DOI: 10.4408/IJEGE.2011-03.B-084

DEBRIS FLOWS IN MOZI GULLY, CHINA FOLLOWING THE 2008 WENCHUAN EARTHQUAKE

Pengcheng SU(*,**,***), Fangqian WEI(**,***), Zunlan CHENG(**,***) & Jingjing LIU(*,**,***)

(*) Key Laboratory of Mountain Hazards and Surface Process, Chinese Academy of Sciences, Chengdu, 610041
(**) Institute of Mountain Hazards and Environment, Chinese Academy of Sciences & Ministry of Water Conservancy, Chengdu, 610041
(***) Graduate School of Chinese Academy of Science, Beijing, 100039, China

ABSTRACT

Numerous landslide that provided abundant material for the mobilization of debris flows were triggered in the Mozi gully on the right bank of Mingjiang River in response to the M8.0 Wenchuan earthquake of May 12, 2008. Following the earthquake, debris flows occurred during July through September of 2008 and again in September of 2009. Five of these events blocked the Mingjiang River. This paper estimates the volume of landslide material contributed to the valley by comparing remote sensing images before and after the quake, and analyzes the resultant landslide dams to estimate the volume of material necessary to block the channel. Return periods of debris flows with varying peak discharges are estimated based on empirical formulas and field surveys of the valley.

Key words: *Mozi gully, Wenchuan earthquake, debris flow, landslide, landslide dam*

INTRODUCTION

The M8.0 Wenchuan earthquake of 2008 triggered a number of landslides and avalanches which provided abundant material for debris-flow mobilization. With the change in the availability of solid material, the critical rainfall necessary for triggering debris flows was lower than before earthquake, the frequency and intensity of potential debris-flow activity increased and the debris-flow potential moved into a new active period (Cui *et alii*, 2008; Tang *et alii*, 2008). In the past two rainy seasons, debris flows have been produced from the area impacted by the Wenchuan earthquake (Xie *et alii*, 2009; Tang *et alii*, 2009). Mozi gulley, located in Yinxing, Wenchuan County, Sichuan Province (Fig. 1), was seriously affected by the Wenchuan earthquake, and debris flows have been active in this gully since the earthquake. During July through September, of 2008 and in September of 2009, five debris flows blocked the Mingjiang River, resulting in flood inundation of a village on the left bank. To analyze

