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FIELD INVESTIGATION AND DYNAMIC ANALYSIS FOR DEBRIS FLOW IN WEIJIA GULLY OF BEICHUAN COUNTY (CHINA) AFTER THE WENCHUAN EARTHQUAKE

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ABSTRACT

A great amount of mountain hazards were triggered by the Wenchuan earthquake, such as rock falls, avalanches, landslides, debris flows and dammed lakes. Heavy rain on 24th September 2008 initiated debris flows in Weijia Gully of Beichuan County, which resulted in serious damage to infrastructures and lifelines. In this paper, the debris flow was investigated and analyzed. The results show that solid loose materials, microtopography and rainfall are the main reason for the event. The total loose mass generated by the collapse and landslides reaches about 2.69×10^5 m^3, which provides abundance material. The conditions of the surface water infiltration, runoff and flow concentration are changed by strong surface disturbance and large-scale destructive vegetation damage, which is beneficial to the formation of the erosion and flood peak. The rainfall was 272.7 mm from 23 to 24 September, 2008 in the study area, and the maximum rain reached 41 mm one hour. Velocity, peak discharge, sediment discharge and impulsive force were calculated. The results were compared with investigation, which provide reference for the design of debris flow protection.

Key words: Wenchuan earthquake, debris flow, field investigation, dynamic characteristics

INTRODUCTION

On 12 May 2008, a devastating mega-earthquake of magnitude 8.0 struck the Wenchuan area, northwestern Sichuan province, China, which caused a large number of mountain hazards, such as rock falls, avalanches, landslides, debris flows. On 24 September, floods and debris flows broke out in many areas due to the heavy rain. Roads and bridges were destroyed; temporary shelters were washed away and a great amount of farmland was buried. Especially the debris flow in Weijia gully and Hushiban gully buried two-third of Beichuan middle school and threatened more than 300 people at the resettlement areas. The heavy rain and debris flows caused 42 people dead and more than 4000 people were besieged because of the road interruption (Tang *et alii*, 2008, 2009). With the development of economy in mountain areas and impaction of global climate, the risk of debris flows is more and more serious. Therefore, it is crucial to understand the characteristics and mechanism of debris flows.

Debris flows are important geomorphic agents in mountainous terrain and can greatly affect mountain stream ecosystems (Swanson *et alii*, 1998). A debris flow is a natural flow of liquefied geomaterials moving down a slope or a stream in mountainous regions (Dai *et alii*, 1999; Crosta, 2001; Zhou *et alii*, 2001; Li *et alii*, 2004; Chen *et alii*, 2006). The liquefied materials are usually a mixture of water, soil and rock particles, with a high concentration of solid particles. Many factors affect the debris flow movement, such as slope of channel, rainfall intensity, and solid materials. Debris flow is usually taken as Bingham flow (Johnson &

Rahn, 1970), Bagnold dilatant fluid model (Takahashi, 1978), generalized viscoplastic flow (Chen, 1986) or other kinds of flows (O'Brien *et alii*, 1993; Liu, 2002).

This paper studies the debris flow of Weijia gully, analysing the formation and calculating the velocity, peak discharge, sediment discharge and impulsive force, and compares the results with field surveys to test their applicability for engineering design andprediction of debris flow.

GENERAL SETTING

STUDY AREA

Beichuan Qiang Autonomous County is in the northwest of Sichuan, 160 km away from north of Chengdu (Figure 1). It belongs to a transition zone from Pingqiu of Sichuan basin to plateau, the altitude is from 540 m to 4,700 m and the area is about 2,869.2 km^2, the longitude is 103° 44' ~ 104° 44', and latitude is 103° 44' ~ 104° 44'. It is 92 km long from east to west, and 59 km from north to south. A total of 75 geo-hazards were found before the Wenchuan earthquake including 48 landslides. After the earthquake, emergency investigation was carried out. 273 geo-hazards points were found, including 158 landslides, 43 sinkholes, 23 debris flows and 49 potential disasters. 78 geo-hazards affected large areas, which mad 20 residents destroyed, 75 roads damaged and 25 river channels blocked.,

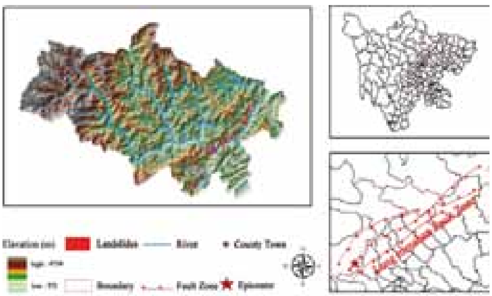

Fig. 1 - Location of study area

Fig. 2 - Geomorphological units of Beichuan County

GEOLOGY AND GEOMORPHOLOGY

A large number of mountains are in Beichuan, and the direction is about NE-SW. The county can be divided into three geomorphological units (Fig. 2). Terrain in northwest is higher than southeast, and the altitude decreases 46 m/km from northwest to southeast. Chaqi Mountain is 4769 m, which is the highest point in this county, and Xiangshuidu Mountain is the lowest point which is only 540 m. The valley slope is generally higher than 25°; some can be up to 40° or even higher.

