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A catastrophic debris flow in the Wenchuan Earthquake area, July 2013: characteristics, formation, and risk reduction

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Abstract: In the Wenchuan Earthquake area, many co-seismic landslides formed blocking-dams in debris flow channels. This blocking and bursting of landslide dams amplifies the debris flow scale and results in severe catastrophes. The catastrophic debris flow that occurred in Qipan gully (Wenchuan, Southwest China) on July 11, 2013 was caused by intense rainfall and upstream cascading bursting of landslide dams. To gain an understanding of the processes of dam bursting and subsequent debris flow scale amplification effect, we attempted to estimate the bursting debris flow peak discharges along the main gully and analyzed the scale amplification process. The results showed that the antecedent and triggering rainfalls for 11 July debris flow event were 88.0 mm and 21.6 mm, respectively. The event highlights the fact that lower rainfall intensity can trigger debris flows after the earthquake. Calculations of the debris flow peak discharge showed that the peak discharges after the dams-bursting were 1.17–1.69 times greater than the upstream peak discharge. The peak discharge at the gully outlet reached 2553 m^3/s which was amplified by 4.76 times in comparison with the initial peak discharge in the upstream. To mitigate debris flow disasters, a new drainage channel with a trapezoidal V-shaped cross section was proposed. The characteristic lengths (h1 and h2) under optimal hydraulic conditions were calculated as 4.50 m and 0.90 m, respectively.

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Introduction

Over recent years, there has been considerable increase in the magnitude and frequency of debris flows since the Wenchuan Earthquake on 12 May 2008. This is attributed to the remarkable increase in loose solid materials (Cui et al. 2010). More than 800 debris flows occurred during the rainy season from 2008 to 2012. These debris flows have caused considerable damages to the resettled communities, hampering reconstruction efforts (Cui et al. 2011 a, b; Zhang et al. 2013). Studies have reported that debris flows in the meizoseismal area of the Wenchuan Earthquake were caused by strong sediment entrainment, dam breaching, progressive bulking of runoff, mobilization and transformation of landslides, or a combination of these processes (Tang et al. 2009; Chen et al. 2012; Tang et al. 2011; Ma et al. 2013). These debris flows were initiated in hill-slopes and sub-gullies, converged in main channel, and were amplified by step-outburst of dams and landslides to become large one and blocked main river (Ge et al. 2015), consequently formed a catastrophic disaster chain to amplify or enlarge the damages (Zhou et al. 2015). For example, two large landslides (650 × 10^3 m^3 and 240 × 10^3 m^3 in volume) were triggered and formed blocking dam (40 m and 30 m in maximum blocking height) in Hongchun gully in the Wenchuan earthquake area (Tang et al. 2011, 2015); two co-seismic landslides initiated as thin earth slides or debris slides, with the incorporation of additional water, mobilized into catastrophic debris flows (Tang et al. 2015). In another case, six co-seismic landslide dams failed to form a big-scale debris flow with volume of 500 × 10^3 m^3 in Ergou gully in Wenchuan County, Sichuan Province; due to the cascading dam-bursting, the debris flow peak discharge along the main channel was amplified by 82% (Guo et al. 2016a).

When the upstream flood or debris flow moves downwards at high speed, the co-seismic landslide dams are crushed; the channel blockage breaks down gradually, and the incision widens rapidly (Costa and Schuster 1988; Chang and Zhang 2010; Cui et al. 2013). This blocking and bursting of landslide dams amplifies the scale of the debris flow and results in severe catastrophes (Zhu et al. 2013; You et al. 2010). For example, before the Zhouqu debris flow on 7 August 2000, there were at least five large landslide dams in the Sanyanyu Gully that had formed as a result of the Wenxian Earthquake in 1879 (Hu et al. 2010; Zhu et al. 2013). The peak discharge of the debris flow was amplified by 60% as a result of the failure of these cascading landslide dams (Tang et al. 2011; Yu et al. 2013). The debris flow finally cut across the urban area of Zhouqu, where streets, houses, and bridges were destroyed, and 1765 people died. Moreover, the debris flow rushed into the Bailong River and formed a dammed lake that was about 550 m long and 70 m wide, which subsequently flooded half of the city (Cui et al. 2013). There are many studies of individual natural-dam failure (e.g., Costa and Schuster 1988; Cleary and Prakash 2004; Korup et al. 2004, 2005). However, the phenomenon of cascading landslide dam failure and resulting flow scale amplification is quite complicated and not yet fully understood (Cui et al. 2013). A well-accepted concept is that the failure of a single landslide dam can cause peak discharge amplification (Walder and O'Connor 1997). It is clear therefore, that studies of the mechanisms that drive both the bursting of channel blockages and the amplification of debris flows are needed to support the development of mitigation measures to prevent debris flows and their associated damage.

On 7–11 July 2013, a heavy rainstorm swept through the earthquake-hit area of the Upper Minjiang River and caused significant damages. The daily average rainfall measured during this event in Xingfu Village, Dujiangyan (about 47 km to the Qipan gully in a straight line), was 751.4 mm, and was the highest rainfall recorded in the previous 60 years (Liu et al. 2014). Numerous debris flows occurred in the area, and many roads were destroyed, including the Dujiangyan–Wenchuan highway that had just been constructed and had been in service for only seven months, the old G213 national road, and the S303 provincial road. The debris flow that occurred in the Qipan Gully was the largest in the area and caused catastrophic damages. To gain an understanding of the processes of dam bursting and subsequent debris flow scale amplification effect, we attempted to estimate the bursting debris flow peak discharges along the main gully and analyze the scale amplification process of July 11, 2013 debris flow event.

1 General Settings

1.1 Location of the study area

The Qipan Gully is a first-order branch of the Upper Minjiang River, and is close to Weizhou Town in Wenchuan County, Sichuan Province, China (Figure 1). The gully mouth is just 5 km from Wenchuan County, to which it is connected by a national road (G213) and the DuJiangyan-Wenchuan Highway (Figure 2). The gully covers an area of 52.65 km^2 and the main channel is 15.51 km long with a longitudinal slope of 19.2%. The catchment shape resembles a tree leaf and the flow is from southeast to northwest.

1.2 Landform condition

The study area is on the eastern edge of the Qinghai–Tibetan Plateau and the northwestern edge of the Sichuan Basin. The terrain is complex and is characterized by high mountains, deep-cut rivers, and steep slopes. The elevation in the gully