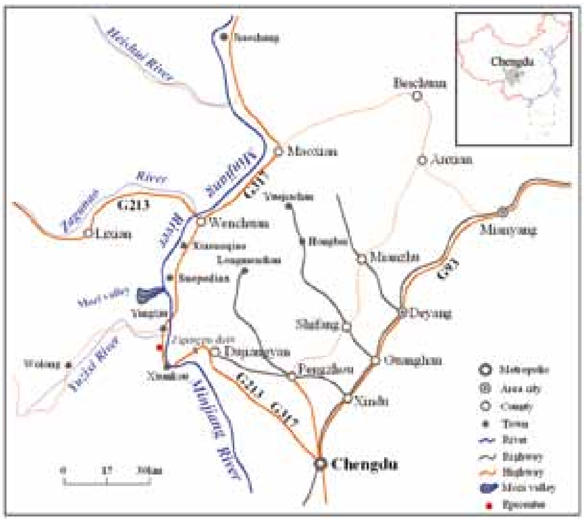

Fig. 1 - Location map of Mozi valley and environs

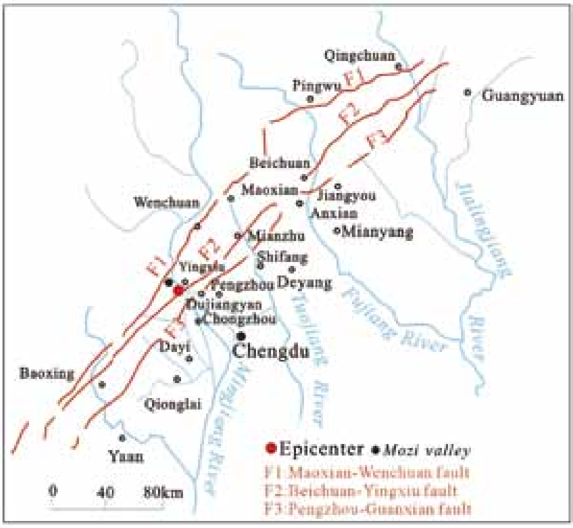

Fig. 2 - Regional geological map around Mozi valley

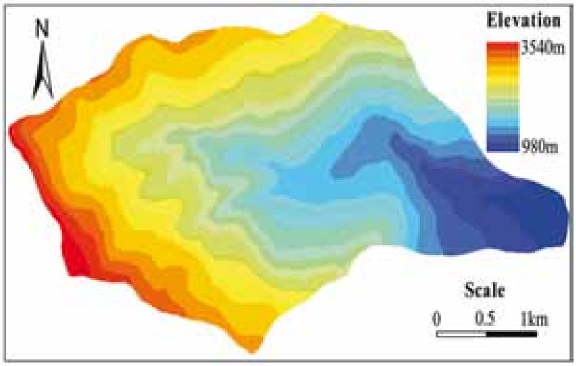

Fig. 3 - Elevation map of Mozi gully

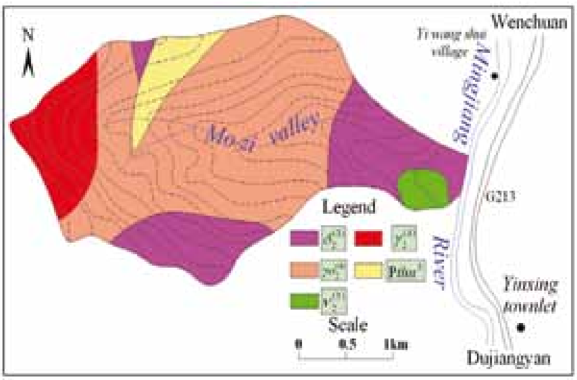

Fig. 4 - Geologic map of Mozi gully(*)
(*)The Second regional geological surveying team, Guanxian geological map (1:200000) of regional geological surveying report, China, 1975)

the causes and characteristics of this post -earthquake debris-flow activity in Mozi gully, field investigations and interpretation of remote sensing and aerial imagery collected over different time periods were used to estimate the volume of material contributed to Mozi gully by earthquake shaking. Combined with information on the regional geological structure, topographic and geomorphologic setting, and rainfall conditions, this paper provides a preliminary analysis of the tendency for debris flows to be generated from the Mozi gully in the future.

STUDY AREA

The Mozi Valley is a tributary of Minjiang River, located in the Yiwanshui village, 45km from Wenchuan (Fig. 1). Geologically, the valley lies just 12km northwest of Wenchuan earthquake epicentre, and is bounded by the Beichuan-Yingxiu fault on the southeast and the Maoxian-Wenchuan fault on the northwest (Fig. 2). According to the Chinese Earthquake Administration (CEA) the valley is located in the area of intensity X and has been completely devastated. The Mozi valley drainage basin is 7.30 km^2 in area, with a 5.20 km long stream (Fig. 3). Basin relief if 2569 m, ranging from 3556 m at the top, to 987 m at the basin outlet. The gradient of the mainstream channel is 49.3 percent.

Outcrops in the valley are mainly Proterozoic intrusive rocks, dominated by medium grained granite ($\gamma o_2^{(4)}$) that has strong resistance to weathering. The lower part of the valley is dominated by a Tertiary quartz diorite ($\delta_2^{(3)}$) and a Tertiary gabbro ($v_2^{(3)}$) outcrops locally south of the main stem channel (Fig. 4). The middle and upper portions of the valley are dominated by a Quaternary plagioclase granite ($\gamma o_2^{(4)}$) with some medium-grained biotite granite outcropping in the upper reaches. A few outcrops of a Tertiary quartz diorite overlain by quartz schist and limestone (*Pthn*^{3}) are observed in the left tributary to the main tem. Quaternary sediment and gravels are mapped at the junction of the Mozi gully and the Mingjiang River.

