DOI: 10.4408/IJEGE.2011-03.B-088

DISASTER CHARACTERISTICS AND OPTIMAL DESIGN OF DRAINAGE CANAL OF DEBRIS FLOW FOLLOWING WENCHUAN EARTHQUAKE IN WEIGOU GULLY IN BEICHUAN COUNTY, SICHUAN PROVINCE, CHINA

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ABSTRACT

The Weigou Gully, a branch of Pingtong River, is located in Guixi Township, Beichuan County. The area was seriously affected by the Wenchuan earthquake and its aftermath. Debris flows occurred on September 24, 2008, July 14, 2009, and September 10, 2009, threatening the safety of the inhabitants and their property. Debris flows in Weigou Gully were mainly supplied by landslides triggered by the earthquake. The debris flows had characteristics of high frequency, high bulk density and coarse particle size. Following the earthquake, the frequency of debris flows increased. Based on the analysis of the disaster characteristics, the optimal cross-section design method for the "trapezoid-v" shaped debris flow drainage canal of the Weigou Gully is discussed. The depths (h_1 and h_2) of the cross-section of the "trapezoid-v" shaped drainage canal and the optimal cross-section parameters using these two measurements are defined. In addition, several formulas for calculating the cross-section measurements are deduced under optimal hydraulic conditions when discharge (Q), debris grain composition (D_{50} and D_{10}) and longitudinal ratio (I) are known. Finally, the optimal dimensions for the cross-section of the Weigou Gully debris flow canal are determined.

Key words: Wenchuan earthquake, debris flow hazards, drainage canal, optimal design, Weigou Gully, Beichuan County

INTRODUCTION

The Wenchuan earthquake occurred along the northeast Yingxiu–Beichuan reverse fault. The area most seriously affected by the earthquake was in the transition zone between the Tibetan Plateau and the Sichuan Basin. Due to the unique topography in the area, the earthquake directly caused more than 15,000 geohazards, mostly in the form of rockfalls and landslides (Yin, 2008; Huang *et alii,* 2008; Wang *et alii*, 2008). The quantity, magnitude, and extent of the damage caused by the geo-hazards were most severe in this area (Cui *et alii,* 2008a; Dong *et alii,* 2008; Huang *et alii,* 2009). These geohazards provided considerable loose materials for debris flows, which are expected to be more frequent and an active period of about 20 ~ 30 years (Cui *et alii,* 2008b; Cui *et alii,* 2009; Xie *et alii,* 2009). Debris flows have been one of the primary factors impeding post-disaster restoration and reconstruction.

Beichuan County, one of the areas most seriously affected by the earthquake, suffered a sudden rainstorm that triggered a large number of debris flows between September 23 and 24, 2008. At that time, a large debris flow formed in the Weigou Gully, in Guixi Township, Beichuan County, flooding villages, burying roads, and silting rivers.

In this paper, we examine the characteristics of the Weigou Gully debris flow. We use data from field survey and the interpretation of remote sensing images to identify the optimal characteristics of the "trapezoid-v" Shaped Drainage Canal.