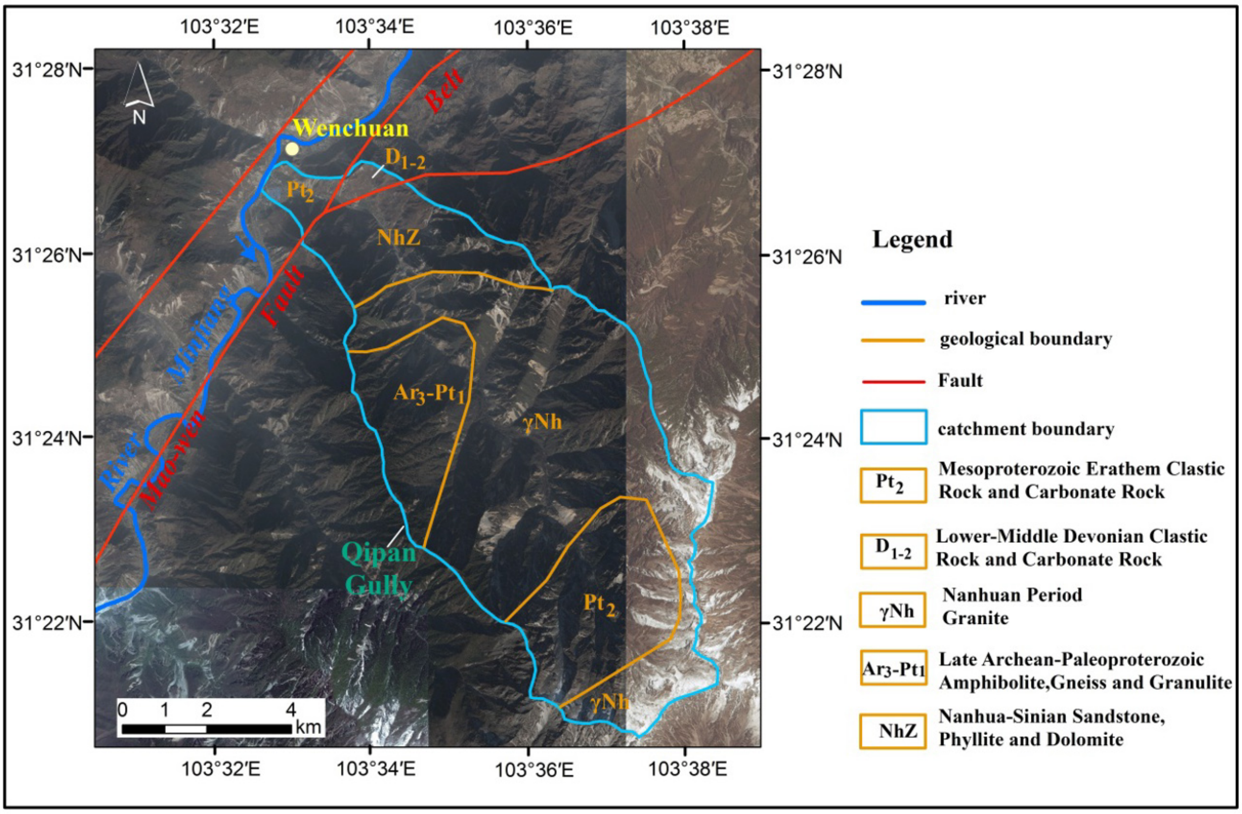

Figure 1 Location and geological setting of the study area. (The satellite image with pixel resolution of 0.60 m was downloaded from Google earth).

spans 3070 m, with a maximum elevation of 4379 m in the southeast of the catchment (Figure 2) and a minimum elevation of 1309 m at the gully mouth. There are 15 tributaries distributed throughout the gully, nine on the left bank and eight on the right bank, the topography parameters of which are listed in Table 1. The elevation ranges in the 15 tributaries vary from 725 (DF12) to 2010 m (DF06), and the channel gradients are all very steep and range from 43.02% (DF05) to 78.87% (DF03).

The Qipan Gully and its tributaries are dominated by steep slopes that are beneficial for the convergence of rainfall runoff. Gently sloping land (<25°), found in the lower reaches, occupies only 13.27% of the total gully area. Steep land (25°–35°) and acutely steep land (⩾35°) occupy 26.72% and 60.01% of the total area, respectively. The steep landscape provides an optimal setting for the formation of debris flows.

1.3 Geology and earthquake condition

The gully is in the Jiudingshan Cathaysian tectonic belt, which is the southern part of the

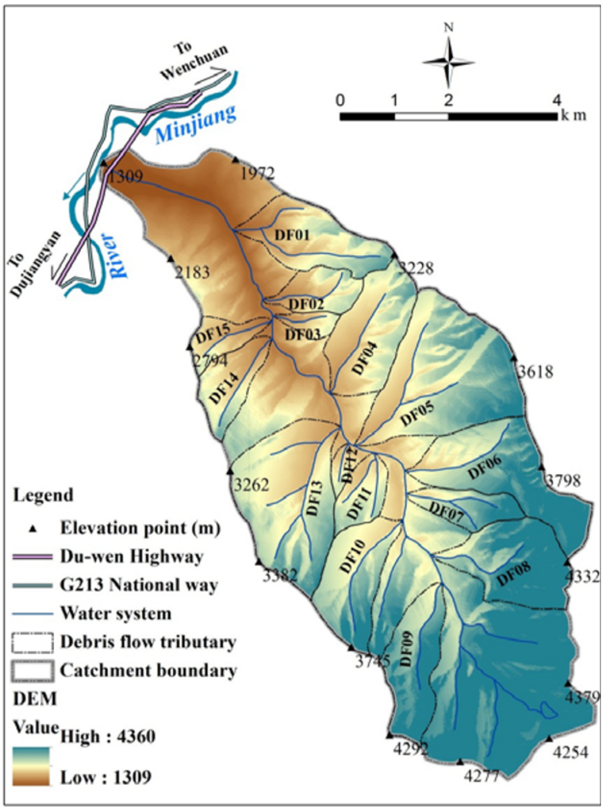

Figure 2 Hydrological network and topography map of the study area.

Table 1 Topography parameters of the 15 tributaries in the Qipan Gully, Wenchuan County, Southwest China

Gully code	Gully name	Basin area (km^2)	Channel length (m)	Channel gradient (%)	Min. elevation (m)	Max. elevation (m)	Elevation difference (m)
DF01	Yutaohua	2.39	3224	53.29	1510	3228	1718
DF02	Xuehuatan	1.08	2045	68.07	1638	3030	1392
DF03	Huangnicao	0.39	1306	78.87	1675	2705	1030
DF04	Madiya	2.67	2879	44.63	1943	3228	1285
DF05	Ganhegou	5.33	3529	43.02	2100	3618	1518
DF06	Shaban	3.56	4260	47.18	2300	4310	2010
DF07	Xiaogou	1.08	2305	71.37	2355	4000	1645
DF08	Hongshichao	2.77	2856	59.24	2640	4332	1692
DF09	Banpeng	2.20	3238	46.85	2775	4292	1517
DF10	Xiaotang	2.33	2757	56.04	2435	3980	1545
DF11	Maancao	0.95	1819	55.80	2165	3180	1015
DF12	Tongmacao	0.24	1082	67.01	2075	2800	725
DF13	Changban	4.51	3020	50.33	2040	3560	1520
DF14	Sanhaoqiao	1.31	2217	66.08	1740	3205	1465
DF15	Tuyao	0.79	1828	67.29	1690	2920	1230

Longmenshan Cathaysian tectonic system. The Mao-Wen Fault goes through the gully mouth (Figure 1). The Mao-Wen Fault belt, a 156-km-long reverse fault, is characterized by a 30°–45° NE strike and dips by 45°–330° NW (Zhou et al. 2000). Exposed strata in the gully include clastic and carbonate rocks of the Mesoproterozoic Erathem (Pt_2); clastic and carbonate rocks of the Lower-Middle Devonian (D_{1-2}); amphibolite, gneiss, and granulite of the Late Archean-Paleoproterozoic (Ar_3-Pt_1); granite of the Nanhuan Period (γNh), and sandstone, phyllite, and dolomite of the Nanhua-Sinian (NhZ) (Figure 1).

Earthquakes occur frequently in the study area and have caused significant destruction to the mountain surface. The Wenchuan Earthquake, which occurred on 12 May 2008, caused widespread destruction in the catchment and caused a large number of landslides that now contain an abundance of loose solid materials for subsequent debris flows (Figure 1). The Qipan Gully belongs to a high-intensity seismic region (VIII degrees), with a peak ground acceleration of 0.2 g and a seismic response spectrum of 0.35 s (Ground Motion Parameter Zoning Map of the Wenchuan Earthquake: GB18306-2001).

1.4 Rainfall condition

The study area has a subtropical semiarid monsoon climate (Liu et al. 2014). The climate is characterized by low rainfall that is unevenly distributed through the year, with obvious dry and rainy seasons. Rainfall was recorded at the Weizhou Meteorological Station, which is about 4.8 km from the study area, from 1958 to 2008. Over this period, the average annual rainfall was 525.3 mm, and the maximum and minimum annual rainfall amounts, which occurred in 1958 and 1974, were 648.6 and 369.8 mm, respectively. Approximately 76.1% of the precipitation is concentrated in the period from May to September. The maximum monthly rainfall generally occurs in July, and daily rainfall events exceeding 30 mm have occurred three times in record time. Precipitation occurs on approximately 151 days every year. The rainfall characteristics favor the formation of debris flows in the Qipan Gully. Collapses, landslides, and other geomorphological disasters occur frequently during the rainy period.