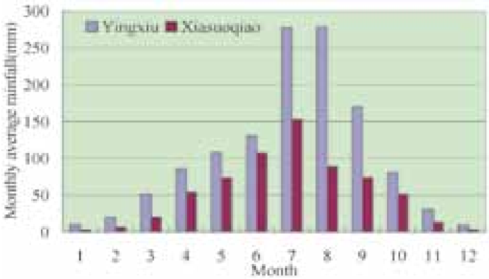

Fig. 5 - Distribution of monthly average rainfall in measured in Yinxiu town and Xissuoqiao village near Mozi gully

Fig. 6 - Remote image of Mozi gully from June 26, 2005 (Before the Wenchuan earthquake)

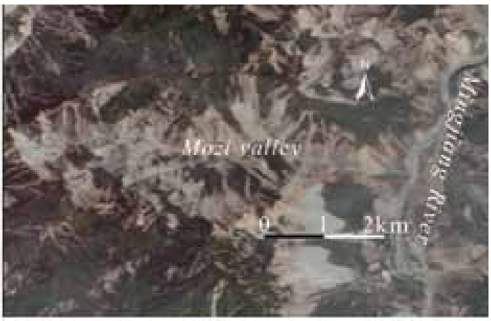

Fig. 7 - Remote image of Mozi gully from June 3, 2008 (after the Wenchuan earthquake)

The climate of Wenchuan County is divided into southern and northern climate zones with boundary of Suopodian town. The northern zone is semi-arid climate of south temperate zone, and the southern zone, which Mozi valley located in, is a humid climate of north subtropical zone (CCWC, 1992). The valley also receives the highest precipitation in west Sichuan Province. The average annual rainfall measured at Xiasuoqiao village and Yingxiu town between 645.2mm and 1253mm, with 49 (315 mm) to 52.9 (726 mm) percent of the rainfall occurring in July and September (Fig. 5).

INFLUENCE OF THE EARTHQUAKE

A comparison of satellite remote imagery taken before and after the Wenchuan earthquake, indicates that the landscape of the Mozi valley has been significantly altered by the earthquake (Figg. 6 and 7), The scars left by landslides, avalanches, and rockfalls triggered by the earthquake occupy approximately 73.2 percent of the valley area. Almost all of the channels are filled with sediment, and some are blocked by the deposits of particularly large failures (Fig. 7). Field surveys in December 2008 and May and July 2009 and aerial photo interpretation identified up to eight large landslide dams in the valley, the largest of which is estimated to contain $7.8x10^5$ m^3 of material (Tab. 1, Figg.8 and 9).

DEBRIS FLOWS FOLLOWING THE EARTHQUAKE

CAUSES AND PROCESSES

Up to 80 surges of debris flow were documented in Mozi gully between July and September of, 2008 and in September, of 2009, five of them blocked the mainstem Mingjiang River. The largest debris flow occurred

Landslide	Landslide source dimensions (length, width, height(m)) and volume (m^3)	Landslide dam dimensions(length, width, height(m)) and volume (m^3)	Position of dam		Stream blockage
1	120*200*8 (1.92×10^5)	80*25*20 (4.00×10^4)	31° 9'27"	103°26'36"	full
2	140*280*10 (3.92×10^5)	60*30*20 (3.60×10^4)	31° 9'28"	103°26'55"	full
3	60*180*12 (1.30×10^5)	90*30*6 (1.62×10^4)	31° 9'23"	103°27'6"	partial
4	280*90*15 (3.78×10^5)	90*35*25 (7.87×10^4)	31° 9'16"	103°27'29"	full
5	200*300*15 (9.00×10^5)	130*30*20 (7.80×10^4)	31° 9'26"	103°28'0.0"	full
6	240*80*15 (2.88×10^5)	60*30*25 (4.50×10^4)	31° 9'22"	103°28'11"	full
7	200*160*12 (3.84×10^5)	100*30*20 (6.00×10^4)	31° 9'12"	103°28'26"	full
8	60*90*5 (2.70×10^4)	50*15*10 ($7.5.\times10^3$)	31° 9'10"	103°28'50"	partial

