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Case Study of the Characteristics and Dynamic Process of July 10, 2013, Catastrophic Debris Flows in Wenchuan County, China

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ABSTRACT

The Wenchuan earthquake of May 12, 2008, generated a significant amount of loose solid material that can produce devastating debris flows. In the five years since the earthquake, there have been many large-scale individual and group catastrophic debris flows that have caused lots of damage to the resettled population and the reconstruction efforts. The reconstructed towns of Yingxiu, Yinxing and Miansi have suffered debris flows and other secondary disasters in the past five years and are still not out of danger in the future. A debris-flow catastrophic event hit four towns of Wenchuan County along the Duwen Highway, part of China's National Highway 213, at midnight on July 10, 2013, following a local extreme rainfall of 176.2mm 24h-1. The debris flows occurred simultaneously along seven gullies. A total of 15000 people were affected due to the destruction of resettlement areas, factories, power stations, and houses. Because of this devastating event, traffic along the Duwen highway was completely disrupted during the disaster and recovery period. The present study focuses on the Lianshan Bridge debris flow gully; the disaster characteristics and cause of the debris flow were analyzed based on field investigations, remote sensing interpretation, and laboratory experiments. The particular dynamic parameters of the debris flow were calculated and analyzed including density, velocity, discharge, total volume and impact force. Also, the dynamic processes and changes that occurred in the debris flow were examined, and the block and burst characteristics of debris flow were studied based on statistical calculation and analysis dynamic characteristic parameters of debris flow. Finally, a program to prevent further debris flow was proposed according to the on-site investigation and based on the analysis of the features and dynamic processes of the debris flow.

Características y procesos dinámicos de los catastróficos movimientos de detritos en el condado de Wenchuan, China, el 10 de julio de 2013 - Caso de estudio

RESUMEN

El terremoto de Wenchuan, el 12 de mayo de 2008, generó una gran cantidad de material sólido suelto que puede producir flujos de detritos devastadores. En los años posteriores al terremoto han ocurrido deslizamientos a gran escala individuales y simultáneos que han causado daño a los habitantes reubicados y a los esfuerzos de reconstrucción. Las ciudades reconstruidas de Yingxiu, Yinxing y Miansi han sufrido flujos de detritos y otros desastres secundarios desde el terremoto, y no están exentas de eventos futuros. Un evento simultáneo de flujo de detritos afectó a cuatro localidades del condado de Wenchuan, a lo largo de la autopista de Duwen, parte de la carretera nacional 213, en la medianoche del 10 de julio de 2013, después de una lluvia extrema de 176,2 mm 24h-1. Los movimientos de detritos ocurrieron en siete pendientes. Un total de 1500 personas resultaron afectadas debido a la destrucción en áreas de reasentamiento, fábricas, estaciones eléctricas y viviendas. Debido a este devastador hecho, el tráfico de la autopista Duwen estuvo interrumpido durante el período del desastre y mientras se recuperaba la zona. Este estudio se enfoca en el deslizamiento del Puente Lianshan, donde se analizaron las características y las causas del flujo de detritos basados en investigaciones de campo, interpretación de detección remota y experimentos de laboratorio. Se calcularon y analizaron los parámetros dinámicos particulares del flujo de detritos como la densidad, velocidad, descarga, volumen total y fuerza de impacto. También se analizaron los procesos dinámicos y los cambios que ocurrieron en el flujo de detritos, al igual que se estudiaron las características de bloqueo y ruptura del flujo con base en cálculos estadísticos y análisis de los parámetros dinámicos característicos. Finalmente, se propone un programa para prevenir mayores movimientos de detritos de acuerdo con la investigación de campo y basado en los análisis de las características y procesos dinámicos del flujo de material sólido suelto.

1. Introduction

Numerous landslides have been triggered in earthquake-affected areas and the largest ones have been located close to the rupture faults (Chen et al. 2009; Huang et al. 2012). Abundant loose solid erodible material from co-seismic rock falls and landslides are then deposited in gullies, which form the source material for debris flows (Shieh et al. 2009). Numerous debris flows have been triggered during the rainy season in the years following an earthquake (Yu et al. 2014). The frequency and magnitude of debris flows were thus increased significantly after the Wenchuan earthquake of 2008 (Cui et al. 2011; Chen et al. 2013); during the rainy seasons in the past five years, over 800 debris flows have occurred and this has caused great damage to the resettled population and the reconstruction efforts (Zhang et al. 2013). Although mitigation measures were constructed in a few gullies such as the Wenjia and Bayi Gullies, disastrous debris flows still occurred; in some small gullies the mitigation measures installed proved to be inadequate and incomplete (Wang et al. 2012, 2013). For example, a catastrophic debris-flow event hit four towns in Wenchuan County along the Duwen highway,

part of the China National Highway G213, at midnight on July 10, 2013; this event broke out simultaneously in seven debris flow gullies. A total of 15000 people were affected; 18 people were reported dead or missing and there was significant destruction of resettlement areas, factories, power stations and houses (Table 1). These debris-flow gullies located along the Duwen highway have seen reoccurring debris flow disasters in the geological history, and it is likely that some part of these gullies will have another debris flow disaster in the near future. Debris flow activity of these small gullies is still very active and poses a serious threat to the local population, property, traffic safety, and the development of the local social economy. Thus, debris flow mitigation measures should be installed in a timely fashion (Xu et al. 2012). Using the Lianshan Bridge debris flow gully as an example, an analysis was performed on the disaster characteristics, cause of the debris flow, the dynamic processes and the changes in the debris flow through field measurements, remote sensing interpretation, and laboratory experiments. It is essential to provide a comprehensive debris flow control scheme which will lay the foundation for future research on regional debris flows.

Table 1. Summary of destruction caused by a Group of Catastrophic Debris Flows that occurred on July 10, 2013.

No.	Gully name	Site	Disaster losses
1	Xingfu Gully	Gengda town, Wenchuan	Reconstructed Housing and the Giant Panda Research Center were destroyed
2	Qipan Gully	Weizhou town, Wenchuan	15 people were dead or missing, 350 houses were destroyed
3	Yangdian Gully	Miansi town, Wenchuan	part of G213 and 100 houses were destroyed
4	Chutou Gully	Miansi town, Wenchuan	3 people were reported dead, part of G213 were destroyed
5	Taoguan Gully	Yinxing town, Wenchuan	8 factories and 2 power stations were destroyed
6	Wayao Gully	Miansi town, Wenchuan	30 houses and motorway service were destroyed,
7	Lianshan Bridge Gully	Yinxing town, Wenchuan	part of G213 was destroyed, Minjiang River deposition 2-3m

2. Study area

2.1 Location of the study area

The Lianshan Bridge debris flow gully is located in Yinxing Town, Wenchuan County, Sichuan Province of China. It is the first order and left branch of the Minjiang River (Figure 1), with coordinates 103°29′49″E, 31°11′24″N at the gully mouth. The catchment covers an area of 0.7 km^2 and the main channel is 1.34km long with a 48.3% longitudinal slope. The flow direction of the gully is from west to east. The dimensions of the watershed from east to west and south to north approximately 3.0 and 4.0 km, respectively. The gully is accessible to traffic via the Duwen highway that passes through its deposition area.