1.5 Historical debris flow events

Many debris flow events have occurred in the Qipan Gully. The earliest recorded debris flow occurred after the Diexi Earthquake that occurred on 25 August 1933 (Xu 1985). This flow destroyed the village of Xuehuaping that was downstream of the gully. Following the 1933 event, 11 debris flows occurred from 1961 to 1978, and caused economic losses of more than 4.38 million RMB (Table 2). For example, on 15 July 1978, a viscous debris flow in the gully destroyed five bridges, 4 km of roadbed, and one drainage channel, at an estimated cost of 0.49 million RMB. Subsequently, a large alluvial fan with an area of 1.04 km^2 formed at the gully mouth. There were no debris flows in the gully between 1979 and 2008. However, a large number

Table 2 Historical debris flow events

Time	Rainfall intensity (mm)				Debris flow type	Occ.-t (min.)	DF-vol. (10^4m^3)	Eco.-l (million)	Damage
	3 days	24 h	1 h	10 min.					
1933	/	/	/	/	Viscous type	/	/	/	Destroyed 1 village
1961-7-6	99.5	79.9	/	/		60	13.5	2.0	Destroyed 1 bridge, roadbed of 400m; Traffic interruption of 15 days
1964-7-23	48.3	41.7	/	1.2	Diluted type	50	9.1	1.0	Traffic interruption of 8 days
1970-7-28	56.5	33.0	/	/		60	5.8	0.21	Destroyed 3 bridges, roadbed of 4 km; buried farmland of 4.0 hectares
1971-7-24	79.4	53.4	/	/		45	8.4	0.25	Destroyed 4 bridges, roadbed of 5 km; buried farmland of 5.3 hectares
1975-7-29	/	32.5	9.6	3.8		40	9.8	0.16	Destroyed 5 bridges, roadbed of 8 km; buried farmland of 8.0 hectares
1977-7-7	/	39.4	7.6	1.6		30	5.8	0.27	Destroyed roadbed of 4 km; buried farmland of 2.7 hectares
1978-7-15	79.5	66.7	36.4	17.0	Viscous type	50	13.5	0.49	Destroyed 5 bridges, roadbed of 4 km and 1 drainage channel
1979-8-15	48.0	30.8	/	6.1	Diluted type	30	3.8	/	/
1980-7-26	/	/	/	4.4		20	5.4	/	/
1981-8-12	/	53.8	9.5	2.1		25	6.7	/	/
1983-7-19	/	31.3	8.1	1.7		15	2.3	/	/
2013-7-11	114.0	54.3	8.9	/	Diluted type	90	78.2	/	See Section 3.1.1 of this paper

Notes: Occ.-t= Occurrence time; DF-vol.= Debris flow volume; Eco.-l= Economic loss at the time.

of landslides occurred in the catchment after the 5.12 Wenchuan Earthquake, which produced a large supply of loose solid materials. Debris flows formed in many tributaries. For example, a debris flow that occurred in the Huangnicao Gully (DF03, Figure 2) in 2009 formed a debris fan and caused a blocking site in the main channel. There were no debris flows in the main gully from 2008 to 2012.

2 Methods

2.1 Map compilation

A 1:50,000 topographic map and a 25-m digital elevation model (DEM), provided by the Sichuan Center of Basic Geographic Information, were used to determine the topographic features of the debris flows. The slope gradients of the gully were determined from the DEM. The 1:200,000 geological map of the study area, compiled by the China Geologic Survey, was used to map the lithology and the locations of the faults. We used aerial photography at a scale of 1:5000 to realize an engineering geomorphological sketch map of the 11 July 2013 debris flow event in the Qipan Gully. We delimited the debris flow deposition range and the destroyed buildings on the engineering geomorphological sketch map. The debris flow gullies were mapped on a 1:50,000 topographic map during field investigations, and were then digitized into a geographic information system (GIS).

2.2 The calculation of bursting peak discharge of debris flow

We used the peak discharge data from the main channel to examine how the debris flow developed, formed, and was amplified in response to the bursting of a series of cascading channel blocking dams in the Qipan Gully.

The peak discharges in the main channel of the Qipan Gully after landslide-dam bursting can be calculated with the following equation (Yu et al. 2013):

$$Q_m = \frac{8}{27}\sqrt{g}\left(\frac{B_0}{b_m}\right)^{1/4} b_m H_0^{\ 3/2} \tag{1}$$

where Q_m is the peak discharge of the debris flow after the blocking dam burst (m^3/s); g is the acceleration of gravity and is equal to 9.8 m/s^2; B_o is the total length of the blocking dam (m); b_m is the length of the broken dam (m), and H_o is the height of the broken dam (m).

During the field investigation, the traces of mud on both banks of the main channel of the

Qipan Gully were measured to determine the depth of the debris flow. With this information, we determined the transverse flowing area of the debris flow for each measured cross section. The debris flow peak discharge of each measured cross section can be calculated with the following equations (Kang et al. 2004):

$$Q_C = V_C S_C \tag{2}$$

$$V_C = \frac{1}{\sqrt{\gamma_H \phi + 1}} \frac{1}{n} R^{2/3} I^{1/2} \tag{3}$$

$$\phi = \frac{\gamma_D - \gamma_W}{\gamma_H - \gamma_D} \tag{4}$$

$$R_C = \frac{Sc}{Pc} \tag{5}$$

where Q_C is the peak discharge of the debris flow (m3/s); V_C is the velocity of the debris flow (m/s); S_C is the measured cross section area for the debris flow (m2); γ_H is the density of the solid material (g/cm3) and is usually taken as 2.65 g/cm3; ϕ is the increase in the coefficient of the debris flow peak discharge; R_C is the hydraulic radius of the measured cross section (m), and n is the roughness coefficient, and was determined from a look-up table that is based on the debris flow fluid characteristics and channel condition (Zhou et al. 1991; Fei and Shu 2004). Here, $1/n$ is taken as 12. I, the hydraulic slope, is determined from the 1:1000 topography map; γ_W is the density of water (g/cm3) and is usually taken as 1.00 g/cm3, and P_C is the wetted perimeter of the measured cross section. γ_D is the debris flow density (g/cm3) and can be calculated from the particle size distribution of the debris flow deposit (Yu et al. 2013).

$$\gamma_D = \gamma_0 + \gamma_V P_2 (P_{0.05})^{0.35} \tag{6}$$

Where, γ_V (2.0 g/cm3) is the minimum density of a viscous debris flow. γ_o (1.5 g/cm3) is the minimum density of a debris flow. P_2 is the weight percentage of coarse particles (>2 mm) in the sediment of the debris flow. $P_{0.05}$ is the weight percentage of fine particles (<0.05 mm) in the sediment.

To calculate the debris flow density, seven debris flow deposition samples were collected from the main channel for sieving and particle size distribution analysis. Field and laboratory dry sieving tests were conducted following the British Standard methods (Chen et al. 2012). Most superficial debris flow materials comprise gravel and pebbles; therefore, the samples were collected from sites where sand and gravel were exposed. The materials were retrieved, weighed, dried, and classified as 2–5, 5–10, 10–20, 20–60, 60–100, 100–150, 150–200, or >200 mm. Fine materials (<2 mm diameter) were tested further using laboratory dry sieving tests.

2.3 The calculation method for the optimal cross-section of drainage channel

In the 7-11 debris flow event, the old drainage channel in the downstream of the Qipan gully was completely destroyed. To decrease the debris flow risk, a new drainage channel was recommended. The method for determining the cross-section of the drainage channel using optimized measurements was introduced as follows.