Statistical table of dams caused by large collapses and landslides in Mozi gully

Tab. 1 - Dimensions of landslide source areas (scars) and resultant landslide dams positions of locations of landslide scars and dams, Position of locations of landslide scars and dams in the mainstem, and degree of stream blockage in Mozi gully

Fig. 8 - Aerial image Showing two of the eight landslide dams in Mozi gully after the earthquake (Scale:5000) (2008.6, National Geomatics Center of China)

Fig. 9 - Photograph of a landslide collapse on the left bank of Mozi gully (2009.7.5)

Fig. 10 - Photograph showing the Mingjiang River partially blocked by debris flow from Mozi gully, 2008 Photograph taken in (December, 2008) The river was completely blocked for only 15 minutes

on July 14th, 2008 when the river was completely blocked for 15 minutes (Fig. 10). According to the Dujiangyang weather station (located 15 km from Mozi gully), between July 1 and September 30, 2008, 605.8 mm of rain fell over a seven day period, with intensities greater than 25 mm/24 h. The largest daily accumulation was 91.9 mm, which occurred over 24 hours on September 23, 2008. Storms on July 14 dropped 70.1 mm of rain, on August 6 dropped a total of 54.8 mm, and between September 23 and 26, the accumulated rainfall was 197.6 mm (Fig. 11). Rainfall accumulations at Mozi gully itself are expected to be somewhat higher than these measurements due to alpine effects. The local observers Huo Dequan, who lived in the house of A Point in Fig. 13, told that the large debris flow happened on July 14th, August 6th, and September

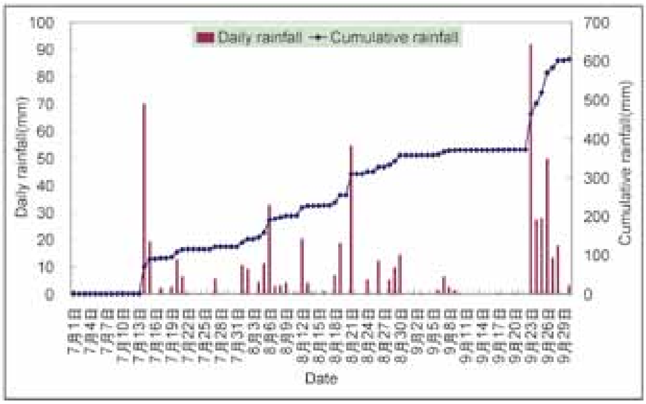

Fig. 11 - Rainfall measured at Dujiangyang meteorology station from July to September of 2008

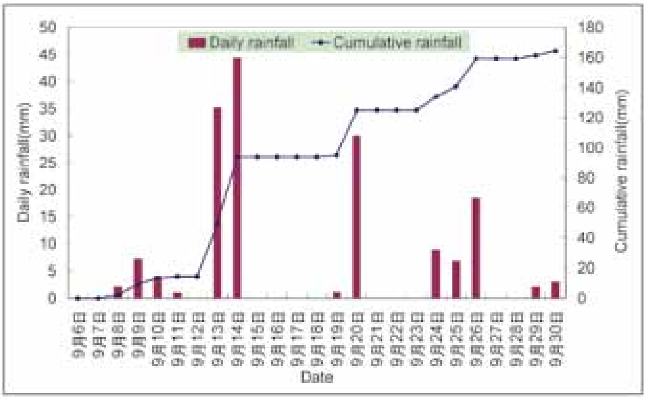

Fig. 12 - Rainfall measured at Dujiangyang meteorology station in September, of 2009

24th in 2008, as well as on September 13th, 14th, 20th and 26th in 2009 (Figg. 12 and 13). The day of debris-flow occurrences had heavy 24-hour rainfall in the area, which exceeded 25 mm.