2.2 Landform conditions

The study area, located on the eastern edge of the Qinghai–Tibetan Plateau, has a complex terrain characterized by considerable elevation differences and steep slopes (Zhang et al. 2006). High mountains, deep-cut rivers, and steep slopes are the main landform characteristics of this area. The elevation difference of the gully is 1159 m from the maximum elevation of 2184m in the west of the catchment to the minimum elevation of 1025 m at the gully mouth.
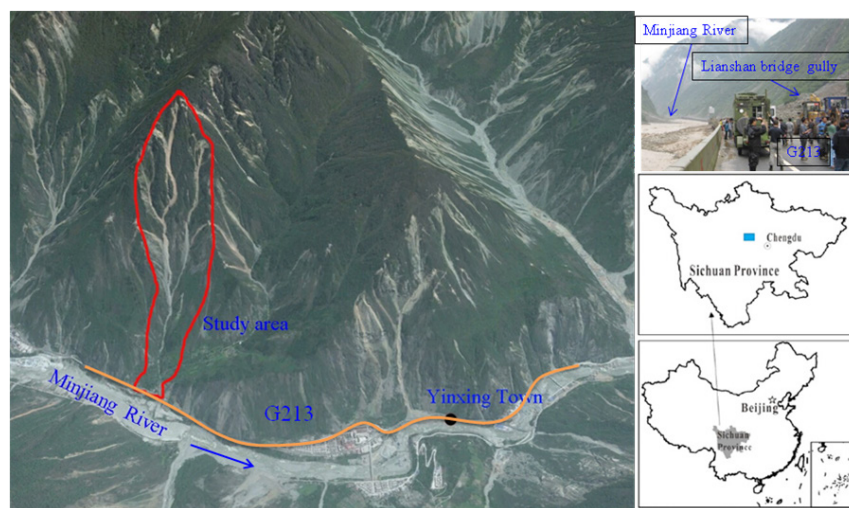

Figure 1. Location of the study area.

2.3 Geological conditions

The geological conditions of the study area are complex; earthquakes occur frequently and cause significant destruction to mountain surface. The "5.12" Wenchuan earthquake that occurred in this area was due to the Longmen Mountain Fault zone. The gully is in the Cathaysian tectonic belt, very close to the deep fracture zone of the Maoxian-Wenchuan reverse fault (Longmen Mountain Fault zone), which lies in the southwest to northeast direction (Zhou et al. 2000). The strata exposed in the gully include diorite ($\delta23$) in the upper reaches, plagioclase granite ($\gamma o24$) in the middle reaches, and granodiorite ($\gamma\delta23$) in the lower reaches. The rock mass of the study area belongs to the magmatic rock formed in the Jinning-Chengjing Period with structural characteristics of high strength, joint fissures, and strongly weathered layers at the surface. Consequently, it is prone to instability, collapse and landslides.

The Lianshan Bridge Gully is located in the area of the active fault. Furthermore, the gully is situated about 5 km from the epicenter of the Wenchuan earthquake. The earthquake caused widespread destruction in the catchment of Lianshan Bridge Gully and formed a large number of landslips and landslides, providing a rich source of loose solid material for the debris flows. Based on "the ground motion parameter zoning map of the Wenchuan earthquake" (GB18306-2001), the study area belongs to the high-intensity seismic region (VIII degrees) with peak ground acceleration of 0.2 g and characteristic period of seismic response spectrum of 0.35 s.

2.4. Rainfall

The study area is in the subtropical humid monsoon climate zone of the Sichuan Basin border and it is situated within the rainstorm center of the west Sichuan region. According to the observation data from the Wenchuan meteorological station, the average annual rainfall is 932.6mm, and the maximum and the minimum annual rainfalls are 1277 and 754 mm, occurring in 1992 and 1998, respectively. The maximum daily rainfall can be up to 166.7mm mm. Precipitation over the year is unevenly distributed, concentrated mainly in the period May to September (Figure 2), which accounts for 79% of the annual rainfall. This period usually has a large number of collapses, landslides, debris flows, and other geological disasters (Liu et al. 2010). In short, the water source condition is favorable to the formation of debris flows in the Lianshan Bridge Gully.
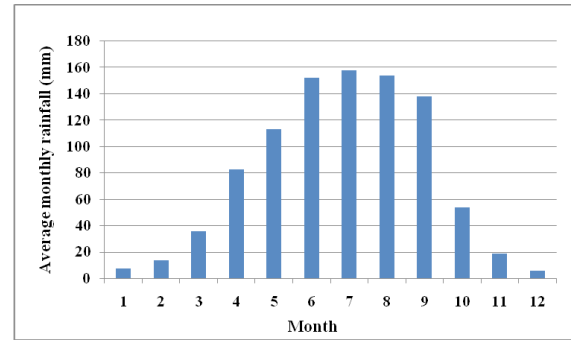

Figure 2. The average monthly rainfall of Yinxing Town, Wenchuan (Data from 1990 to 2010).

