ANALYSIS OF A DEBRIS FLOW AFTER WENCHUAN EARTHQUAKE AND DISCUSSION ON PREVENTIVE MEASURES

by

Zhi-Long ZHANG [a], ***Jing XIE*** [a*], ***De-Ke YU*** [a], **and *Zhi-Jie WEN*** [b]

[a] State Key Laboratory of Hydraulics and Mountain River Engineering,
College of Water Resource and Hydropower, Sichuan University, Chengdu, China
[b] State Key Laboratory of Mining Disaster Prevention and Control
Co-Founded by Shandong Province and the Ministry of Science and Technology,
Shandong University of Science and Technology, Qingdao, China

Original scientific paper
https://doi.org/10.2298/TSCI180811224Z

This paper addresses a debris flow disaster in Yingxiu town after the Wenchuan earthquake. Through site investigation and data review, the geography and geological environment of the basin and the development, formation conditions and activity characteristics of the debris flow in the basin are analyzed. Calculate and analyze the characteristics of the debris flow, such as gravity, flow velocity and impact force. According to the management idea of combination of blocking and discharging, this paper proposes to arrange three blocking dams in the main ditch, construct drainage gullies in the downstream accumulation section, and prevent and control the aqueduct in the intersection of the main ditch and the G213 national road, which will be similar to the earthquake in the future. It is provided as a reference for research and prevention of the debris flow.

Key words: *Wenchuan earthquake, debris flow, debris flow control, debris flow characteristics*

Introduction

Wenchuan county, located at the epicentral region, suffered debris flow disasters in succession years after the earthquake: on August 13, 2010, Hongchun gou debris flow at Yingxiu town washed out with 7105 m^3, Minjiang river was blocked and caused 72 deaths and more than 8000 people were forced to transfer [1]. On July 10, 2013, a large-scale debris flow disaster broke out along the Du wen Highway, Minjiang river was also blocked and formed 24 barrier lakes, roads, bridges and tunnels were seriously damaged, [2]. On both sides of the provincial road 303 parallel to the Yuzi river, almost every rainy season will cause traffic disruption due to the destruction of heavy rain and debris, [3]. Caopo town ship rebuilt after the earthquake was forced to relocate and rebuild as a whole, [4]. On August 13, 2010, mudslides broke out in 44 trenches in the Longxi river Basin in Dujiangyan, and a large number of post-disaster reconstruction facilities were destroyed and caused major property damage, [5]. There are significant differences in formation mechanism, outbreak scale and risk between pre-earthquake and non-earthquake areas, [6-10].

After the Wenchuan earthquake, the loose solid material in a debris flow gully area of Yingxiu town was increased significantly, and some unfavorable geological phenomena such as landslides and collapses also occurred. The gully accumulation sector was located in the plan-

[*] Corresponding author, e-mail, xiejing200655@163.com

ning area of restoration and reconstruction of Yingxiu town. This paper mainly focused on a debris flow disaster in Yingxiu town after the Wenchuan earthquake. Through site investigation and data review, the geography and geological environment of the basin and the development, formation conditions and activity characteristics of the debris flow in the basin were analyzed. The characteristics of the debris flow, such as gravity, flow velocity and impact force were calculated and analyzed. According to the management idea of combination of blocking and discharging, three blocking dams were suggested to be arranged in the main ditch in this paper, drainage gullies were suggested to be constructed in the downstream accumulation section, and preventive measures with aqueducts were suggested to be set-up in the intersection of the main ditch and the G213 national road, which will provide similar reference for research and prevention of debris flow induced by earthquake in the future.

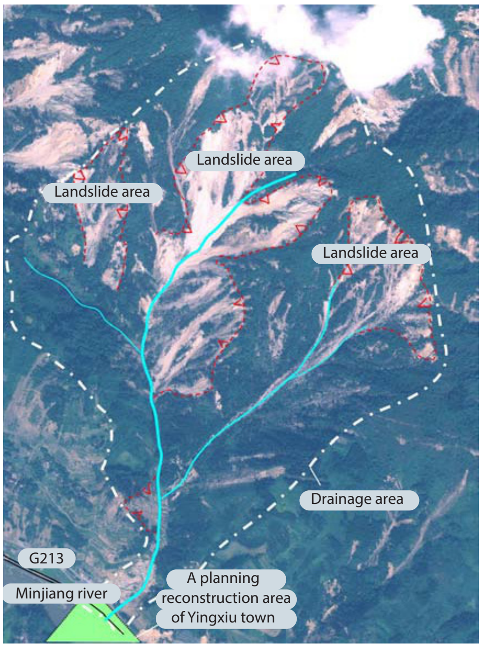

Figure 1. Schematic diagram of the debris flow pattern
(*for color image see journal web site*)