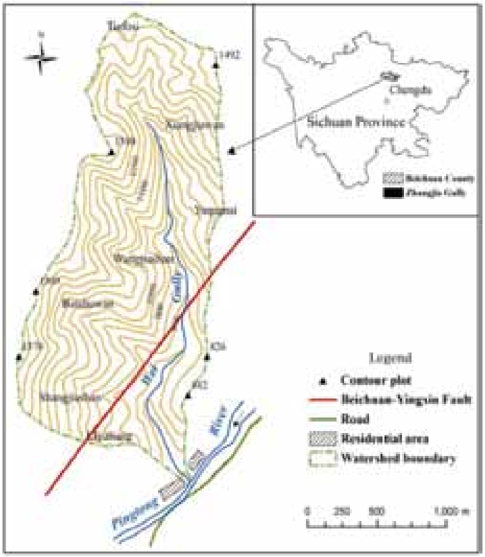

Fig. 1 - Sketch of the Weigou Gully catchment

ENVIRONMENTAL SURVEYS

DRAINAGE BASIN SURVEY

Weigou Gully (104°38′36″E, 32°00′19″N), in Guixi Township, Beichuan County, is a branch of Pingtong River, an arterial branch of the Fujiang River. The gully is characterized by a basin area of 3.11 km^2, a gully length of 3.68 km, and a longitudinal slope of 187 ‰ (Fig. 1). The altitude of the catchment varies from 630 m. to 1,492 m, with an altitude difference of 862 m.

PHYSIOGNOMY

The Weigou Gully is located to the east of the Tibetan Plateau and forms part of the transition zone between the Tibetan Plateau and the Sichuan Basin. Its physiognomy is complex.

The gully slopes are characterized by a higher elevation in the north and a lower elevation in the south. Gentle land (<25°), mainly located in the middle and lower reaches, occupies 18.33 % of the total area of the gully. Steep (25°-35°) and very steep (≥35°) land occupy 20.90 % and 60.77 % of the total area, respectively. The upper reaches are dominated by steep and very steep land (Tab. 1).

Neo-tectonic movement has created a strong incision in the gully, resulting in a v-shaped cross-section and a steep longitudinal gully slope (187‰). The steep mountain and gully slopes provided favorable conditions for the formation of debris flows.

Characteristics	Slope				Total
	< 15°	15-25°	25-35°	≥ 35°	
Surface area (km^2)	0.18	0.39	0.65	1.89	3.11
Ratio(%)	5.79	12.54	20.9	60.77	100.00

Tab.1. Characteristics of the Weigou Gully slope

GEOLOGICAL SETTING

The Weigou Gully lies on the eastern edge of the Tibetan plateau and is part of the Longmenshan Mountain geosynclines. This region is characterized by elevations of up to 7,500 m above sea level and by topographic reliefs of more than 5,000 m over distances of less than 50 km (Densmore *et alii,* 2007). The Beichuan reverse fault, located on the boundary between the front and back Longmenshan Mountain fold belts, passes through the lower reaches of this gully. It's an active thrust fault that trends northwest with a dip of 60°-70°, pushing the Cambrian stratum above the Silurian, Devonian, and Carboniferous strata (Fig. 2). The cutting depth is great and the vertical fault is greater than 1,000 m. Since they are affected by the impact of the Beichuan fault, the main geological structures and rocks in this area trend toward the northeast. The strata in the gully are mainly Cambrian and Silurian, and a large area of Cambrian rock has been exposed to the northwest of the Beichuan fault zone. It shows mildly dynamic metamorphism, likely due to the intense dynamic regional metamorphism associated with the activities of the Beichuan fault. A few Silurian sandstones have been exposed downstream. Strongly weathered rocks provide abundant material for geological disasters.

METEOROLOGICAL SETTING

The study area has a subtropical moist, monsoon climate with four normal seasons, a mild climate, and an average temperature of 15.6°C (Tab. 2). The annual average precipitation is 1,399.1 mm, with an annual maximum of 2,340.0 mm, a daily maximum of 101.0 mm, and an hourly maximum of 32.0 mm. Most rainfall occurs between June and September, accounting for 70-90 % of the annual rainfall (Committee of Beichuan County annals, 1996).

Months	1	2	3	4	5	6	7	8	9	10	11	12	Annual
Temp.	5.3	7.0	11.3	12.9	20.4	21.6	24.4	24.4	20.2	16.0	11.3	6.8	15.6
Rainfall	5.9	11.4	22.8	52.6	97.3	135.3	370.8	350.4	206.6	64.4	18.6	4.1	1,399.1