On August 17, 2009, debris flows travelled out of Mozi gully and buried about 500 m of the National 213 highway, and the existing V-shaped channel was turned into the U-shaped (Figg. 13, 14, 15, 16 and 17). The deposits from these debris flows formed a mound with an average thickness of 20 m and width of 400 m, giving an estimated volume of $9x10^5$ m^3. The density of the debris flow measured from samples of the deposits was 1.95 g/cm^3. With this high value, the debris flows are expected to be highly viscous and move as a series of surges, as reported by eye-witnesses.

In this event, debris flows generated from Mozi gully completely blocked the Minjiang River, forming a dam. The dammed water rose 15 m above the streambed and inundated a village located 3 km upstream from the confluence of Mozi gully and the river (Fig. 18). In December of 2008 the water was 8 m deep and the backwater extended 1km upstream (Fig. 19).

Fig. 13 - Photograph showing Mingjiang River blocked by debris flow from Mozi gully in 2009(front edge of deposits have been removed). Photograph taken on July, 2009

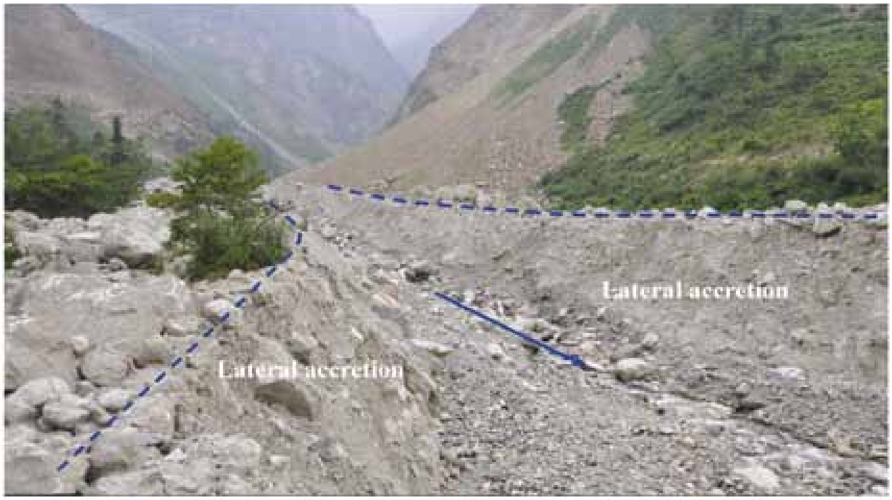

Fig. 14 - Debris flow deposits in downstream reach of Mozi gully

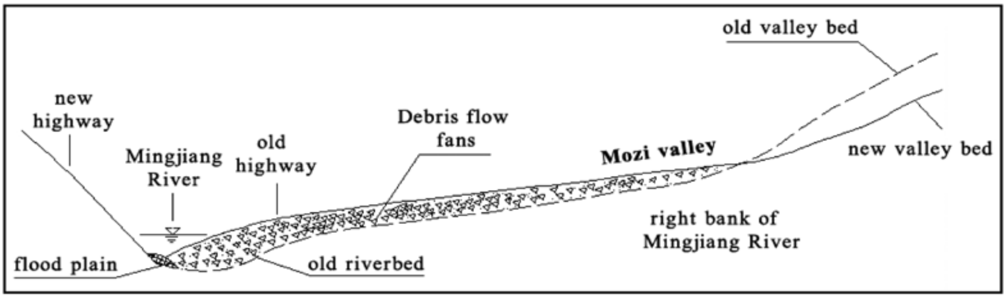

Fig. 15 - Comparison of landform change before and after debris flow events in Mozi gully