Brief introduction of debris flow

Terrain and landform conditions

The debris flow basin is located in Yingxiu Ttown, Wenchuan county, on the right bank of Minjiang river. The gully area is a deep cut V-type valley. The gully is generally wide in the upper and lower reaches, narrower in the middle reaches, and shows the characteristics of time-width and time-narrow variation. The gully area is about 2.1 km^2, the main gully length is 2.1 km, the relative height difference is 1090 m. The tributaries of the debris flow are well developed, and there are 5 larger ones, as shown in fig. 1.

Water source conditions

The debris flow basin is mainly recharged by atmospheric precipitation, and its discharge is greatly affected by precipitation. There are no reservoirs, lakes and other surface water bodies in the valley. Therefore, the water source conditions of debris flow outbreak are mainly short-term floods in the valley under the action of rainstorm.

Provenance conditions

According to the survey report, the amount of debris flow in this gully is 1.46 m^3 × 104 m^3, the amount of solid material is 0.64 m^3 × 104 m^3, the peak flow rate of debris flow in gully mouth is 30.78 m^3/s, the total amount of solid material source in gully area is 4.4 m^3 × 104 m^3, and the dynamic reserve that may participate in debris flow activity is 2.58 m^3 × 104 m^3. The total amount of solid material source in gully accumulation is 30.36 m^3 × 104 m^3, which may participate in debris flow activity. The dynamic reserves are 8.37 m^3 × 104 m^3. The total amount of loose solid source is 34.76 m^3 × 104 m^3, and the potential dynamic reserves involved in debris flow are 10.95 m^3 × 104 m^3.

The debris flow is rich in loose solid material sources and concentrated in the main gully section above the mouth of No. 2 branch gully. According to the characteristics of gully and the law of development and distribution of solid loose material, the debris flow can be divided into formation area, circulation area and accumulation area. The gully source to the gully mouth of No. 2 branch to the gully mouth of No. 1 branch is the formation area, the gully mouth of No. 2 branch to the gully mouth of No. 1 branch is the circulation area, and the accumulation area below the gully mouth of No. 1 branch is the accumulation area. At the front of the gully accumulation sector, G213 National Road passes through, which is also the scope of Yingxiuchang town's restoration and reconstruction planning area.

Meteorological conditions

The basin is located in the subtropical humid monsoon climate zone of the mountainous area. It is located in the rainy central area of western Sichuan. It is one of the areas where heavy rains often occur. According to the 25-year survey of the Yuzixi hydrological station, the average annual precipitation is 1253.1 mm, and the maximum annual precipitation is 1688 mm (appeared in 1964), the minimum annual precipitation is 836.7 mm (appeared in 1974), the maximum continuous four months (June-September) precipitation is 853.2 mm, accounting for 68.2% of the annual precipitation, the daily maximum precipitation The amount is 269.8 mm, and it is a flood season from May to August every year. It is rainy and sloppy, and the autumn rain is seriously harmful, [11].

According to the conur map of the heavy rainfall attached to the handbook for storm floods in the small and according to the conur map of the heavy rainfall attached to the handbook for storm floods in the small and medium-sized basins of Sichuan province, the average annual maximum rainfall of 1/6 hour, 1 hour, 6 hours, and 24 hours in Yingxiu area is 15 mm, 35 mm, 90 mm, 130 mm, respectively. The coefficients are 0.42, 0.35, 0.50, and 0.60, respectively. According to the coefficient of variation, the Pearson III curve obtained the modulus ratio at different frequencies and the statistics of the rain intensity at different frequencies are shown in tab. 1.

Table 1. Calculation of rain intensity at different frequencies in Yingxiu town

Frequency *P*		1%	2%	5%	10%
1/6 hour	Average value [mm]	15			
	Variation coefficient	0.42			
	Modulus coefficient	2.39	2.15	1.82	1.56
	Design rain strong [mm]	35.85	32.25	27.30	23.40
1 hour	Average value [mm]	35			
	Variation coefficient	0.35			
	Modulus coefficient	2.11	1.92	1.67	1.47
	Design rain strong [mm]	73.85	67.20	58.45	51.45
6 hours	Average value [mm]	90			
	Variation coefficient	0.50			
	Modulus coefficient	2.47	2.42	1.99	1.66
	Design rain strong [mm]	222.30	217.80	179.10	149.40
24 hours	Average value [mm]	130			
	Variation coefficient	0.60			
	Modulus coefficient	3.20	2.76	2.20	1.77
	Design rain strong [mm]	416.00	358.00	286.00	230.30