The cross section design of the drainage channel was also optimized. The slope of the accumulation area is small and equals to 8% which usually caused siltation in the old trapezoid-shaped drainage channel. The trapezoidal-V shape drainage channel is characterized by an increased debris-flow velocity, improved discharge capacity, and reduced siltation (Chen et al. 2016). Therefore, we chose a trapezoidal-V shape for the cross section design of the drainage channel as it is more suitable for draining gentle slopes than the previous trapezoid-shaped cross section design. The hydraulic cross section of the drainage channel is optimal when: the passage area of the cross section (A_C) is minimized, or the hydraulic radius (R_C) is maximized; and the values of the inside of the longitudinal gradient of the section (I), roughness coefficient (n), and design peak discharge of the debris flow (Q_C) are fixed. That is, the minimum A_C that is required to drain the design peak discharge Q_C (You et al. 2011).

As shown in Figure 3, h_1 and h_2 are the characteristic lengths of two overflowing cross-sections. m_1 is the side slope coefficient and m_2 is the groove transverse slope coefficient. To evaluate the optimal hydraulic condition, the cross section configuration parameter of the trapezoidal V-shaped debris flow drainage canal (M) was defined as the ratio of the wetted perimeter (P_C) to the hydraulic radius (R_C) (You et al. 2011).

$$M = \frac{P_C}{R_C} = \frac{P^2}{A_C} = \frac{A_C}{R_C{}^2} \tag{7}$$

After Eq.(7) is calculated, the cross section configuration parameter of the trapezoidal V-shaped debris flow drainage channel (M) can be calculated as follows (You et al. 2011).

$$M = \frac{\left[2\beta\sqrt{1+m_1^2}+2\sqrt{1+m_2^2}\right]^2}{m_1\beta^2+2m_2\beta+m_2} \quad (8)$$

$$\beta = \frac{m_2(\sqrt{1+m_1^2}-\sqrt{1+m_2^2})}{m_1\sqrt{1+m_2^2}-m_2\sqrt{1+m_1^2}} \quad (9)$$

Where β is defined as a size parameter of the drainage channel ($\beta=h_1/h_2$).

The continual debris flow discharge equation is:

$$Q_C = A_C V_C \quad (10)$$

If we plug Eq.(7) into Eq.(10), we can solve the equation for the velocity of the debris flow.

$$V_C = \frac{Q_C}{MR_C^{\ 2}} \quad (11)$$

By solving Eq.(3) and Eq.(11), we get:

$$R_C = \left[\frac{nQ_C\sqrt{\gamma_H\emptyset+1}}{M\sqrt{I}}\right]^{3/8}. \quad (12)$$

If we assume that the peak discharge of the debris flow (Q_C), the roughness coefficient of the drainage channel (n), the side slope coefficient (m_1), the groove transverse slope coefficient (m_2), and the hydraulic slope of the drainage channel (I) are known, we can calculate the characteristic lengths (h_1 and h_2) of the optimal cross-section (You et al. 2011).

$$h_1 = \frac{\beta M}{2(\beta\sqrt{1+m_1^2}+\sqrt{1+m_2^2})}\left[\frac{nQ_C\sqrt{\gamma_H\emptyset+1}}{M\sqrt{I}}\right]^{3/8} \quad (13)$$

$$h_2 = \frac{M}{2(\beta\sqrt{1+m_1^2}+\sqrt{1+m_2^2})}\left[\frac{nQ_C\sqrt{\gamma_H\emptyset+1}}{M\sqrt{I}}\right]^{3/8} \quad (14)$$

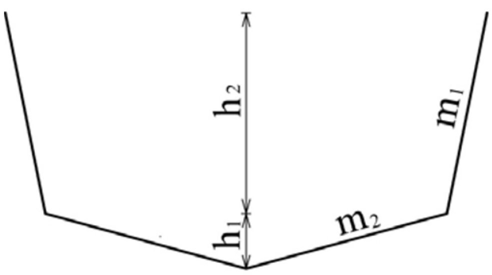

Figure 3 Measurements of trapezoid-V shaped drainage channel (You et al. 2011).

3 Results and Discussions

3.1 Disaster characteristics

3.1.1 Damages of the 7-11 debris flow event

From 7 to 11 July 2013, a widespread heavy rainstorm hit Wenchuan County and triggered many debris flows along the Upper Minjiang River, including the one in the Qipan Gully. The 11 July debris flow in the gully was the largest and caused extensive damage. Eight people died, six people went missing, and about 90% of the homes of residents in the area downstream of the gully were completely devastated (Figure 4, section A-B; Figure 5). About 1600 people from 480 households in 5 villages and 2800 people from 737 households in the Sunshine Home community were severely affected by the disaster (Figure 4, section B-C). Two hundred and eighty five buildings, 4 km of drainage channel (Figure 4, section A-C), three transformer substations, and factories of seven companies were completely destroyed by the debris flow. The debris flow rushed out of the gully, passed through the bridge culvert of the DuJiangyan- Wenchuan Highway and encroached on right branch of the Minjiang River to form a debris fan (Figure 4). The fan was 80 m long, 450 m wide, and had an average depth of 10 m. Measurements from the aerial photograph estimated the area and volume of the deposition area at 1.8×10^4 m² and 18.0×10^4 m³, respectively. The debris flow deposition pushed the Minjiang River to its right bank and about 400 m of the roadbed of the G213 national road was destroyed by the ensuing flood (Figure 4). Moreover, a barrier lake formed a 3.5-km-long, 8–10-m-deep reservoir. Consequently, part of the Xinqiao Village, a vehicle management office, and a bus station upstream were submerged by the backwater of the barrier lake (Figure 4). The debris flow also destroyed about 15 km of rural road downstream of the Qipan Gully. The economic loss of the 11 July 2013 debris flow event was estimated at 415 million RMB.

3.1.2 Triggering rainfall

Before the Wenchuan Earthquake, daily rainfall of 80–100 mm and hourly rainfall of 30–50 mm were needed to trigger a debris flow in the study area (Tan 1996). However, because of the huge increase of loose materials in the debris flow gullies following the earthquake, the amount of rainfall needed to trigger a debris flow decreased (Tang et al. 2009). Tang and Liang (2008) demonstrated that the critical accumulated precipitation and the hourly intensity needed to initiate debris flows in Beichuan County were as little as 14.8% – 22.1% and 25.4% – 31.6%, respectively, of the before-earthquake amounts.

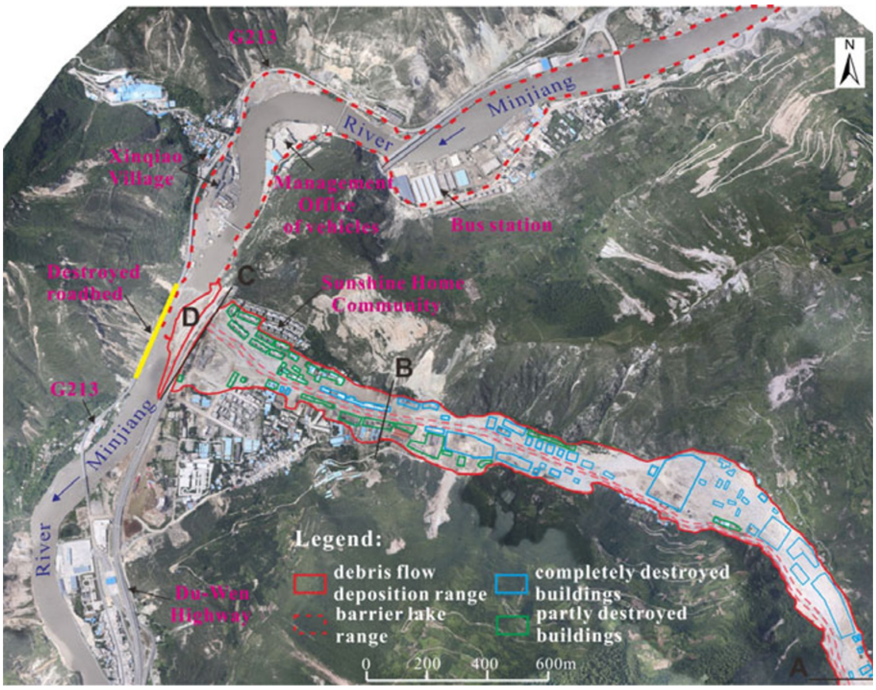

Figure 4 Engineering geomorphological sketch map of the 11 July 2013 debris flow on an aerial photograph.