Remark: the temperature unit is ˚C, and the rainfall unit is mm

Tab. 2 - Beichuan county mean temperature and rainfall between 1971 and 2000

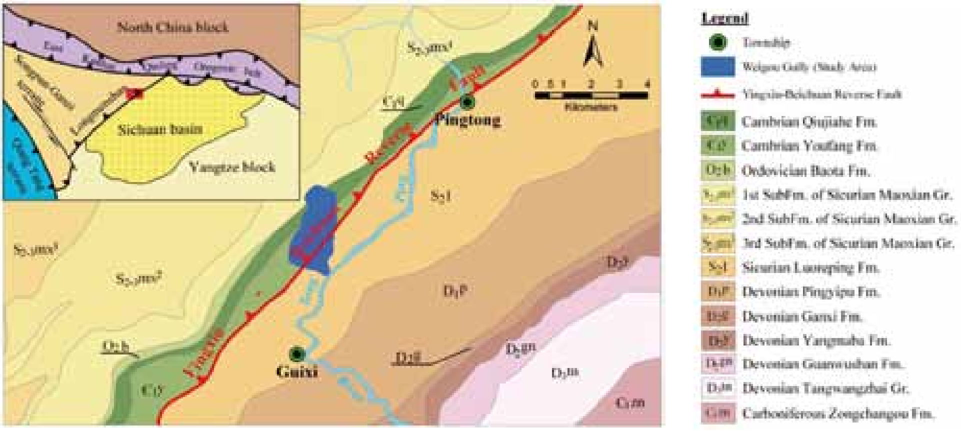

Fig. 2 - Regional geological map of the Weigou Gully

Fig. 3 - Houses destroyed by the September 24, 2008 debris flow

Fig. 4 - Debris flow fan formed after the September 10, 2009 debris flow

EARTHQUAKE

The study area belongs to the Longmenshan fold belt, where neo-tectonic movement has mainly consisted of intermittent uplifts characterized by intensely cutting, vertical and horizontal displacements. The Wenchuan earthquake occurred along the fold belt and extended from southwest to northeast. The maximum displacement caused by the earthquake was up to 5 m near Beichuan City. The "seismic ground motion parameter zonation map of China" (GB18306-2001) was revised after the earthquake. According to the map, the seismic peak ground acceleration was 0.2g and the seismic intensity was VIII in Beichuan County.

DEBRIS FLOW CHARACTERISTICS

HAZARDS

Although there was no record of debris flows in this gully prior to the earthquake, the Weigou Gully has since become a typical, viscous debris flow gully. Three large debris flows occurred on September 24, 2008, July 17, 2009, and September 10, 2009, respectively. Three houses and one temporary settlement were buried or destroyed (Figg. 3 and 4) during these events. A debris flow fan with 300 m long and 200 m wide formed. Farmland with an area of 20,000 m^2 was buried and the majority of which cannot be recovered without considerable difficulty. This has seriously endangered the lives and livelihood of local residents. In addition, a considerable amount of sediment was carried into the Pingtong River by the debris flows, resulting in the main channel being pushed to the other side (Fig. 4). In the future, this gully will continue breaking out debris flows that pose a serious threat to the lives and property of nearly 100 people. Once debris flows block the main river, flooding will seriously threaten the roads and villages located in the lower reaches.

LANDSLIDES CAUSED BY THE EARTHQUAKE

The distribution of the landslides in the gully is interpreted by using a 1:25,000 aerial photograph taken at the end of May 2008 (Figure 5). Four large landslides and more than ten smaller landslides distributed

Fig. 5 - Aerial image of the Weigou Gully after the Wenchuan earthquake (1:25,000, National Geomatics Center of China)

along the hanging wall of the Yingxiu-Beichuan fault. The total landslide area was about 1.05 km^2, accounting for 33.80 % of the catchment area. The total landslide volume was about 3.28 million cubic meters. The enormous amount of loose materials will easily form debris flows with adequate rainfall.

ACTIVITY CHARACTERISTICS

<u>*1. High Frequency*</u>

The gully has broken out three large debris flows since the earthquake. Because the catchment contains abundant loose material, debris flows will occur very easily with sufficient rainfall. Therefore, the gully will experience a high frequency of debris flows over the next 5-20 years.