Analysis of fluid characteristics of debris flow

Severe characteristics

In the upper and middle reaches of this section, debris flow slurry is mixed by debris flow deposits and gully water. Villagers who have seen the occurrence characteristics of debris flow are asked to mix the slurry into the concentration of debris flow slurry at that time (mainly referring to the characteristics of debris flow after the 2008 earthquake) and weigh it. The volume of slurry is measured, and its weight is calculated according to the calculation method of debris flow gravity based on clay content as Ningsheng, [12, 13]. As the gravity of debris flow fluid, the calculated results are as in tab. 2.

Table 2. Debris flow fluid gravity calculation table

Calculated location	Water discharge [m^3s^{-1}]				Sediment repair positive coefficient	Blocking coefficient	Peak flow rate of debris flow [m^3s^{-1}]			
	$P = 1\%$	$P = 2\%$	$P = 5\%$	$P = 10\%$			$P = 1\%$	$P = 2\%$	$P = 5\%$	$P = 10\%$
Near the main ditch mouth	12.78	11.63	10.11	8.90	1.765	1.5	50.73	33.8	30.78	26.77
Downstream section of main ditch	10.93	9.95	8.65	7.62	1.765	1.4	40.5	27	24.58	21.38
No. 2 branch ditch mouth section	5.83	5.31	4.62	4.07	1.765	1.2	18.53	12.4	11.24	9.78
No. 3 branch ditch mouth section	3.47	3.16	2.75	2.42	1.765	1.2	11.03	7.35	6.689	5.818
No. 4 branch ditch mouth section	2.66	2.42	2.10	1.85	1.765	1.2	8.451	5.63	5.124	4.457
Near H01 ditch section	6.35	5.78	5.03	4.43	1.765	1.2	20.18	13.5	12.24	10.65
Near H02 ditch section	6.20	5.65	4.91	4.32	1.765	1.2	19.72	13.1	11.96	10.4
Near B02 ditch section	6.50	5.91	5.14	4.53	1.765	1.2	20.65	13.8	12.53	10.89
Near B01 ditch section	6.87	6.25	5.44	4.79	1.765	1.2	21.82	14.5	13.24	11.51

Traffic characteristics

The surface water catchment flow is calculated according to the empirical formula proposed by China Highway Science Research. When the catchment area, F, is more than 3 km^2, the formula can be written as [14]:

$$Q_p = \psi F^{2/3} s \tag{1}$$

When the catchment area, F, is less than 3 km^2, we have [14]:

$$Q_p = \psi F s \tag{2}$$

The peak flow of debris flow can be written as [14]:

$$Q_c = (1+\varphi) Q_p D_c \tag{3}$$

where Q_c is the peak discharge of debris flow section, Q_p – the peak discharge of rainstorm flood, ψ – the runoff coefficient of rainstorm, F – the catchment area, s – the hourly rainfall intensity. Accordingly, the peak flow of debris flow can be obtained by rainflood method, see [15], as shown in tab. 3.

Table 3. Debris flow peak flow table

Test location	Preparation mud weight, G_c [kg]	Reparation mud volume, V [L]	Debris flow severity, γ_c [tm^{-3}]	
			Single value	Average value
QJ07 (No. 3 branch ditch mouth section)	12.70	5.88	2.16	1.99
	12.00	6.38	1.88	
	12.20	6.33	1.93	
QJ06 No. 2 branch ditch mouth section)	12.60	7.60	1.66	1.79
	14.40	7.60	1.89	
	11.40	6.30	1.81	
QJ04 (Near H02 ditch section)	12.40	7.36	1.68	1.69
	11.90	7.10	1.68	
	8.70	5.10	1.71	
QJ03 (Near H01 ditch section)	8.60	4.50	1.91	1.83
	12.70	6.90	1.84	
	14.70	8.50	1.73	

Velocity analysis

The velocity of debris flow is one of the most important parameters of its dynamic characteristics. Considering that the large-scale debris flow in the main gully needs large rainfall and strong hydrodynamic conditions, and under the condition of large rainfall, the fluid property will tend to be dilute. Therefore, the flow velocity of the debris flow can be expressed, [16]:

$$V_c = \frac{1}{\sqrt{\gamma_H \phi + 1}} \frac{1}{n} H_c^{2/3} I_c^{1/2} \tag{4}$$

where V_c is the velocity of debris flow, γ_H – the density of solid matter, ϕ – the correction coefficient of debris flow sediment, n – the roughness coefficient of debris flow ditch bed, H_c – the average depth of mud, and I_c – the longitudinal slope ratio of mud level. To sum up, the velocity values of debris flow at different cross-section locations obtained by the formula of the Second Iron Institute are detailed in tab. 4.