3. Methodology

3.1 Field investigations

This research used field investigations, remote sensing interpretation and model calculation to determine the dynamic characteristics of the debris flow. The steps taken to collect and analyze the data are shown in Figure 3. Field work was conducted from July 12 to August 28, 2013, by interviewing local residents to ascertain the debris flow history in Lianshan Bridge gully (We will visit and inquiry many local residents of different ages in near Lianshan Bridge gully. Some older local residents can remember their grandparents, parents who tell them the history of debris flow disasters. We ascertain the frequency of the debris flow disasters based on investigative information) and show that the "7.10" debris flow was the largest debris flow in the past century in this gully. A 1:1000 topography map of the deposition area and a 1:200 cross-section map of the downstream channels are given in Figure 4A and B. As shown in Figure 4, nine test pits in the downstream channel and debris flow samples at six sites (S1–S6) from the downstream channel and debris fan were collected for sieving and particle gradation analysis (Figure 4A and C). Field and laboratory dry sieving tests were conducted following the British Standards (Chen et al. 2012). The seven materials identified (smaller than 2 mm diameter) were tested further using laboratory dry sieving tests. Grain sizes were determined by using field weighing and laboratory particle size analysis techniques, from which the debris flow bulk density was then obtained.
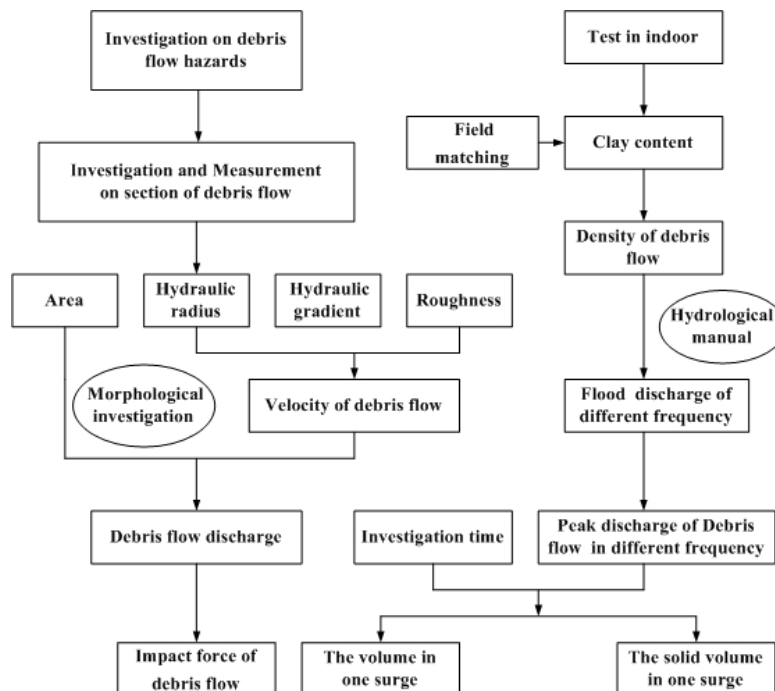

Figure 3. Schematics of investigation methods for debris flow dynamic characteristics
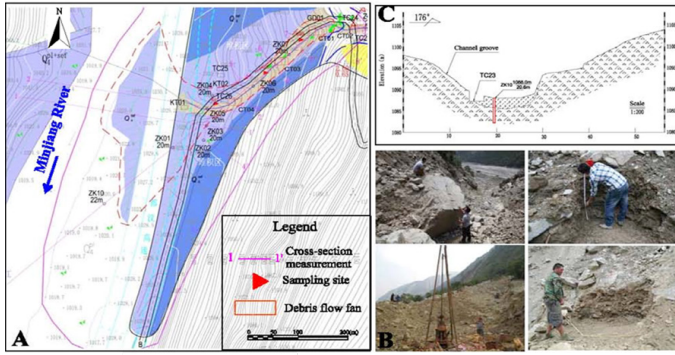
Figure 4. Field investigation methods of debris flow gully.

3.2 Parameter calculating

3.2.1 Density of debris flow

Density of debris flow was calculated using field matching and statistical analysis methods.

a. The field matching method

In the field matching method, first of all, we measured the size of bucket before sampling, and then we can calculate the volume of samples. Secondly, soil samples were uniformly mixed in the field in order to help local residents to compare it with 7.10 debris flow (Figure 5). Finally, we got the weight of the soil samples, and at the same time we can use these data to calculate the mean value of debris flow density. We select five soil samples to calculate debris flow density; the results of debris flow density are shown in table 2.

Figure 5. The field weighing of debris flow density.

Table 2. The calculation results of debris flow density.

No.	Weight（kg）	Volume（10^{-3}m³）	Density（kg/m³）	No.	Weight（kg）	Volume（10^{-3}m³）	Density（kg/m³）
1	10.2	5.2	1962	4	9.4	4.9	1918
2	10.2	5.2	1962	5	9.4	4.9	1918
3	9.8	5.1	1922	Mean value of debris flow density			1936

b. The statistical analysis method.

The density of debris flow was calculated using the Formula 1 (Chen et al. 2003). This formula was obtained from data collected from a large number of debris flow gullies located in the southwest region of China; this reflected the relationship between the percentage of clay particles in the debris flow (< 0.005mm) and the density of the debris flow.

$$\gamma_c = -1.32 \times 10^3 x^7 - 5.13 \times 10^2 x^6 + 8.91 \times 10^2 x^5 - 55x^4 + 34.6x^3 - 67x^2 + 12.5x + 1.55 \quad (1)$$

where γ c is the density of the debris flow (kg/m³), and × is the percentage of clay particles in the debris flow. Formula 1 is mainly suitable for the calculation of the viscous debris flow density that clay content of debris flow is less than 10%.

The percentage of debris flow clay particles was obtained by particle size analysis tests conducted in the laboratory, and the results of debris flow density with clay content are shown in table 3.

The debris flow density of Lianshan Bridge debris flow gully is 1940kg/m³ according to the calculation results of the above two methods.

3.2.2 Velocity of debris flow

The velocity of the viscous debris flow was calculated using the experiential Formula 2 (Chen et al. 2011a), which was obtained from statistical data of a large number of debris flow gullies located in the southwest region of China.

$$V_c = (1/n_c) H_c^{2/3} I_c^{1/2} \quad (2)$$

where V_c is velocity of the viscous debris flow (m/s); n_c is the roughness values of debris flow gully, the nc is empirical coefficient that it was determined by the hydraulic radius of the debris flow; H_c is the hydraulic radius of the debris flow (m); I_c is the longitudinal gradient of debris flow gully bed (‰). The hydraulic radius and longitudinal slope of 10 debris flow sections were measured from the top of gully to the gully mouth (Figure 6). The velocity of 10 debris flow sections were calculated through these acquired parameters, and the results are showed on the Table 4.

Table 3. The results of debris flow density with clay content.