<u>*2. High Density and Carrying Capacity*</u>

One sample from the September 24, 2008 Weigou Gully debris flow was collected for analyzing its grain composition. Figure 6 shows the particle size distribution curve. The clay particle (<0.005 mm) content is 3.72 %, indicating that it was a high viscosity debris flow. Based on data from the field survey, the debris flow density was 1.90-2.10 t/m^3. The gravel (>2 mm) content was 84.58 %, indicating that the debris flow was dominated by coarse gravel. The carrying capacity of the debris flow was very high. Approximately

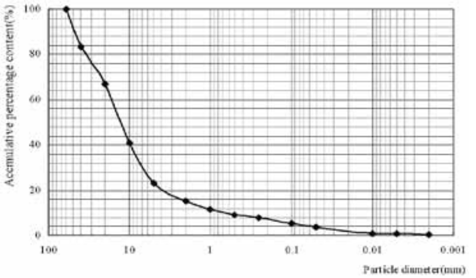

Fig. 6 - Grain grading graph for the Weigou Gully debris flow

0.10 million cubic meters of solid materials were carried to the outlet of the gully.

<u>*3. Decrease in Initiation Rainfall*</u>

The accumulated rainfall and the critical initiation rainfall prior to the earthquake were 320-350 mm and 50-60 mm per hour, respectively (Tang *et alii,* 2008). However, both decreased significantly after the earthquake. Taking the September 24, 2008 debris flow as an example, the accumulated rainfall was 272.70 mm and the critical initiation rainfall was 41.00 mm. Following the earthquake, they decreased by 14.80 %-22.10 % and 25.40 %-31.60 %, respectively.

OPTIMAL CROSS-SECTION DESIGN FOR THE DEBRIS FLOW DRAINAGE CANAL

OPTIMAL OVERFLOWING CONDITION

To mitigate debris flow disasters in the Weigou Gully, three check dams and five consolidation dams have been planned in the main channel. These dams will help stabilize the channel and slope, decrease loose soils, and minimize the peak discharge of debris flows. Meanwhile, a drainage canal will be constructed between the outlet and the Pingtong River to prevent debris flow overflow fans and protect buildings and farms. The optimal cross-section design of the drainage canal is discussed as follows.

Few studies have considered how to select cross-sectional shapes and measurements in order to ensure optimal drainage capacity. Wang *et alii* (1996) compared the hydraulic conditions of v-shaped, circular, trapezoidal, and rectangular cross-section drainage canals with the same overflow. You *et alii* (2006) compared optimal hydraulic conditions for the four drainage canal shapes and examined the optimal cross-section design for debris flows in vshaped drainage canals (You *et alii,* 2008). Fei *et alii* (2004) examined v-shaped and trapezoidal drainage canals,

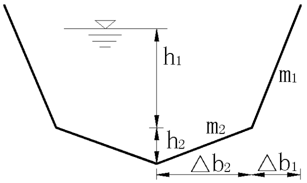

Fig. 7 - Measurements for the "trapezoid-V" shaped drainage canal

but didn't present the method used for deriving the measurements under random slope conditions. Few studies presented methods for calculating measurements under optimal hydraulic conditions.

The optimal cross-section of a drainage canal minimizes the passage area of the cross-section (*A*) or maximizes the hydraulic radius (*R*) when the values of inside section longitudinal gradient (*I*), roughness coefficient (*n*), and design discharge (*Q*) are fixed. The

measurements for the "trapezoid-v" shaped drainage canal are shown in Figure 7. Here, m_1 is the side slope coefficient ($m_1=\Delta b_1/h_1$) and m_2 is the groove transverse slope coefficient ($m_2=\Delta b_2/h_2$).