Table 4. Debris flow velocity

Calculated location	Unit weight of soil, γ_c [kN/m]	Mean velocity [ms^{-1}]	Impact force, P [kN]
Downstream section of main ditch	17.24	1.21	3.43
No. 2 branch ditch mouth section	17.24	2.69	16.93
No. 3 branch ditch mouth section	17.24	3.85	34.68

Impact force analysis

The impact force of debris flow is related to the selection of follow-up prevention technology, the formulation of structure size and the design of reinforcement, see [17, 18], *etc.* The calculation is carried out according to the recommended formula of *Investigation Code for Debris Flow Disaster Prevention and Control Engineering Z/T0239-2004*. The building is rectangular, and the angle between the impact force at the calculating site of the gully debris flow and the stress surface of the building is considered as frontal impact. The calculation results are shown in tab. 5.

Table 5. Calculating table of impact force of debris flow

Calculated location	Average mud depth [m]	Gully slope [‰]	Sediment correction, coefficient, *t*	Roughness coefficient	Solid matter gravity [tm^{-3}]	Average current speed [ms^{-1}]
No. 2 branch ditch mouth section	0.5	317	1.765	0.075	2.65	2.69
No. 3 branch ditch mouth section	0.7	412	1.765	0.075	2.65	3.85
No. 4 branch ditch mouth section	0.9	625	1.765	0.075	2.65	5.60
Near H01 ditch section	0.3	235	1.765	0.075	2.65	1.65
Near H02 ditch section	0.32	290	1.765	0.075	2.65	1.91
Near B02 ditch section	0.23	244	1.765	0.075	2.65	1.40
Near B01 ditch section	0.17	270	1.765	0.075	2.65	1.21

Analysis of climbing height and maximum rise height

When debris flow encounters a reverse slope, it advances along a straight line due to inertia force, and the impact height refers to the phenomenon-that the debris flow is blocked in the process of rapid flow and its huge kinetic energy is rapidly converted into potential energy, which makes the mud and wrapped stones splash at the impact site. The climbing height and maximum scouring height of debris flow are calculated according to the calculation formula provided in Appendix I of DT/T0220-2006 Code for Exploration of Debris Flow Disaster Prevention and Control Engineering. The results are shown in tab. 6.

Table 6. Calculating table of debris flow climbing and scouring heights

Calculated location	Mean velocity [ms^{-1}]	Maximum impulse height [m]	Climbing height [m]
Downstream section of main ditch	1.21	0.07	0.12
No. 2 branch ditch mouth section	2.69	0.37	0.59
No. 3 branch ditch mouth section	3.85	0.76	1.21

Debris flow control measures

Target of threat

According to the defined range of debris flow hazard zone, the main target of the threat is the planning area of Yingxiu Town in Gugou, the dispersed inhabitants, and the safety of G213 National Highway, passing vehicles and pedestrians in Gugou. Therefore, it is very important to investigate and control Zhang debris flow.

Prevention and control measures

According to the formation conditions, basic characteristics and harmfulness of the aforementioned debris flow, and management ideas, we have the following treatment proposals. Damping dams are arranged in the main ditch, respectively, in the downstream of the main ditch and the gap of the $3^{\#}$ branch ditch, the middle main ditch and the downstream section of the $2^{\#}$ branch ditch and the downstream main ditch and the junction of the $1^{\#}$ branch ditch. According to the topography and site conditions of the project, it is recommended to use the grille dam form to fully utilize the conditions of good dam construction between the wide and narrow channels, so as to achieve better control effect, see [17, 18]. The drainage channel is built in the accumulation section downstream of the ditch area, the groove section is adjusted, the curvature of the curve is reduced, the section of the road bridge and culvert is taken as the control section, and the debris flow material downstream of the intercepting dam is smoothly introduced into the Minjiang river. An aqueduct is set up at the intersection of the main ditch and the G213 national road in the ditch area to protect the traffic safety of the road section. There are a large number of rock accumulations in the debris flow channel of the ditch. The lithology is mainly granite, granitic diorite and sandstone. The rock has high strength and can be taken locally when construction, which is conducive to saving construction costs.

Conclusion

In the present task, the geography and geological conditions of the basin and the development of the debris flow, the formation conditions and activity characteristics of the basin, as well as the gravity, flow velocity and impact force of the debris flow were comprehensively analyzed in detail. In view of this kind of similar debris flow disaster, the debris flow prevention and control measures with both safety and economy were discussed in detail.