No.	Site	Percentage of clay	Density（kg/m³）
1	N31°11′25″, E103°29′48″	3.89	1940
2	N31°11′44″, E103°30′08″	3.34	1943
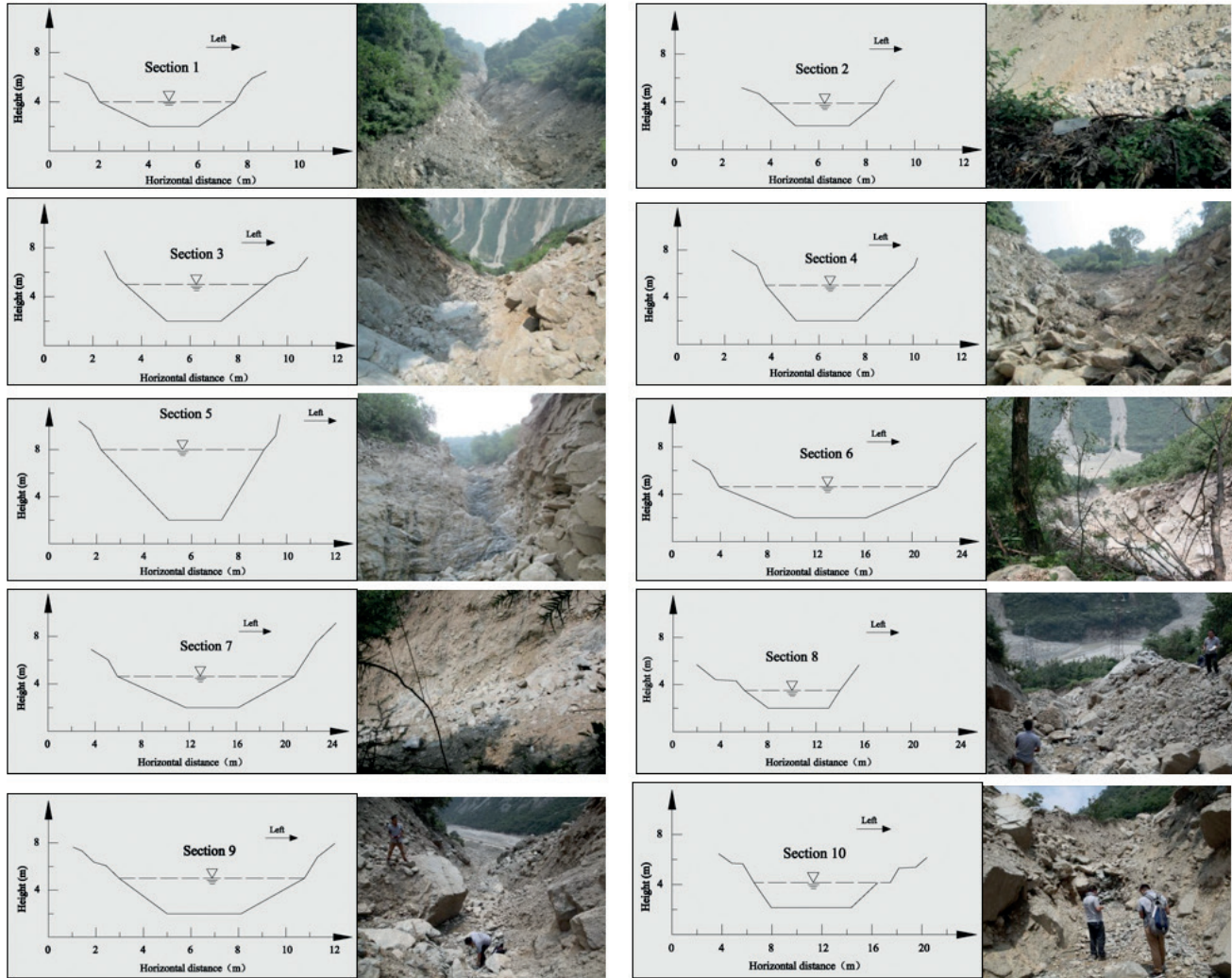
Figure 6. The field investigation of debris flow section.

Table 4. The calculation of debris flow velocity.

No.	Section site	I_C (‰)	H_C (m)	$1/n_c$	V_C (m/s)	No.	Section site	I_C (‰)	H_C (m)	$1/n_c$	V_C (m/s)
1	N31°11′21.57″ E103°30′55.8″ H:1560.4m	560	2.0	4.0	3.0	6	N31°11′20.26″ E103°30′1.96″ H:1218.4m	430	2.0	7.0	7.3
2	N31°11′21.56″ E103°30′54.8″ H:1538m	530	2.0	5.5	4.2	7	N31°11′20.11″ E103°29′59.87″ H:1173.1m	330	2.3	8.0	8.0
3	N31°11′21.43″ E103°30′42.7″ H:1440.3m	510	3.0	3.5	5.2	8	N31°11′21.99″ E103°29′54.22″ H:1102.5m	269	2.9	8.0	8.4
4	N31°11′21.31″ E103°30′32.4″ H:1335.8m	550	3.0	4.0	6.1	9	N31°11′20.94″ E103°29′57.34″ H:1058.7m	300	3.6	7.0	9.0
5	N31°11′21.16″ E103°30′17.6″ H:1248.1m	610	3.5	3.0	7.7	10	N31°11′20.59″ E103°29′50.41″ H:1052.1m	320	2.1	10.0	9.3

3.2.3 The discharge of debris flow

The peak discharge of debris flow Q_c was calculated by both the morphological investigation method and the hydrological manual method.

a. The morphological investigation method

The discharge of debris flow based on the morphological investigation method was calculated using the area of each debris flow section and the corresponding velocity of debris flow. The results are showed in Table 5.

Table 5 The calculation of discharge using the morphological investigation method

Section No.	Area of Section (m²)	V_c (m/s)	Q_c (m³/s)	Section No.	Area of Section (m²)	V_c (m/s)	Q_c (m³/s)
1	7.0	3.0	21.0	6	22.1	7.3	161.3
2	8.0	4.2	33.6	7	21.3	8.0	170.4
3	12.0	5.2	62.4	8	21.0	8.4	176.4
4	12.0	6.1	73.2	9	20.9	9.0	188.1
5	20.5	7.7	157.8	10	21.3	9.3	198.1

b. The hydrological manual method.

Firstly, the flood peak discharge (Q_P) of Lianshan Bridge gully was determined in order to calculate the debris flow peak discharge (Q_c). The flood peak discharge (Q_P) can be calculated by Formula 3 that the flood peak discharge calculated from this formula is more suitable for the southwest region of China (Ni et al. 2012), and the results are given in Table 6.

$$Q_P = 0.278 \psi \frac{S}{\tau^n} A \qquad (3)$$

where A is the watershed area of debris flow gully; ψ is the runoff coefficient of the flood peak; S is the rainfall intensity; τ is the runoff confluence time of the rainstorm, and n is the attenuation index of the rainstorm; L is the length of debris flow gully; J is the mean gradient of debris flow gully bed; P is the rainstorm frequency, for example, P=1% means that the rainstorm was a once-in-a-century.

Table 6. The calculation of the flood peak discharge.

Section No.	A (km²)	L (km)	J (‰)	D_U	Flood peak discharge Q_P (m³/s)				Debris flow peak discharge Q_c (m³/s)			
					P=1%	P=2%	P=5%	P=10%	P=1%	P=2%	P=5%	P=10%
10	0.7	1.34	483	3	5.49	4.65	3.52	2.66	41.80	31.54	20.51	14.16
8	0.65	1.16	625	3	5.08	4.12	3.08	2.13	38.57	28.13	18.09	10.79
2	0.44	0.4	849	2	3.61	2.93	2.25	1.69	25.48	17.87	11.12	6.99
1	0.1	0.35	601	2	0.91	0.72	0.57	0.44	6.57	4.56	2.98	1.84

The debris flow peak discharge (Q_c) can be calculated using the Formula 4.

$$Q_C = (1+\varphi) Q_P \cdot D_U \qquad (4)$$

where D_U is the blockage coefficient in the debris flow gully. Usually, the degree of blockage is classified as very serious blockage (D_U=3.0–2.5), serious blockage (D_U=2.5–2.0), normal blockage (D_U=2.0–1.5) and minor blockage (D_U=1.5–1.0). For the situation in the Wenchuan earthquake area, the values were calculated to be 5.5–4.5, 4.5–3.5, 3.5–2.5 and 2.5–1 (You et al. 2012). Based on the field investigation and the channel blockage as identified from aerial photography, the blockage coefficient for the Lianshan Bridge gully is considered to be 2 and 3. is the increase coefficient of debris flow peak discharge, which can be calculated (Formula 5) as follows.

$$\varphi = (\gamma_c - \gamma_w)/(\gamma_s - \gamma_c) \qquad (5)$$

where γw is the density of water (kg/m3), usually determined as 1000 kg/m3; γs is the density of the solid material (kg/m3), usually determined as 2650kg/m3, and γc is the density of debris flow (kg/m3).