If h_1, h_2 and F (F is defined as size parameter, $F=h_1/h_2$) are known, the overflow area (*A*) and the wetted perimeter (*P*) can be calculated by formulas (1) and (2).

$$A=f(F,h_1) \tag{1}$$

$$P=f(F,h_1) \tag{2}$$

The optimal cross-section is:

$$\begin{cases} A = const \\ P = \min \end{cases}$$

That is:

$$\frac{dA}{dF}=0,\quad \frac{dP}{dF}=\frac{\partial P}{\partial F}+\frac{\partial P}{\partial h_1}\frac{dh_1}{dF}=0 \tag{3}$$

The overflow area (*A*) and the wetted perimeter (*P*) can be expressed as:

$$A=m_1h_1^2+m_2h_2^2+2m_2h_1h_2 \tag{4}$$

$$P=2h_1\sqrt{1+m_1^2}+2h_2\sqrt{1+m_2^2} \tag{5}$$

By plugging $F=h_1/h_2$ into (4) and (5) we get:

$$\mathrm{F}=\frac{m_2(\sqrt{1+m_1^2}-\sqrt{1+m_2^2})}{m_1\sqrt{1+m_2^2}-m_2\sqrt{1+m_1^2}} \tag{6}$$

The cross-section configuration parameter (*M*) for the trapezoidal debris flow drainage canal is defined as the ratio of the wetted perimeter (*P*) to the hydraulic radius (*R*). That is:

$$M=\frac{P}{R}=\frac{P^2}{A}=\frac{A}{R^2} \tag{7}$$

The greater the hydraulic radius, the smaller the *M* and the greater the debris flow drainage discharge. This represents the optimal hydraulic condition. Thus, the cross-section configuration parameter (*M*) can be used to express the optimal hydraulic condition of the debris flow drainage canal. Plugging (4), (5), and (6) into (7), the cross-section configuration parameter (M) under the optimal hydraulic conditions, we get:

$$M=\frac{\left[2\mathrm{F}\sqrt{1+m_1^2}+2\sqrt{1+m_2^2}\right]^2}{m_1\mathrm{F}^2+2m_2\mathrm{F}+m_2} \tag{8}$$

OPTIMAL CROSS-SECTION MEASUREMENTS

1. Related Parameters

The related parameters of trapezoidal-V shaped cross-sections include the debris flow discharge (*Q*), the composition of the material, the longitudinal slope of the drainage canal (*I*), and the velocity of the debris flow (*V*).

The discharge of viscous debris flow (*Q*) can typically be confirmed by data or calculated using an equation. However, because there is no precipitation rainfall or mountain torrents discharge data for the Weigou Gully, we must use an equation to determine *Q* (Zhou, 1991). We can ascertain the flood discharge for different frequencies in order to calculate the debris flow discharge. The discharges are $Q_{1\%}$=559 m³/s, $Q_{2\%}$=433 m³/s, $Q_{5\%}$=221 m³/s, and the drainage canal has a frequency of 5.00 %.

The longitudinal slope (*I*) can typically be determined based onthe terrain. For the outlet of the Weigou Gully, the longitudinal slope (*I*) is 0.08.

Several equations have been presented for calculating the velocity of viscous debris flows (Xu *et alii* 2001, Hong 1996, Mart *et alii* 2001, Yu 2001). Here we use (Yu 2008):

$$V=1.1(gR)^{1/2}I^{1/3}\left(\frac{D_{50}}{D_{10}}\right)^{1/4} \tag{9}$$

Where *V* is the average velocity of the debris flow (m/s), *R* is the hydraulic radius (m), D_{50} is the average diameter of the particles making up 50 % of the grading curve (mm), D_{10} is the average diameter of the particles making up less than 10%, and *I* is the longitudinal gradient.