Figure 5 (A) a few buildings of local residents and factories located in the downstream gully before the 11 July debris flow event; (B) almost all the buildings were destroyed after the 11 July debris flow event; (C), (D) debris deposition on the alluvial fan and buildings destroyed by the debris flow.

The Qipan Gully debris flow of 11 July was the biggest in the upstream part of the Min River in 2013. The intensity of the triggering rainfall event was ascertained from rainfall data collected from a rain gauge sited at the alluvial fan of the Qipan Gully. Figure 6 shows the hourly and cumulative rainfall recorded at the station from 7 to 11 July 2013. The rainfall started at about 05:00 on 8 July and ended at about 7:00 on 11 July. On 8 July, 2 days before the debris flow in the Qipan Gully, 32.6 mm of rainfall were recorded between 05: 00 and 24: 00. A total of 15.8 mm, 49.5 mm, and 21.1 mm were recorded for 9 July, 10 July, and 11 July, respectively. The cumulative rainfall during the 75 h from 05:00 on 8 July to 07:00 on 11 July was 118.3 mm, and the maximum 12-hour rainfall was 30.4 mm which can be classified as rainstorm (China Meteorological Administration 2012). Field investigations indicated that the debris flows first occurred in the tributaries, such as the Yutaohua (DF01), Huangnicao (DF03), Xiaotang

(DF10), Changban (DF13), and the Sanhaoqiao (DF14), and in the Tuyao (DF15) gully. Then, a large-scale debris flow occurred in the main channel of the Qipan Gully. Witnessed reported that the debris flows in the tributaries occurred at 09:00 on 10 July, while the debris flow in the main channel occurred at 02:00 on 11 July. The antecedent and triggering rainfalls for the debris flows in the tributaries and the main channels have been separated in Figure 6. Records indicate that the antecedent (AR-01 in Figure 6; from 05:00 on 8 July to 23:00 on 9 July) and the triggering rainfalls (TR-01 in Figure 6; from 00:00 to 09:00 on 10 July) for the tributary debris flow were 47.7 and 33.7 mm, respectively. The antecedent (AR-02 in Figure 6; from 05:00 on 8 July to 21:00 on 10 July) and the triggering rainfalls (TR-02 in Figure 6; from 22:00 on 10 July to 02:00 on 11 July) for the debris flow that occurred in the main channel of the Qipan Gully were 88.0 and 21.6 mm, respectively.

The rainfall data for the 11 July event (Figure 6) show that the 3-d, 24-h, and 1-h rainfall amounts that triggered the Qipan Gully debris flow were 114.0 mm, 54.3 mm, and 8.9 mm, respectively. We examined the relationships between the triggering rainfall and the magnitude of the debris flow of the historical events (Table 1) and the 11 July event (Figure 7). To determine the relationship between the rainfall and the magnitude of the events (Figure 7), we used data from 6 historical events with 3-d rainfall, 10 historical events with 24-h rainfall, and 5 historical events with 1-h rainfall (Table 1). The 3-d, 24-h, and 1-h triggering rainfall amounts are positively correlated with the magnitude of historical debris flow events (Figure 7). While the R^2 values are not so high, ranging from 0.62 to 0.65, there is an obvious positive trend. However, when added to the analysis, the data for 11 July 2013 stood out as a single point and did not fit the pattern of the historical events. This indicates that, because of the abundant supply of source material for debris flows supplied by the Wenchuan Earthquake, post-earthquake debris flows in the study area can be triggered by lower rainfall intensities (Tang et al. 2011).

In current situation of Western China, rainfall gauges are seldom located in gullies, especially in debris flow source regions where rainfall is usually higher than at the lower elevation gully outlets (Guo et al. 2016b). Therefore, the rainfall data we generally used inadequately represents the rainfall conditions necessary to set in motion the unconsolidated material which forms debris flows.

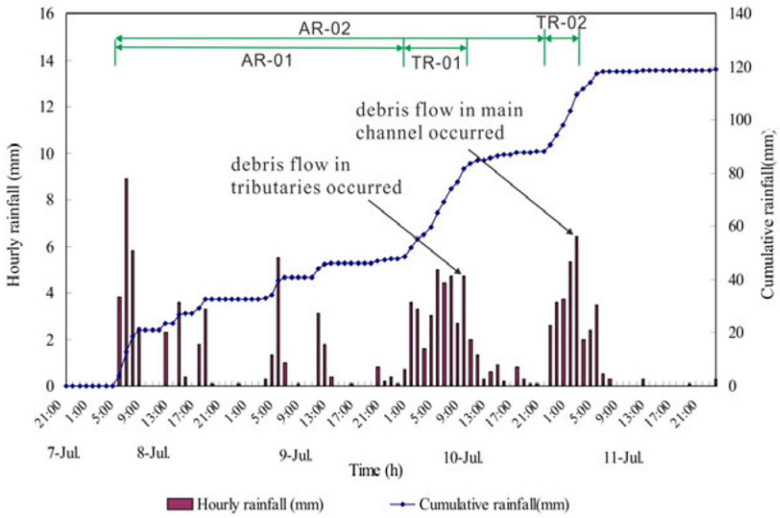

Figure 6 Distribution of hourly and accumulated rainfall on July 7–11, 2013.

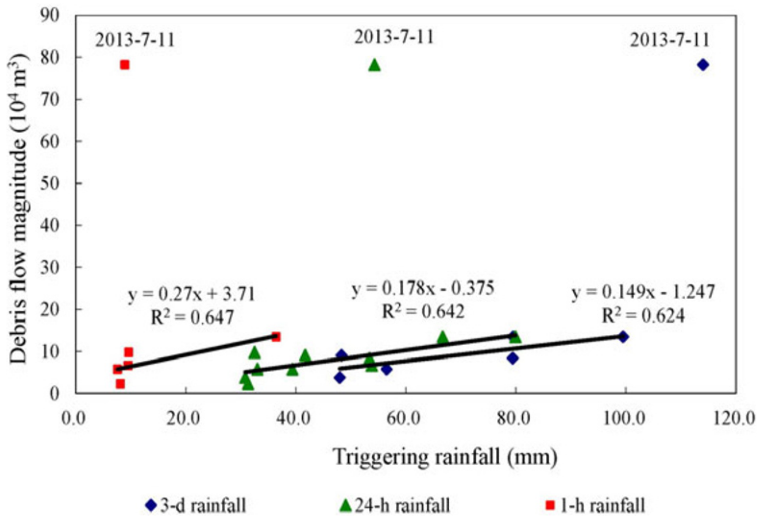

Figure 7 The relation between triggering rainfall and debris flow magnitude of historical events and the 2013-7-11 event.

This variation of rainfall with elevation caused some uncertainness for triggering rainfall in the upstream gully was believed to be much higher than that monitored at the outlet (Guo et al. 2016b, c). If there is a weather station at the upper stream, they will enable us to record a series of continuous data concerning the source area. This would allow us to assess, from the analytical point of view, the trigger possibility of debris flow events (Faccini et al. 2009).

