of Yucheng district (2022)
2. Takahashi, T.: Debris flow. Annu. Rev. Fluid Mech. **13**, 57–77 (1981)
3. Wu, J., Cheng, Z., Geng, X.: Formation mechanism of debris flow blocking dam in Southeastern Tibet. J. Mt. Sci. **04**, 4399–4405 (2005)
4. David, C., Froehlich: Peak discharge of breached earth and rock dams. Dam and Safety **4**, 63–69 (1996)
5. Xiang, G., Zhang, D., Chang, M., Qu, Y.: Hydraulic characteristics and initiation conditions of debris flow in Qipanguo after the breach of barrier lake. Water Resour. Power **33**(04), 143–146 (2015)
6. Li, Y.: Preliminary study on the critical value of rainfall-induced landslides in Yucheng district, Ya'an city Sichuan province. Hydrogeol. Eng. Geol. **01**, 26–29 (2005)
7. Yue, H.: Geological Hazard Characteristics and Prevention Suggestions for Yucheng District, Ya'an City after the Lushan Earthquake on April 20th. Southwest Jiaotong University (2015)
8. Wu, J., Tian, L., Kang, Z., Zhang, Y., Liu, J.: Debris Flow and Its Comprehensive Control. Science Press, Beijing (1993)
9. Kuang, S.: Formation mechanism and mathematical model of debris flow from natural dam breach. J. Sed. Res. **04**, 42–57 (1993)
10. Fei, X., Shu, A.: Mechanism of Debris Flow Movement and Disaster Prevention. Tsinghua University Press, Beijing (2004)

11. Fei, X.: Sediment concentration and flow velocity of water-sediment flow. J. Sed. Res. **04**, 8–12 (2002)
12. Zhao, S., Zhao, Z., Yuan, G.: Study on characteristics of debris flow source in Jiuzhaigou seismic zone. J. Sichuan Geol. 41(01) (2021)