3.2.4 The total and solid volume of debris flow

The total and solid volumes of debris flow were calculated using the experiential Formulae 6 and 7(Chen et al. 2011b). The results are given in Table 7.

$$W_C = \frac{19 T_c Q_c}{72} = 0.264 T_c Q_c \qquad (6)$$

$$W_S = (\gamma_C - \gamma_w) W_C /(\gamma_s - \gamma_w) \qquad (7)$$

where W_c is the total volume of debris flow (m³); T_c is duration of the debris flow (s); Q_c is the debris flow peak discharge (m³/s); γw is the density of water (kg/m³); γc is the density of the debris flow (kg/m³); γs is the density of the solid material (kg/m³); is the solid volume of the debris flow.

Table 7. The total volume of debris flow in different frequency.m

P (%)	Density	T(s)	Q_C (m³/s)	W_C (10⁴m³)	W_S (10⁴m³)
1	1.9	600	41.8	0.662	0.361
2	1.82	600	31.54	0.500	0.248
5	1.7	600	20.51	0.325	0.138
10	1.62	600	14.16	0.225	0.085

3.2.5 The impact force of the debris flow

The impact force of debris flow is an important parameter in debris flow control engineering design that includes the impact force of the debris flow due to the dynamic pressure and the maximum stone size.

a. The impact force of debris flow dynamic pressure

The impact force of the debris flow due to the dynamic pressure was calculated using the Formula 8 (He and Wu 2009). The results are shown in Table 8.

$$\sigma = \lambda \frac{\gamma_c}{g} V_c^2 \sin\alpha \qquad (8)$$

where σ is the impact force of the debris flow due to the dynamic pressure (kg/m²); γ_c is the density of the debris flow (kg/m³); λ is the building shape coefficient, usually determined as 1.33 when the building is rectangular; V_c is velocity of debris flow (m/s); σ is the angle between the buildings and the stress surface pressure direction, which is usually determined as 90°.

Table 8. The results of the impact of the debris flow.

No.	γ_c (kg/m³)	V_c (m/s)	σ (kg/m²)	No.	γ_c (kg/m³)	V_c (m/s)	σ (kg/m²)
1	1600	3.0	1954	6	1940	7.3	14030
2	1700	4.2	4070	7	1940	8.0	16850
3	1940	5.2	7119	8	1940	8.4	18577
4	1940	6.1	9797	9	1940	9.0	21326
5	1940	7.7	15610	10	1940	9.3	22772

b. The impact force of the maximum stone size

The impact force of debris flow dynamic pressure resulting from the maximum size of individual stones was calculated by the Formula 9 (He and Wu, 2009). The results are shown in the Table 9.

$$F = K_c n a^{2/3} \tag{9}$$

$$n = [\frac{16 R_{s2}}{9\pi^2 (k_1 + k_2)^2}]^{1/2} ; \quad a = (\frac{5V^2}{4 n n_1})^{2/5} \quad k_1 = (1 - v_1^2)/(\pi E_1) ; k_2 = (1 - v_2^2)/(\pi E_2); \quad n_1 = 1/m_2$$

where F is the impact force of the maximum article size in the debris flow (kN); K_c is the correction coefficient and usually determined as 0.1; R_{s2} is the radius of the maximum stone size and determined as 2.9m; V_1 is the Poisson's ratio of material and V_2 is Poisson's ratio for the maximum stone size; m_2 is quality of the maximum stone (kg) in the gully; V is relative velocity of the stones (m/s) and determined as the 70% of V_c ; is the modulus of elasticity of binding material and is modulus of elasticity of the maximum stones (kg/m²).

Table 9. The impact of debris flow calculated using the elastic impact method.

Material	Poisson ratio	E (kg/m²)	F (kN)
Concrete	0.167	2000000000	4955
Wood	0.1	80000000	823
Mortar	0.2	180000000	1458
Rubber	0.47	6820000	167

4. Disaster characteristics

4.1 Triggering rainfall

4.1.1 The previous rainfall amount

The previous rainfall amount is a very important factor in calculating potential debris flow. The daily precipitation from July 5 to July 10, 2013 at the Lianshan Bridge debris flow gully was collected through the Taoguan Village meteorological station (E103°29′13″, N31°15′05″, H: 1113m) located 100m upstream of the gully and the Dongjielaonao Village

meteorological station (E103°29′13″, N31°15′05″, H: 955m) located 50m downstream of the gully. The previous rainfall amounts are given in Table 10. There has been rainfall within 3 days before debris flow triggered. Taoguan Village meteorological station showed that maximum daily rainfall is up to 57.5 mm and the cumulative rainfall is 102.5mm within 3 days before debris flow triggered, the Dongjielaonao Village meteorological station showed that maximum daily rainfall is up to 185.5mm and the cumulative rainfall is 240.9 mm within 3 days before debris flow occurred.

Table 10. Daily rainfall occurring before July 10, 2013 (mm).

Stations \ Date	July 5	July 6	July 7	July 8	July 9	Cumulative rainfall
Taoguan	0	0	0.2	44.8	57.5	102.5
Dongjielaonao	0	0	0	55.4	185.5	240.9

4.1.2 Characteristics of 24 hour rainfall

24 hour rainfall data from July 5th to July 10th were collected from Taoguan and Dongjialaonao Village meteorological stations. (Table 11 and Figure 7). Table 11 indicates that from 1hr to 5hr, rainfall has a maximum intensity which reaches up to 88.1mm. The maximum 1 hour rainfall is 21mm on July 10th and Lianshan Bridge debris flow triggered at the same time around 3 am.
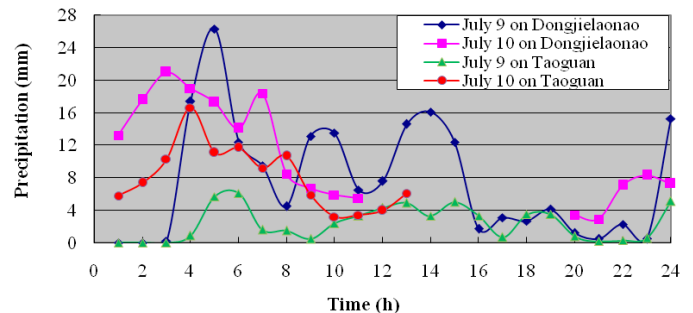

Figure 7. 24 hour rainfall curve.