3.1.3 Deposition characteristics

We derived the properties of the debris flow deposition material from samples collected at seven sites (S1–S7) in the main channel of the Qipan Gully (Figure 8). We measured the weight percentage of coarse particles (>2 mm) and fine particles (<0.05 mm) of the seven samples. The results show that coarse particles (>2 mm) made up between 28.0% and 66.0%, while fine particles (<0.05 mm) accounted for between 1.0% and 12%, of the debris flow materials at the seven sites (Table 3).

Based on the sieving tests of debris flow deposition samples, the debris flow densities at different locations from upstream to downstream of the main gully were calculated by using Eq.(6). The calculation results show that the debris flow density ranged from 1.663 g/cm^3 and 1.853 g/cm^3 (Table 3), which, based on the classification of Zhou et al. (1991), means that the debris flow in the Qipan gully was the diluted type.

Figure 8 Debris flow sampling sites and the arrangement of the measured cross-section on the 1:5000 aerial photography.

3.2 Formation mechanism

3.2.1 Channel blocking

As well as triggering serious co-seismic landslides, the Wenchuan Earthquake has had a significant influence on slope stability in the Qipan Gully. The earthquake produced an abundant supply of loose solid materials, which has served as source material for rainfall-induced debris flows (Figure 8). After the Wenchuan Earthquake, six blocking dams formed in the main channel of the Qipan Gully (Figure 8), between elevations of 1587 and 2455 m (Table 4). Among the six blocking dams, four formed from landslides (B01, B03, B04, and B06, Figure 8) and two formed from deposition of debris flow from tributaries (B02 and B05, Figure 8).

The biggest blocking dam was upstream of the Xiaotang Gully (DF10 in Figure 8). This dam formed as a result of a co-seismic landslide triggered by the Wenchuan Earthquake (B01 in Figure 8). The landslide was 150 m long, 650 m wide, and approximately 20 m deep. The volume of the landslide was estimated as 337 × 10^4 m^3. Part of the landslide entered the main channel and formed a blocking dam (B01 in Figure 8). The dam had an average width of 61.6 m, and was 650 m long and between 20 and 30 m deep. The volume of the dam (V_o) was estimated at 96.2 × 10^4 m^3 (Table 4).

The Laoyingyan landslide dam (B06 in Figure 8) was the last blocking site in the main channel before the gully outlet. The Laoyingyan landslide was a co-seismic landslide, triggered by the Wenchuan Earthquake. The landslide spanned an elevation of 473 m, with a maximum elevation of 2060 m at the edge of scarp and a minimum elevation of 1587 m at the toe. After sliding into the main channel, the landslide formed a fan-shaped dam with a volume of 19.1×10^4 m^3. The dam was 150 m long, 170 m wide, and between 15 and 20 m deep. During the field investigation, we found that the fan-shaped dam was covered by many large dolomite boulders. The largest boulder measured 16×12×6 m. In the July 11 event, some of the large boulders were transported downstream, thereby increasing the destructive power of the debris flow. After the Wenchuan Earthquake, a barrier lake formed as a result of this landslide blocking dam and existed for about 5 years until the July 11 debris flow event. The lake was 110 m long, 43 m wide, and between 8 and 10 m deep (Figure 9). The volume of the water storage was approximately 4.25×10^4 m^3. In the 11 July event, the blocking dam burst, the lake emptied (photo comparison of B06-1 and B06-2 in Figure 8), and, the scale of the debris flow greatly increased.

3.2.2 Formation mechanism of the 11 July debris flow event

The peak discharge is an important parameter in the debris flow process. To back-calculate the bursting peak discharges at the landslide-dam sites during the 11 July debris flow, we measured and mapped six cross sections of the blocking dams (B01–06 in Figure 8) at a scale of 1:200 (for example, B06 cross section in Figure 9) to obtain key parameters (B_o, b_m, and H_o in Eq.(1)). In addition, we set 15 cross sections of the main channel (C01, C03–C16 in Figure 8) and one tributary cross section (C02 in Figure 8) to calculate the debris flow peak discharge by using Eq.(2) to Eq.(5) for discovering the amplification process in 11 July debris flow event. The calculating results of peak discharges of the 22 cross sections of the main channel are listed in Table 4 and Table 5.

Table 3 The weight percentage of coarse and fine particles (P), the calculation results of debris flow density (γ_D)

Samples	P>2 mm	P<0.05 mm	γ_D (g/cm^3)
S_1	0.41	0.09	1.853
S_2	0.28	0.05	1.696
S_3	0.45	0.065	1.846
S_4	0.66	0.01	1.763
S_5	0.32	0.02	1.663
S_6	0.30	0.12	1.786
S_7	0.31	0.06	1.732

Table 4 Basic parameters of the 6 blocking sites in the main channel

Blocking dams	Elevation (m)	H_o (m)	B_o (m)	b_m (m)	V_o (10^4m^3)	Q_m (m^3/s)
B01	2455	8.0	61.6	38.3	96.2	905.2
B02	2340	7.2	81.5	62.6	5.1	1198.3
B03	1830	8.5	59.4	59.4	4.4	1365.4
B04	1755	12.3	41.2	41.2	5.5	1648.5
B05	1683	8.5	85.2	85.2	9.6	1958.4
B06	1587	16.0	43.0	43.0	19.1	2552.6

Notes: H_o is the height of the broken dam. B_o is the total length of the blocking dam. b_m is the length of the broken dam. V_o is the total volume of landslide dam. Q_m is the peak discharge of the debris flow after the blocking dam burst.

Before and after the Wenchuan Earthquake, the factors that triggered and controlled the formation of the debris flows mainly depended on the supply of loose material rather than on rainfall (Cui et al. 2010). This was also the case for the Qipan Gully. As shown in Figure 1 and Figure 8, many landslides formed during the earthquake and were distributed throughout the whole catchment. There were abundant source materials to form debris flows.

Field investigations indicated that the debris flow in the Qipan Gully was the rainstorm-induced, channel-blocking/bursting type. The debris flow event was triggered by rainfall of 118.3 mm over a period of 75 hours. During the 11 July event in the Qipan Gully, the debris flow first occurred in the tributaries; the six blocking dams in the main channel burst one-by-one from upstream to downstream, and, as a result, the scale of the debris flow increased sufficiently to cause catastrophic damage downstream and on the alluvial fan. Figure 10 shows changes in the peak discharge of the debris flow along the main channel in the July 11 event in the Qipan Gully. When the debris flow was forming in the main channel, the peak discharge of the debris flow at a velocity of 6.49 m/s reached 535.8 m^3/s (C01 cross-section in Figure 8) because of convergence with flow from a 14.25 km^2 drainage area upstream of the C01 cross section in the upper reaches of the Qipan Gully. When the debris flow was transported to the first blocking site (B01), the blocking dam partly burst open (b_m/B_o=0.62, Table 4), with an erosion depth of 8 m. Consequently, the debris-flow peak discharge increased to 1.69 times that of the upstream peak discharge (Table 4 and Table 5). Before the debris flow reached the second blocking site (B02), its peak discharge and velocity were 985.8 m^3/s and 6.11 m/s, respectively (C03). The second blocking dam was also burst open (b_m/B_o=0.77, Table 4) by the upstream incoming flow. After bursting, the debris-flow peak discharge increased to 1.22 times that of the upstream incoming flow (Table 4 and Table 5). The debris flow then entered into the wide valley of the main channel (C04 to C06 in Figure 8). Because of the wider channel (100–125 m wide), the velocity of the debris flow decreased to 5.52 m/s and its peak discharge decreased to 1068.2 m^3/s in section C05 (Figure 8). Later, the debris flow entered into the narrow valley (30 to 85 m wide on average) of the main channel (C06 to C10 in Figure 8). After passing the three blocking sites (B03, B04, and B05), the debris flow completely burst open the three blocking dams (b_m/B_o=1, Table 4). Consequently, the debris-flow peak discharge reached 1365.4 m^3/s, 1648.5 m^3/s, and 1958.4 m^3/s at B03, B04, and B05, respectively. These peak discharges were 1.21 times, 1.19 times, and 1.17 times the peak discharges upstream of B03, B04,