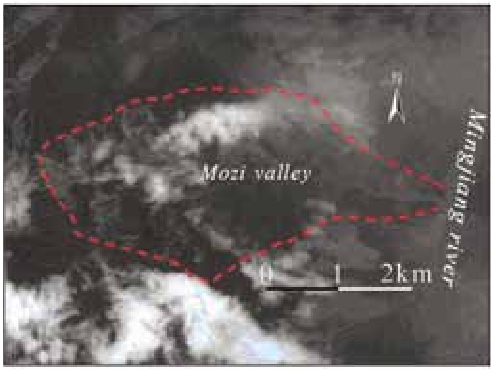

Fig. 16 - Remote image of Mozi gully after debris flows on August 17, 2009

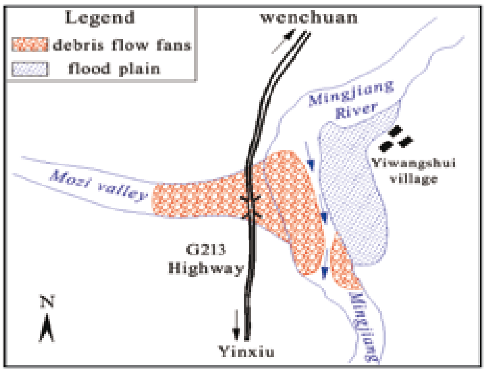

Fig. 17 - Sketch map of Mingjiang River blocked by debris flow from Mozi gully in December, 2008

ANALYSIS OF THE DAMMING PROCESS

MAGNITUDE OF THE DEBRIS FLOW

The volume of debris flow damming Minjiang River can be estimated empirically using the following formula (ZHOU *et alii*, 1991):

$$V_c = \left(\frac{1}{2tg14^\circ} + \frac{1}{2tg\Phi_s} \right) B_w H_w^2 \qquad (1)$$

where B_w is the width of the mainstream channel, and H_w is its depth. The slope downstream the dam is the initiation angle of debris flow, 14º; Φ_S is the internal

Fig. 18 - Submerged houses in lake upstream from landslide dam at confluence of Mozi gully and the Mingjiang River in December of 2008

Fig. 19 - Lake formed by landslide dam at confluence of Mozi gully and the Mingjiang River in December, 2008. Blue arrow indicates direction of flow

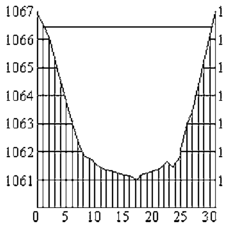

Fig. 20 - Channel cross section I — I′ (Fig.13) (in m)

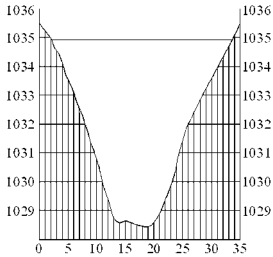

Fig. 21 - Channel cross section II — II′ (Fig.13) (in m)

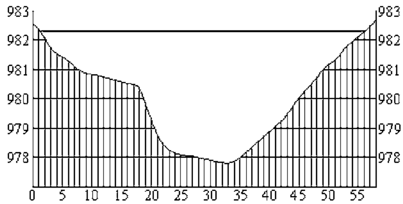

Fig. 22 - Channel cross section III — III′ (Fig.13) (in m)

	H_c (m)	I_c (‰)	S (m^2)	U_c (m/s)	Q_c (m^3/s)
— ′cross section	5.5	466 (25°)	105	4.78	502
— ′cross section	6.3	364 (20°)	117	4.62	541
III—III′cross section	4.5	306 (17°)	145	3.39	491

Tab. 2 - Shape parameters of cross section and estimated velociies and peak discharges of debris flows in Mozi gully

friction angle of the material; V_c is the smallest volume of material know to block the river. According to field surveying by GPS Trimble R8, Φ_S = 25º, B_w = 115 m, H_w = 12 m, and then $V_c = 5.1\times 10^4$ m^3.

It follows that the five events blocking the river should have a volume larger than $V_c = 5.1\times 10^4$ m^3. Field surveys indicated that there is still approximately 80 × 10^4 m^3 of sediment left in the valley. The material transported by debris flow is assumed to be more than one third of the total, so there have been more than 1.2 million of sediment carried out of the valley in the rainy season after the earthquake.

As for the discharge, we have measured three cross-sections in the valley (Figg. 13, 20, 21 and 22), with parameters listed in Table 2. Those cross-sections are used to estimate a peak discharge of the debris flow.