Table 11. 24 hour rainfall data from July 5 to 10.

Date \ Time (hr)	5	6	7	8	9	10	5	6	7	8	9	10
	Taoguan station (mm)						Dongjielaonao station (mm)					
1	0	0	0	0	0	5.8	0	0	0	0	0	13.2
2	0	0	0	0.3	0	7.4	0	0	0	1	0	17.6
3	0	0	0	0.8	0	10.3	0	0	0	0.3	0.2	21
4	0	0	0	1.2	0.9	16.6	0	0	0	3.8	17.4	19
5	0	0	0	4	5.7	11.1	0	0	0	13.1	26.3	17.3
6	0	0	0	13.1	6.1	11.7	0	0	0	17	12.4	14.1
7	0	0	0	17	1.6	9.2	0	0	0	9.6	9.5	18.4
8	0	0	0	1.7	1.5	10.7	0	0	0	1.1	4.5	8.5
9	0	0	0	0.1	0.5	5.9	0	0	0	0.3	13.1	6.7
10	0	0	0	0	2.4	3.2	0	0	0	0	13.5	5.9
11	0	0	0	0	3.3	3.4	0	0	0	0	6.5	5.5
12	0	0	0	1.1	4.3	4	0	0	0	0.3	7.6	0
13	0	0	0.2	0.2	4.9	6.1	0	0	0	1.9	14.6	0
14	0	0	0	2.6	3.3	0	0	0	0	5.4	16.1	0
15	0	0	0	2.7	5	0	0	0	0	0.4	12.4	0
16	0	0	0	0	3.3	0	0	0	0	0	1.7	0
17	0	0	0	0	0.7	0	0	0	0	0	3.1	0
18	0	0	0	0	3.5	0	0	0	0	0	2.7	0
19	0	0	0	0	3.5	0	0	0	0	0	4.1	0
20	0	0	0	0	0.8	0	0	0	0	0	1.2	3.4
21	0	0	0	0	0.2	0	0	0	0	0	0.5	2.9
22	0	0	0	0	0.3	0	0	0	0	1.2	2.3	7.1
23	0	0	0	0	0.6	0	0	0	0	0	0.5	8.3
24	0	0	0	0	5.1	0	0	0	0	0	15.3	7.3

4.2 The loose solid material

The Wenchuan earthquake of May 12, 2008 produced a great deal of loose solid material that can lead to the development of devastating debris flows (Tang et al. 2009, 2011). Shieh et al (2009) pointed out that the loose sediments, deposited by the co-seismic landslides, were the main reason for a lowering of the meteorological thresholds for debris flows. The debris flow activity in these earthquake-affected areas is very high in the first 5–10 years after an earthquake, while the total period with an increased potential for debris flow activity can last 20 to 40 years (Tang et al. 2012). The distribution of loose solid materials in Lianshan Bridge debris flow gully was mapped through post-disaster field investigations and remote sensing interpretation (Figure 8). Pit tests were used to determine the thickness of solid materials, and the total volume of loose solid materials was calculated through field measurements. Radar mapping was used to determine the thickness of the solid materials in some areas of the gully bed where pit tests were difficult to undertake, and the volume of solid materials calculated (Figure 9). The area and thickness of old debris flow deposits and landslide deposits were obtained by remote sensing, which measured the area of colluvial deposits; the function (Guzzetti et al. 2008) was used to calculate the volume of the colluvial deposits. The loose solid material in the Lianshan Bridge debris flow gully was 140.5×10^4 m3 based on the field investigation and remote sensing interpretation, including collapse sediments 197,000 m3, landslide 721,000 m3, bed sediments 57,000m3, slope erosion loose solid materials 325,000 m3, old debris flow sediments 105,000m3. Such abundant loose solid material provided source conditions for the large-scale debris flow outbreak.
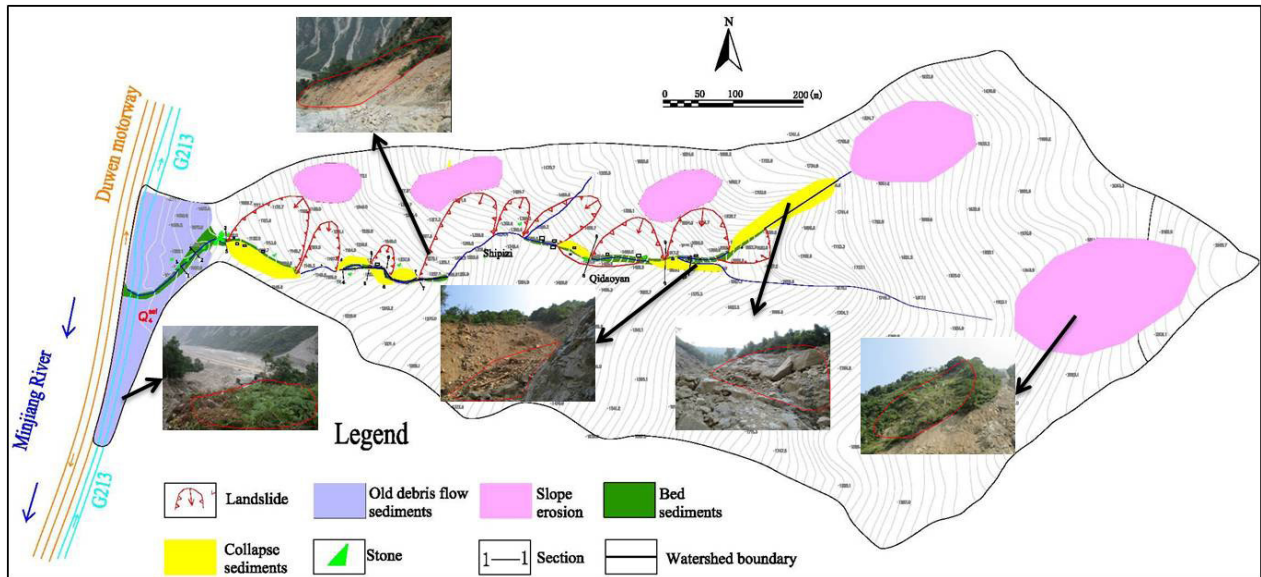

Figure 8. Field measurement and radar test.

Figure 9. The distribution map of loose solid materials.