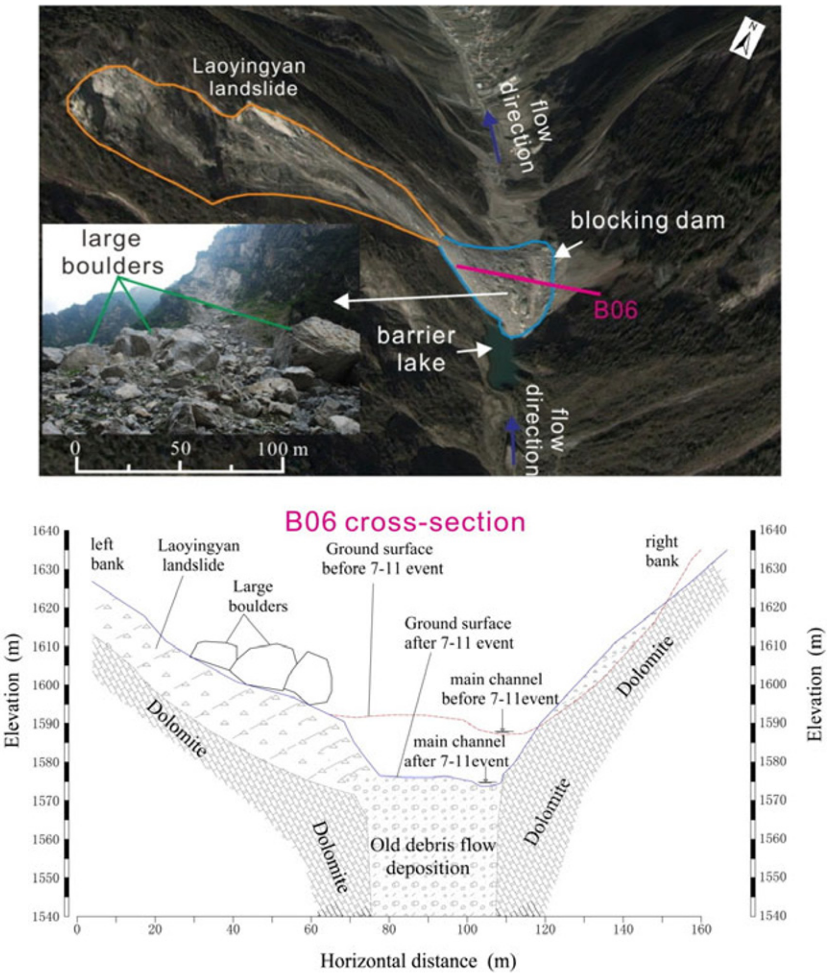

Figure 9 The Laoyingyan landslide dam and its cross-section.

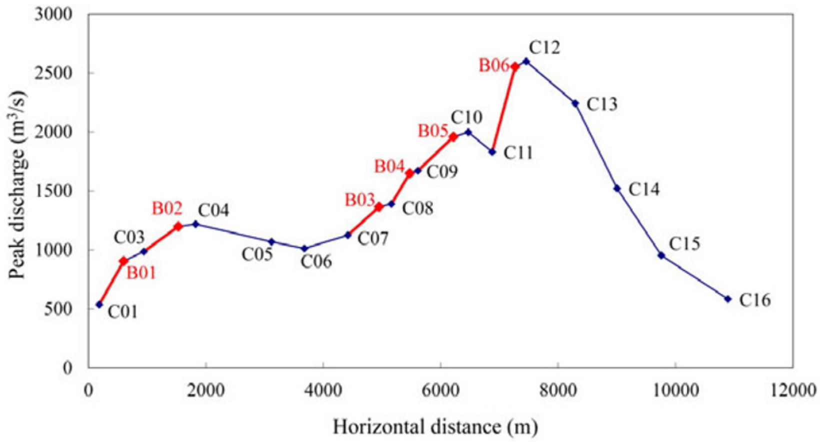

Figure 10 Changes in the peak discharge of the debris flow along the main channel through the 11 July event in the Qipan Gully. Red line shows the peak discharge amplification of the 6 channel blocking –bursting process.

and B05, respectively (Table 4 and Table 5). When the debris flow finally reached the Laoyingyan barrier lake, the lake water level increased, which caused the blocking dam to overflow (B06 in Figure 8) and burst open. After the dam burst, the debris flow peak discharge increased to 2552.6 m³/s and was 1.39 times that of the upstream flow. Before the debris flow entered into the hazard range of the 11 July event (upstream of C12), its peak discharge was 4.85 times that at C01 (Figure 8).

After passing through the Laoyingyan landslide dam, the debris flow with large boulders was transported to the residential area downstream of the main channel of the Qipan Gully (Figure 8). Because the width of the channel increased and the channel longitudinal slope decreased, the debris flow quickly deposited in the main channel, resulting in burial of the buildings. The peak discharge and velocity of the debris flow decreased along the main channel (Table 5). Before the debris flow entered into the Minjiang River, its peak discharge and velocity were 583.0 m³/s and 3.18 m/s, respectively.

Table 5 The peak discharges of the 16 cross sections of the main channel

Cross-section	γ_D (g/cm³)	S_C (m²)	P_C (m)	R_C (m)	I	ϕ	V_C (m/s)	Q_C (m³/s)
C01	1.853	82.5	35.5	2.32	0.365	1.07	6.49	535.8
C02	1.853	13.8	11.4	1.21	0.382	1.07	4.30	59.4
C03	1.853	161.3	73.2	2.20	0.347	1.07	6.11	985.8
C04	1.853	181.8	69.2	2.63	0.330	1.07	6.70	1218.3
C05	1.696	193.6	112.3	1.72	0.300	0.73	5.52	1068.2
C06	1.846	146.5	48.2	3.04	0.285	1.05	6.91	1011.7
C07	1.846	172.4	61.3	2.81	0.282	1.05	6.52	1124.6
C08	1.763	198.6	69.5	2.86	0.275	0.86	7.00	1389.7
C09	1.763	202.5	52.2	3.88	0.254	0.86	8.25	1669.6
C10	1.663	232.4	62.2	3.74	0.246	0.67	8.60	1997.5
C11	1.663	254.5	79.6	3.20	0.212	0.67	7.19	1830.3
C12	1.786	341.7	92.3	3.70	0.239	0.91	7.60	2597.5
C13	1.786	465.3	178.2	2.61	0.153	0.91	4.82	2242.4
C14	1.732	365.5	161.6	2.26	0.126	0.80	4.16	1520.4
C15	1.732	263.2	122.2	2.15	0.102	0.80	3.62	953.5
C16	1.732	183.3	80.5	2.28	0.073	0.80	3.18	583.0

Notes: γ_D is the debris flow density. S_C is the measured cross section area for the debris flow. P_C is the wetted perimeter of the measured cross section. R_C is the hydraulic radius of the measured cross section. I is the hydraulic slope. ϕ is the increase in the coefficient of the debris flow peak discharge. V_C is the velocity of the debris flow. Q_C is the peak discharge of the debris flow.

For the above proposed method for calculating the debris flow peak discharge, some parameters of the empirical equations were determined empirically which caused the uncertainties of the calculating results (Liu et al. 2014). For example, the velocity (V_C) of debris flow can increase about 25.0% when the roughness coefficient ($1/n$) is determined as 15 instead of 12 (Eq.(3)). Accordingly, the peak discharge (Q_C) can increase about 1.25 times. To make the calculating results more rational and accurate, the determination of these parameters in the used empirical equations needs to be improved in future studies. Moreover, for calculating the bursting peak discharge, we just used three dimension parameters of the blocking dam (B_o, b_m, and H_o in Eq.(1)). The calculating results are barely testified because direct measurements of debris flows are nearly impossible (Iverson 1997). Costa and Schuster (1988) pointed out that the peak discharges amplification caused by natural-dam failures appears to be controlled by dam characteristics and failure mechanisms. Therefore, to better understand the process of cascading landslide dam failures and the formation of debris flows, physically based studies of the complicated hydrodynamic process of cascading landslide dam failures should be modeled in large flumes to correctly capture the key modes of cascading landslide dam failure (Cui et al. 2013).