Acknowledgment

The present work was financially supported by National Natural Science Foundation of China (Grant No. 51822403, 51674170).

References

[1] Li, D. H., *et al.*, Analysis of Formation Conditions and Motion Characteristics of the 8.14 Extra Large Debris Flow in Hongchungou, Yingxiu Town, Wenchuan County, Sichuan Province (in Chinese), *Chinese Journal of Geological Hazard and Control*, *23* (2012), 3, pp. 32-38
[2] Zhou, X. J., *et al*., Distribution and Activity Characteristics of Debris Flows Along the Duwen Highway after the Earthquake, *Journal of Highway and Transportation Technology*, *6* (2013), 12, pp. 5-10
[3] Gee, M. J. R., *et al*., Friedmann, Giant Striations at the Base of a Submarine Landslide, *Marine Geology*, *214* (2004), 1, pp. 287-294
[4] Xu, Q., The 13 August 2010 Catastrophic Deberis Flows in Sichuan Province: Characteristics, Genetic-Mechanism and Suggestions (in Chinese), *Journal of Engineering Geology*, *18* (2010), 5, pp. 596-608
[5] Liu, Q. H., *et al*., Features of Febgtongyan Debris Flow Hazard on August 13, 2010 in Longchi Town of Dujiangyan, Sichuan, China, Journal of Chengdu University of Technology (in Chinese), *Science and Technology Edition*, *39* (2012), 5, pp. 636-642

[6] Penserini, B. D., *et al*., A Morphologic Proxy for Debris Flow Erosion with Application the Earthquake Deformation Cycle, Cascadia Subduction Zone, USA, *Geomorphology*, *282* (2017), 1, pp. 150-161
[7] Tang, C., *et al*., Rainfall-Triggered Debris Flows Following the Wenchun Earthquake, *Bulletin of Engineering Geology and the Environment*, *68* (2009), 2, pp. 187-194
[8] Cui, P., *et al*., Charateristics and Countermeasures of Debris Flow in Wenchuan Area after the Earthquake, Journal of Sichuan University (in Chinese), *Engineering Science Edition*, *42* (2010), 5, pp. 10-19
[9] Qiu, J. L., *et al*., The Catastrophic Landside in Maoxian County, Sichuan, SW China, *Natural Hazards*, *89* (2017), 3, pp. 1485-1493
[10] He, K., *Study on the Genetic Model and Movement Characteristics of Slope-Type Debris Flow in Yingxiu Magmatic Rock Area of Wenchuan Earthquake* (in Chinese), Chengdu University of Technology, Chengdu, China, 2015
[11] Kang, Z. C., *et al*., *Debris Flow Researches in China* (in Chinese), Science Press, Beijing, 2004, pp. 21-22.
[12] Mei, Y., *et al*., Laboratory Study on Submarine Debris Flow, *Marine Georesources and Geotechnology*, *36* (2018), 8, pp. 950-958
[13] Tang, C., *et al*., Characteristics of Debris Flows in Beichuan Epicenter of the Wenehuan Earthquake Triggered by Rainstorm on September 24, 2008 (in Chinese), *Journal of Engineering Geology*, *16* (2008), 6, pp. 751-758
[14] Xiang, B., *et al*., Characteristics and Hazard Analysis of Debris Flow in Zhongzhao Gully, Journal of Chengdu University (in Chinese), *Natural Science Edition*, *33* (2014), 1, pp. 92-95
[15] Gan, J. J., *et al*., Study on Mechanism of Formation and River Blocking of Hongchungou Giant Debris Flow at Ying Xiu of Wen Chuan County (in Chinese), *Journal of Catastrophology*, *27* (2012), 1, pp. 5-9
[16] Hu, Y. F., *et al*., Movement and Accumulation Characteristics of Debris Flows in Cimarong Valley (in Chinese), *Journal of Geological Hazards and Environment Preservation*, *24* (2013), 2, pp. 16-20
[17] Cui, P., *et al*., Debris Flow and Disaster Reduction Strategies in Western China (in Chinese), *Quaternary Sciences*, *23* (2003), 3, pp. 142-151
[18] Cui, P., *et al*., Mountain Disasters and Disaster Mitigation Measures Induced by 5-12 Wenchuan Earthquake, *Journal of Mountain Research*, *26* (2008), 3, pp. 280-282

Paper submitted: August 11, 2018
Paper revised: November 28, 2018
Paper accepted: January 27, 2019