4.3 Deposition characteristics

4.3.1 The characteristics of particle size along the gully

The gully is divided into 6 parts based on the changes in the particle size characteristics (Figure 10). These are: (a) From the top of gully to Qidaoyan, the particle size is mostly gravel-cobble, containing angular diorite and granite, without sorting. The gravel size is generally in the 3-10cm range, and the gravel content is 40-50%. The stone size is generally 20-40cm, and the content is about 30%. The largest stone size is up to 3m. (b) From the right branch ditch to the entrance of the main gully, the particle distribution is mostly stone, containing angular diorite and granite, without sorting. The gravel size is generally in the 5-15cm range, and the gravel content is 30-40%. The sizes of the stones are generally in the 30-60cm range, and the stone content is approximately 40%, with the largest stone size up to 2.5m. (c) From Qidaoyan to Shipizi, the particles are mostly stone and soil; the stone is angular diorite and granite, without sorting. The gravel size is 6-16cm, and the gravel content is 20-30%. The stone size is generally in the 20-60cm range, and the stone content is about 50%. The largest stones are up to 2m. (d) In the Shipizi gully, the characteristic particle size shows mostly gravel and soil, containing angular diorite and granite, without sorting. The gravel size is generally 5-15cm, and the gravel content is 40-50%. The stone size is mostly in the 20-40cm range, and the content of stone is about 25%; the stone size can be up to 4m. (e) From Shipizi to an altitude of 1100m, the particles are mostly gravel and soil; the gravel is angular diorite and granite, without sorting. The gravel size is 5-20cm, and the content is 30-40%. The stone size is in the 20-60cm range, and the stone content makes up about 20%, with the largest stones up to 2m. (f) From an altitude 1100m to the mouth of gully, the particles are mostly gravel and soil; the gravel is angular diorite and granite, without sorting. The gravel size is generally in the 5-15cm range making up 10-15% of the whole. The stone size is mostly 20-60cm, and the stone content is about 5%; the largest stones can be up to 1.5m.
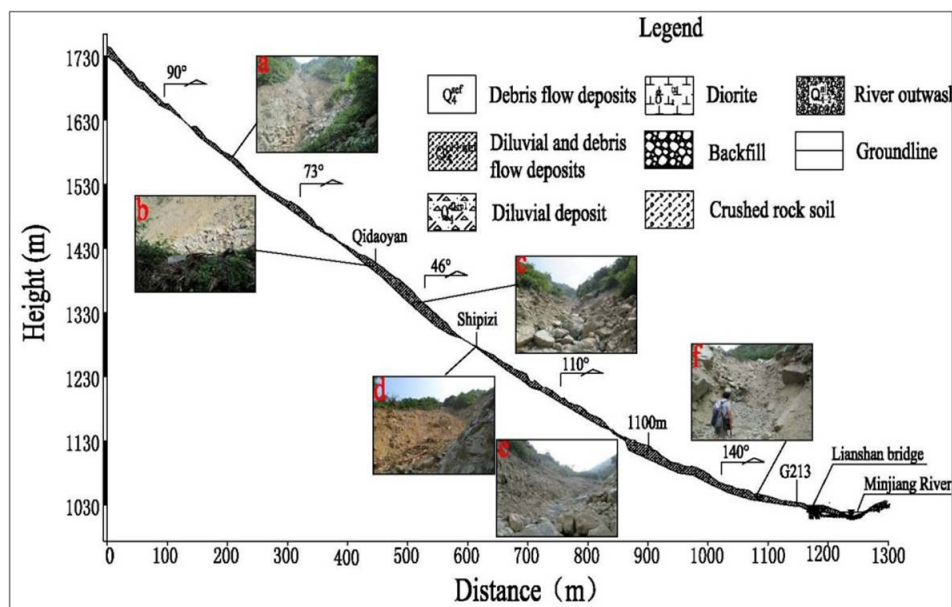

Figure 10. The changed characteristics of particle size along the gully.

4.3.2 The particle characteristics on debris flow deposition

The debris flow partition accumulation characteristic of the gully is significant because of the gradient of the gully. The debris flow deposition is mainly distributed on the lower slopes and wider regions of gully downstream. From the field investigation, it was found that the composition of the material has a wide grading of soil, and the clay fraction is less. The majority of the stone is angular, and the stone content is about 50-60%. Lithology varies between mostly anorthosite and granodiorite (Table 12).

Table 12. Statistics of particle survey on the gully mouth（site: N31°11′26.2″E103°29′57.5″ H:1068m）.

No.	Particle size （cm）	Lithology	Psephicity	No.	Particle size （cm）	Lithology	Psephicity
1	55×50×23	plagioclasite	subangular	31	36×20×10	plagioclasite	subangular
2	60×30×24	plagioclasite	angular	32	<2	\	\
3	45×33×26	diorite	subangular	33	<2	\	\
4	<2	\	\	34	60×30×27	plagioclasite	subangular
5	20×5×3	plagioclasite	subangular	35	40×40×30	diorite	subangular
6	26×22×9	plagioclasite	subangular	36	120×70×50	plagioclasite	subangular
7	18×14×12	diorite	subangular	37	<2	\	\
8	16×9×5	plagioclasite	subangular	38	<2	\	\
9	<2	\	\	39	10×10×8	plagioclasite	subangular
10	<2	\	\	40	120×90×40	diorite	subangular
11	35×15×9	plagioclasite	subangular	41	<2	\	\
12	25×20×7	plagioclasite	subangular	42	<2	\	\
13	22×13×7	plagioclasite	subangular	43	16×10×8	plagioclasite	subangular
14	9×6×3	plagioclasite	subangular	44	45×40×20	plagioclasite	subangular
15	50×34×15	plagioclasite	subangular	45	47×35×20	plagioclasite	subangular
16	12×9×7	plagioclasite	subangular	46	<2	\	\
17	12×5×3	granite	subangular	47	17×15×9	plagioclasite	subangular
18	18×16×5	plagioclasite	subangular	48	<2	\	\
19	<2	\	\	49	<2	\	\
20	76×50×14	plagioclasite	subangular	50	13×10×7	granite	subangular
21	<2	\	\	51	<2	\	\
22	<2	\	\	52	<2	\	\
23	26×10×7	diorite	subangular	53	30×10×7	plagioclasite	subangular
24	<2	\	\	54	<2	\	\
25	<2	\	\	55	<2	\	\
26	13×9×4	diorite	subangular	56	30×19×7	plagioclasite	subangular
27	34×15×13	plagioclasite	subangular	57	<2	\	\
28	<2	\	\	58	16×9×5	granite	subangular
29	30×13×9	diorite	subangular	59	25×20×8	plagioclasite	subangular
30	14×12×10	plagioclasite	subangular	60	<2	\	\