The discharge is estimated as the product of the velocity of the material passing through the cross-section and the cross-sectional area. Velocity is calculated by the following formula, which has been widely used in the southwest of China (Chen *et alii*, 1983; Zhou *et alii*, 1991):

$$U_c = (1/n_c)\ H_c^{2/3}\, I_c^{1/2} \tag{2}$$

where U_c is the velocity, n_c is the roughness of the streambed, H_c is the average depth of flow, and I_c is the hydrological slope of the flow, usually equal to the channel gradient. The results are listed in Table 2.

According to hydrology stations, the perennial average discharge of the Minjiang River near the junction with Mozi gulley is about Q_H =363 m^3/s, which is smaller than the estimated debris flow peak discharges. This is the reason for the blockage.

DEBRIS FLOW DISCHARGES FROM VARYING RAINFALL RATES

Debris flow discharge can be estimated by combining flood water discharge and the entrained sediment (Chen *et alii*, 1983; Zhou *et alii*, 1991). The flood water discharge is calculated by

$$Q_p = 0.278\phi i F = 0.278\phi \frac{S}{\tau^n} F \tag{3}$$

For complete confluence, $\tau \le t_0 \,.\, \phi = 1 - \frac{\mu}{S}\tau^n$ (4)

and for partial confluence, $\tau \ge t_0$, $\phi = n\left(\frac{t_c}{\tau}\right)^{1-n}$ (5)

where: $t_c = \left[(1-n)\frac{S}{\mu}\right]^{\frac{1}{n}}$, $\tau = \tau_0 \phi^{-\frac{1}{4-n}}$

$$\tau_0 = \frac{0.278^{\frac{3}{4-n}}}{\left(\frac{mJ^{1/3}}{L}\right)^{\frac{4}{4-n}} (SF)^{\frac{1}{4-n}}} \tag{6}$$

Here Q_p is flood discharge (m^3/s) under rainfall of frequency P, Φ is the runoff coefficient, i is the rainfall intensity (mm/h) and S is 1-hour rainfall (mm), F is the drainage area of the valley (m^2), τ is confluence time (h), μ is an empirical coefficient for flood, τ is the runoff parameter, i.e. the infiltration rate during runoff (mm/h), n is the index, τ_0 is time of confluence at $\Phi = 1$, t_c is duration of runoff (h), m is the confluence parameter, J is the average gradient of the mainstream channel (‰), L is the mainstream length (km). Seven parameters are to be determined: F, L, J, S, n, m, μ. The first three can be drawn from the topographic map; S and n are independent parameters, and values of m, μ from are experience parameters, which can be get from regional flood references (WREPDS, 1984). Detailed values are shown in Table. 3, and computed results are in Table.4.

Discharge of debris flow can be derived from the flood discharge calculated above by combining the content of sediment:

$$Q_c = Q_p\,(1 + \varphi)\, D \tag{7}$$

where Q_p is the water discharge and Q_c the debris flow discharge; D is the blockage coefficient, taken as 1.1~3.0 for the situation; φ is the sediment coefficient, defined as $\varphi = (\gamma_C - 1) / (\gamma_H - \gamma_C)$, with γ_C and γ_H the unit weight of flow and solid grains. Field test indicated that γ_C = 1.95 g/cm^3, γ_H = 2.7 g/cm^3. Debris flow discharges in response to rainstorms with return periods of 10, 20, 30 50 and 100 (Probabilities of 10, 5, 3.3, 2 and 1percent) years are listed in Table 4.

In summary, we estimate that about 1 million m^3 of sediment was carried out from the valley of Mozi in 2008, and more than 30 Mm^3 of sediment remains in the valley. This material will continue to supply debris flows for a long time.