2. Optimal Cross-section Design

The continual debris flow discharge equation is:

$$Q=AV \tag{10}$$

Plugging (7) into (10), we can solve for viscous debris flow velocity:

$$V = \frac{Q}{\mathrm{M}R^2} \tag{11}$$

Solving (9) and (11), we get:

$$R = 0.61\frac{Q^{2/5}}{M^{2/5}I^{2/5}}(\frac{D_{10}}{D_{50}})^{1/10} \tag{12}$$

When Q, D_{50}, D_{10}, and I are known, the hydraulic radius (R) under optimal hydraulic conditions can be calculated by using (12).

For trapezoidal-V shaped drainage canals, we have:

$$MR = 2h_1\sqrt{1+m_1^2} + 2h_2\sqrt{1+m_2^2} \tag{13}$$

$$MR^2 = m_1h_1^2 + m_2h_2^2 + 2m_2h_1h_2 \tag{14}$$

Plugging (6), (8), and (12) into (13) and (14), we can determine the measurements of the cross-section under optimal hydraulic conditions.

In practice, both the slope and transverse coefficients vary within a certain range. If they varied, m_1 and m_2 should be recalculated by repeating the above steps.

3. Cross-section Design of the Weigou Gully Debris Flow Drainage Canal

The slope coefficient of the trapezoidal-V shaped drainage canal in the Weigou Gully is m_1=0.20 and the transverse coefficient m_2=5.00. Plugging these values into equations (6) and (8), we get the size parameter (F=5.02) and the configuration parameter (M=6.93). Plugging F, M, $Q_{5\%}$=221 m^3/s, D_{50}=13.00 mm, and D_{10}=0.04 mm into (12), we get the hydraulic radius under optimal hydraulic conditions (R=2.58 m). Plugging all of these parameters into (13) and (14), we get h_1=4.38 m and h_2=0.87 m (Table 3). The measurements for the optimal cross-section of the Weigou Gully drainage canal are shown in Figure 8.

CONCLUSION

Among the environmental changes following an earthquake, the formation and accumulation of loose solid materials are the primary factors involved in the formation of debris flows.

The "trapezoid-v" drainage canal is one of the shapes most widely used for preventing debris flows. Shape and size are important parameters. This paper discusses a method for designing its optimal cross-section. Firstly, the depths (h1 and h2) of the crosssection of the "trapezoid-v" shaped drainage canal and the optimal cross-section parameters using these two measurements are defined. Then, the formulas for calculating the cross-section measurements are deduced under optimal hydraulic conditions when discharge (Q), debris grain composition (D50 and D10) and longitudinal ratio (I) are known.

ACKNOWLEDGEMENTS

This research was financially supported by the National Natural Science Foundation of China (40971014) and the National Basic Research Program of China (973 Program) (2011CB409903).

P	Q (m^3/s)	D_{50} (mm)	D_{10} (mm)	I	F	M	R (m)	h_1 (m)	h_2 (m)
5%	221	13.0	0.04	0.08	5.02	6.93	2.58	4.38	0.87

Tab. 3 - Measurements for the optimal cross-section of theWeigou Gully drainage canal

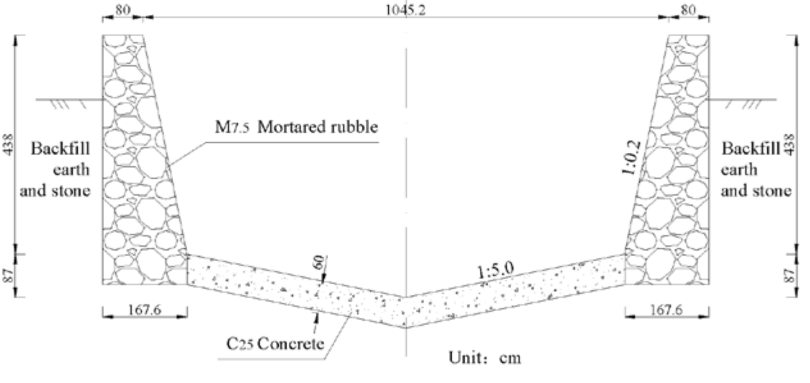

Fig. 8 - Cross-section of the Weigou Gully debris flow drainage canal

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