5. The block and burst characteristics of a debris flow gully

It is unusual that such a large-scale debris flow outbreak should occur in such a small debris flow gully. Blockage of debris flow gully is the main reason for large-scale debris flow outbreaks in small debris flow gullies in earthquake-affected areas. In Lianshan Bridge debris flow discharge case, it was found that there were two discharge alteration points, in section No. 2 to No. 3 (the discharge increased from 33.6m^3/s to 62.4m^3/s, an increase of nearly 100%) and in section No. 4 to No. 5, where the discharge increased from 73.2m^3/s to 157.8m^3/s, a discharge increase of over 100% (Figure 11).
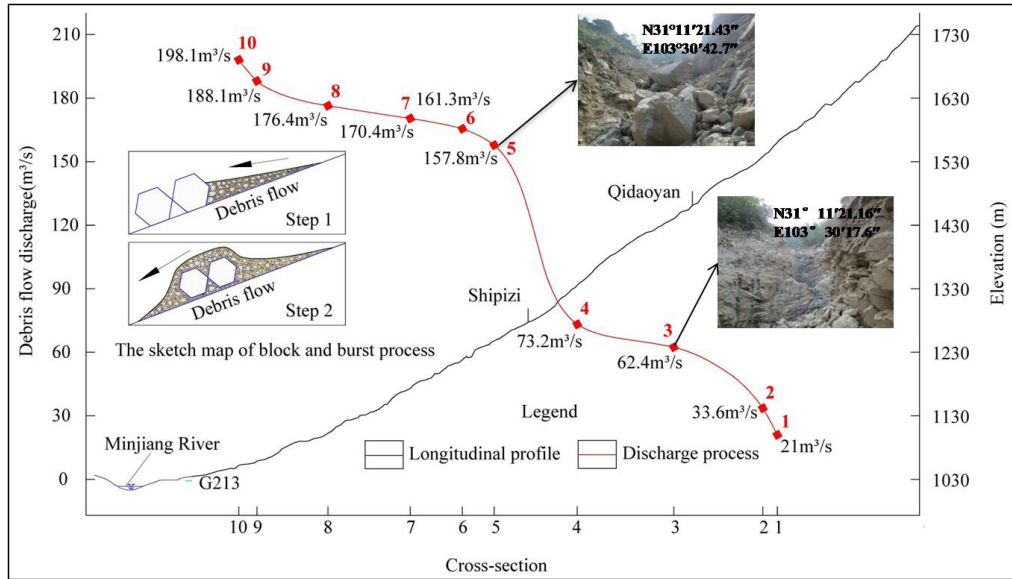
Figure 11. The block and burst characteristics of debris flow gully.

Site investigations make it apparent that large stones (greater than 1.5m in length) in the Lianshan Bridge channel were considered to have a statistical effect on the debris flow discharge (Table 13). Because the shape of large stone is irregular, the volume of stone is calculated based on the cuboids, and multiplied by the experiential coefficient 0.7 for China's western mountains (Hu et al.2011; Chen et al. 2005).

The channel distribution of these large stones is shown in Figure 9 and 11. The main reason for the change in debris flow discharge is these large landslides and massive stones. Two sections 3 and 5 block the movement of debris flow. Because of higher hydraulic gradient and strong impact of landslide around this section, it offers more resistance as compared to section 3 (Figure 11 and 12).

Table 13. Statistics of the large stones size on the channel   (Units: m and m³).

Stone No.	Length	Width	Height	Volume	Stone No.	Length	Width	Height	Volume
1	2.3	1.7	1.5	4.1	16	2.3	1.6	1.3	3.4
2	1.8	1.5	1.3	2.5	17	1.7	1.4	0.8	1.3
3	2	1.6	1.4	3.2	18	2.2	1.8	1	2.8
4	4.5	3.8	3.1	37.1	19	2.8	2.2	2	8.6
5	3	2.4	2	10.1	20	2.2	1.8	1.2	3.4
6	2.4	2	1.5	5.0	21	1.8	1.3	1.2	2.0
7	4	2	1.8	10.1	22	2	1.7	1.4	3.4
8	3.8	3.2	2.6	22.1	23	1.7	1.5	1.3	2.3
9	4.2	2.3	2	13.5	24	2.1	1.9	1.2	3.4
10	4.3	3.7	3	33.4	25	3	2	1.3	5.5
11	2.5	2	1.7	6.0	26	2.4	1.8	1.5	4.6
12	2.8	2.4	2	9.4	27	2.3	2.1	1.7	5.7
13	2.8	2.4	2	9.4	28	1.9	1.6	1.4	3.0
14	4.6	4	2.8	36.1	29	1.8	1.6	1.3	2.6
15	1.7	1.5	1.2	2.2	30	2.2	1.7	1.4	3.6

6. Prevention and control measures

Strong earthquakes often induce a large number of collapses, landslides and unstable slopes and also generate abundant unconsolidated material that contributes to debris flow. Debris flows will be a major hazard in the Wenchuan earthquake area for many years (Cui et al. 2014). Characteristics of debris flow in the Wenchuan earthquake area compel us to take engineering measures before the active period of debris flows. New engineering structures are proposed in this paper to mitigate debris flow

hazards along some small gullies and slopes. The appropriate engineering measures include the buildup of one or more block dams, to stop the huge stones, and a fence wall to resist the loose solid materials to reach on the outside of gully. A block dam engineering measure has already been applied in the circulation area of debris flow which makes the steady flow of the loose solid materials. One horizontal grilled dam was built in the accumulation area to intercept large stones. The debris flow will then be channeled into a drainage groove, and finally drained into the Minjiang River (Figure 12).

Figure 12. Aerial photograph of the Lianshan Bridge gully (A: shoot on August, 2013; B: November, 2014).

7. Summary

After the Wenchuan earthquake, debris flows from Yinxing to Miansi Town in Wenchuan County along the G213 road occurred often, resulting in frequent interruption of traffic on both the G213 road and Duwen highway. Using field investigations, remote sensing interpretation, laboratory experiments, model calculation and interviewing local residents, it was concluded that the factors influencing the debris flow were the formation processes and dynamic characteristics of "7.10" Lianshan Bridge debris flow. The following conclusions were drawn from the available information. (a) In areas with long term seismic activity, intense rainfall can easily induce debris flow. (b) Bank collapse and large rocks also contributed to an increase in debris flow scale and discharge, and eventually led to the "7.10" large scale debris flow in the Lianshan Bridge gully watershed. (c) Currently, there is still considerable loose solid material available for debris flow formation in these gullies. Landslide deposition, channel deposition, and soil erosion sediment are three kinds of sediment that supply material for debris flow formation. The total volume of loose solid material is 140.5×10^4 m³. Such large amounts of solid loose sediment could generate debris flows easily given adequate rainfall. (d) Reliable prevention and control measures should be put forward with the purpose of reducing debris flow disasters in these debris flow gullies (e) Monitoring and early warning systems should be set up and government should strengthen propaganda on disaster prevention and mitigation to improve residents' consciousness of debris flow disasters, which could effectively reduce the human and infrastructure losses caused by debris flow hazards.

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