3.3 Risk Reduction

A drainage channel was constructed in the downstream channel on the alluvial fan of the Qipan Gully in 1980 (Xu 1985) and was repaired in 2009 after 29 years of service. The total length of the drainage channel was 3256 m. The channel had a trapezoidal-shaped cross section that was 2.5–3.0 m deep and 12.0–15.0 m wide, and was able to drain the debris flow at a rate of 250 m³/s. The old drainage channel was almost completely destroyed in the 11 July event (Figure 11, A and B). Because all of the cascading channel blocking dams had burst, the peak discharge of the debris flow at the entrance of the drainage channel was much larger than its drainage capacity. In addition, the cross section shape (trapezoid shape) of the drainage

Figure 11 The drainage channel before and after the debris flow event.

channel was not suitable for draining debris flows from gentle channel slopes, such as the slope of the alluvial fan area in the Qipan Gully, which had a gradient of 8%.

To mitigate debris flow disasters in the Qipan Gully, plans were developed to construct five check dams, two pile dams, one silt dam, one ground sill, three channel-stabilized sills made of Cabion wire boxes, one protection embankment in the main channel, and 14 consolidation dams in the Xiaotang (DF10), Ganhegou (DF05), and Changban (DF13) Gullies (Investigation of emergency actions to mitigate debris flow hazards in the Qipan Gully, Wenchuan County, Aba Prefecture, Sichuan Province, compiled by the Sichuan Shutong Geotechnical Engineering Co. Ltd, 2013). These mitigation measures will stabilize the channel and slope, decrease the amount of loose soils, and minimize the peak discharge of the debris flows. In addition, a new drainage channel on the deposition area (about 2.4 km in length) should be constructed between the Laoyingyan landslide and the Minjiang River to protect the buildings that will be reconstructed downstream of the Qipan Gully in the future.

To determine the optimized cross-section of the trapezoidal V-shaped drainage channel, the side slope coefficient (m_1) and the transverse coefficient (m_2) of were determined as 0.20 and 5.00, respectively. When these values were entered into equations (8) and (9), we obtained the size parameter (β = 5.00) and the configuration parameter (M = 6.94). When the comprehensive mitigation program (including the installation of check dams, consolidation dams, and pile dams) is completed, the debris flow is expected to be controlled to a small-scale one or converted to a high-concentrated flow, such that, when it enters the drainage channel, it will be within the occurrence frequency of the 50-y return period. The peak discharge of the 11 July debris flow was estimated at 365.0 m^3/s when it entered the drainage channel (The investigation report on emergency mitigation works of debris flow hazard in the Qipan gully in Wenchuan County, Aba Prefecture of Sichuan Province", Compiled by the Sichuan Shutong Geotechnical engineering Co., Ltd). The measurements for the optimal cross-section of the drainage channel in the Qipan Gully are listed in Table 6 and a diagram of its structure is shown in Figure 12.

4 Conclusions

Clusters of landslide dams formed by intense earthquakes, and which completely or partially block channels before debris-flow events, can burst like dominoes (Cui et al. 2013). This cascading failure process can lead to debris flow peak discharge amplification, and consequently, cause catastrophic damages to personal injury, infrastructures and homes at downstream locations. The debris flow occurred in the Qipan gully on 11 July 2013 was the rainstorm-induced, channel-blocking/bursting type. The debris flow density, calculated from the particle grading of the deposited materials, ranged from 1.663 g/cm^3 to 1.853 g/cm^3. The debris flow that occurred in the Qipan Gully was therefore classified as the diluted type.

Based on the rainfall data collected from the

Table 6 Measurements for the optimal cross-section of the Qipan Gully drainage channel

Q_C (m³/s)	I	m_1	m_2	n	β
365.0	0.08	0.2	5.00	0.04	5.00
M	V_C (m/s)	R_C (m)	h_1 (m)	h_2 (m)	
6.93	7.54	2.64	4.50	0.90	

Notes: Q_C is the debris flow discharge needed to be drained into the main river. I is the hydraulic slope. m_1 is the side slope coefficient and m_2 is the groove transverse slope coefficient. n is the roughness coefficient. β is defined as a size parameter of the drainage channel. M is the cross section configuration parameter of the trapezoidal V-shaped debris flow drainage canal. V_C is the velocity of the debris flow. R_C is the hydraulic radius of the measured cross section. h_1 and h_2 are the characteristic lengths of two overflowing cross-sections.

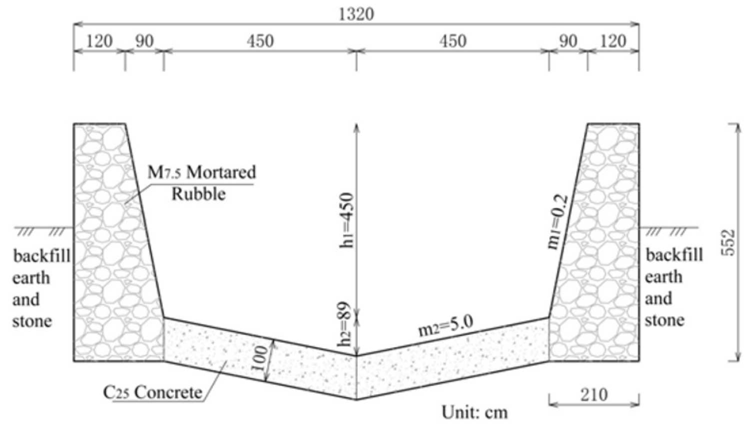

Figure 12 Diagram of the structure of the debris flow drainage channel in the Qipan Gully.

rain gauge sited at the alluvial fan of the Qipan Gully, the antecedent and triggering rainfalls that triggered the debris flows in the tributaries of the Qipan Gully were 47.7 mm and 33.7 mm, respectively. The antecedent and triggering rainfalls for the debris flow that occurred in the main channel of the Qipan Gully were 88.0 mm and 21.6 mm, respectively. When the 11 July event is compared with historical debris flow events, it is clear that debris flows can be triggered with lower intensity rainfall after an earthquake than before.

We identified and measured six blocking dams in the main channel during field investigations to back-calculate the peak discharge during the 11 July debris flow event. The bursting of these cascading blocking dams, from upstream down, amplified the scale of the debris flow and was the key cause of the catastrophic damage in the 11 July event. The debris flow first occurred in the tributaries, and then, the six blocking dams in the main channel burst one-by-one from upstream to downstream. Calculations of the debris flow peak discharge at different cross sections of the main channel show that the peak discharges after the dams burst were 1.17–1.69 times greater than the upstream peak discharge. After the last blocking site (the Laoyingyan blocking dam) in the main channel burst, the peak discharge of the debris flow reached 2552.6 m³/s (Figure 10, B06) which was amplified to 4.76 times compared with the initial peak discharge (Figure 10, C01) in the upstream.

To mitigate similar debris flow disasters in the Qipan Gully in the future, and to protect the buildings that will be reconstructed downstream of the gully, a new drainage channel should be constructed between the Laoyingyan landslide and the Minjiang River. A trapezoidal V-shaped cross section has been chosen to replace the trapezoid shaped cross section of the drainage channel. The characteristic lengths (h_1 and h_2) under optimal hydraulic conditions were calculated as 4.50 m and 0.90 m, respectively, using the design method for the cross section of the debris flow drainage channel.

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