Tab. 3 - Coefficients used for estiamtion of peak water discharges in Mozi gully

F (km^2)	L (km)	J (‰)	m	n	μ	$\overline{H}_{24}$	ϕ
7.3	5.2	493	0.293	0.725	4.11	120	1.13

Tab. 4 - Debris flow discharges estimated from Mozi gully for varying rainstorm frequencies

P (%)	D	γ_C (g/cm^3)	γ_H (g/cm^3)	φ	Q_p(m^3/s)	Q_c(m^3/s)
10	1.10	1.95	2.7	1.27	99.9	249.5
5	1.20	1.95	2.7	1.27	127.5	347.2
3.3	1.35	1.95	2.7	1.27	146.1	464.4
2	1.50	1.95	2.7	1.27	165.2	562.5
1	2.00	1.95	2.7	1.27	194.1	881.3

CONCLUSIONS

The Wenchuan earthquake turned the Mozi valley into an active source for debris flows. Many debris flows occurred in the rainy season after the earthquake in 2008, and analyses of these events leads to the following conclusions:

1. The landform has been drastically changed by the earthquake. About 73.2 percent of the valley is covered by the scars of landslides and avalanches. Approximately 30 Mm^3 of material provided abundant sources for debris flow.
2. Debris flow in the valley is typically of high density and high viscosity. The density is estimated as 1.95 g/cm^3; the peak discharge on July 14, 2008 is estimated to have been approximately 541 m^3/s, with a return period of 50 years. The critical volume to block the river is 5.1×10^4 m^3, meaning that there must be many blockages in the future.

Debris flows will continue to be an active process because of the abundant material in the valley, discharge of which depends on the triggering rainfall. For example, a debris-flow discharge of approximately 250 m^3/s is estimated in response to a 10-year -recurrence rainstorm, and of 880 m^3/s for a 100-year-recurrence rainstorm.

Furthermore, the dam residual in the mainstream has raised the water level and still dammed a certain volume of water, and the right bank downstream the valley has been strongly eroded. This stored material are very likely to form debris flows and dam the river again, this is the great threat of the valley to the local people and properties.

ACKNOWLEDGEMENTS

This research was financially supported by the Research Fund for Commonweal Project of the Ministry of Water Conservancy (200801032), the national Science and Technology Program of China (2008BAK50B04), International collaboration program of the Ministry Science and Technology (09B2420420), and the Research Fund for Commonwealth Projects (Meteorology) (GYHY201006039).

REFERENCES

Chen G., Wang J. & Wang L. (1983) - *The Prevention of Debris Flow* [M]. Beijing: China Railway Publishing House. (in Chinese)

Cheng D.M. (2000) - *Mechanisms of Confluence between Debris flow and the Main River* [D]. The Institute of Water Resources and Hydropower Research. (in Chinese)

Committee of Chorography of Wenchuan County (1992) - *Aba Zang and Qiang Nationality Autonmous District, Sichuan Province. Chorography of Wenchuan County [M]*. Beijing:The ethnic publishing house. (in Chinese)

Cui P., Wei F., He S. et alii (2008) - *Mountain Disasters Induced by the Earthquake of May 12 in Wenchuan and the Disasters Mitigation*. Journal of Mountain Science[J], **26** (3): 280-282.

Hydrology and water resources survey bureau of Sichuan province [EB/OL] (2008) - http://www.schwr.com /Otype.asp?newid=A bulletin of water resources and quality in Sichuan province. (in Chinese)

Tang C. & Liang J. (2008) - *Characteristics of Debris flow in Beichuan Epicenter of the Wenchuan Earthquake Triggered by Rainstorm on September 24, 2008* [J]. Journal of Engineer Geology, **16** (6): 751-758.

Water Resources Electric Power Department of Sichuan province (1984) - *Storm flood calculation manual of middle and small basins in Sichuan province* [M]. Beijing: Science press, (in Chinese)

Xie H., Zhong D., Jiao Z. et alii (2009) - *Debris Flow in Wenchuan Quake-hit Area in 2008*. Journal of Mountain Science [J], **27**(4): 501-509.

Yin Y., Wang F. & Sun P. (2009) - *Landslide hazards triggered by the 2008 Wenchuan earthquake, Sichuan, China*. Landslides, **6**: 139-151.

Zhou B., Li D., Luo D. et alii (1991) - *Guide to Prevention of Debris flow* [M]. Beijing: Science press, (in Chinese)