Beichuan County (Qushan town) is located in southeast of Beichuan Qiang Autonomous Aounty County and Jian river flow through the town, which belongs to one of the most serious disaster area after the Wenchuan earthquake. It is also located in the junction between front and back Longman mountain fold belt, and Beichuan- Yingxiu fault (central fault in Longman mountain) across it, which the alignment is NS, trend is NE. The lower Cambrian Qingping group (including siltstone, sandstone, chert, calcium phosphate rock) exposed above the fault, and upper Carboniferous Huanglong group and Chuanshan group (including limestone, crystalline limestone) and lower Permian (including limestone, argillaceous limestone and shale) are exposed below the fault. Due to the lithological complexity, geo-hazards are prone to occur. According to the field investigation, a total of 13 geo-hazards were found before Wenchuan earthquake, including 8 landslides, 3 sinkholes and 2 debris flows. After the earthquake, there are 20 geo-hazards points, including 13 landslides, 5 sinkholes, 2 debris flows

CLIMATE

Beichuan County is located in the transitional zone from Sichuan basin to eastern Tibet plateau, between the western edge of eastern subtropical humid monsoon climate zone and the Plateau dry-hot valley climate. The highest annual rainfall is 2340 mm, maximum daily rainfall is 101 mm and maximum rainfall is 42 mm per hour. The extreme maximum temperature is 36.5 Celsius degree (on Aug. 1972); minimum temperature is -4.8 Celsius degree (on Dec. 1975). Figure

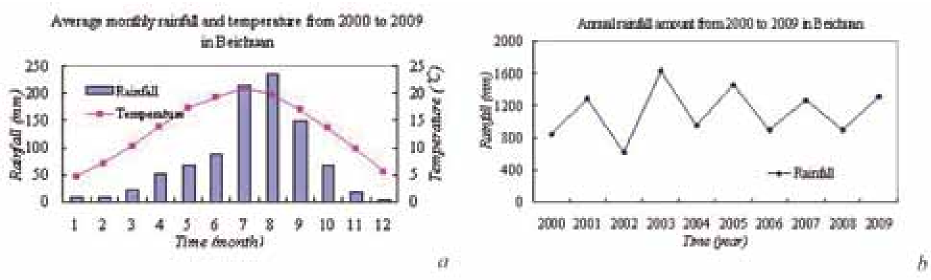

Fig. 3 - Rainfall amount from 2000 to 2009 in Beichuan

Fig.4 - The activity of debris flow and its hazards in Beichuan County after the earthquake a) The Beichuan County after the earthquake (but before the debris flow). b) The Beichuan County after the earthquake (and also after the debris flow)

Fig. 5 - Debris flow in Weijia gully a) The trunk of Weijia gully. b) the branches of Weijia gully

3a shows the mean monthly rainfall and temperature from 2000 to 2009. The mean annual rainfall is 929.6 mm, and the mean annual temperature is 13.3 Celsius degree (no data recorded from June to November in 2008 because of earthquake). The rainfall concentrates in June to September, accounting for 73.8% of annual rainfall. Figure 3b shows the annual rainfall from 2000 to 2009 in Beichuan, indicating the distribution of rainfall in the study area is non uniform.

INVESTIGATION AND ANALYSIS OF DEBRIS FLOW IN WEIJIA GULLY

Weijia Gully is located in the southwest of Beichuan County, nearby the right bank of Jianjiang River. It is about 450 m far from the county. A large number of landslides, debris flow and dammed lakes were triggered by the earthquake. In the gully, the loose mass generated by a total of 17 landslides reached about 2.69×10^5 m^3, which provided abundance materials for debris flow. In history, debris flows occurred three times in Weijia gully, which were in 1955, July 24th, 1992, August 12th, 1995 respectively. For the latest debris flow from Weijia gully, Xijia gully and Huashi ban gully on September 24^{th,} 2008, a volume of about 340,000 m^3 was rushed out and 144,097 m2 debris flow fan was formed, which buried a large area of Beichuan County (Fig. 4). The solid materials of Weijia gully rushed into Beichuan middle school, formed a 400 m wide, about 300 m long, about 3 m to 5 m high debris flow fan.

THE INVESTIGATION OF DEBRIS FLOW IN WEIJIA GULLY

There is one main trunk and two branches for the Weijia gully (Fig. 5). The main trunk is about 1.5 km long, the left branch is about 0.155 km, and the right branch is about 0.156 km. The GPS of debris entrance is 104°26′27″E, 31°48′48″N, the height is about 650 m, the area is about 0.52 km^2. Bedrock is exposed at the source area, the rock strike angle is NW281°, tendency is NE11°, and dip angle is 59°. Solid materials are mainly from the landslides after the earthquake, surface area of landslides is up to 0.226 km2, which accounts for 42% of catchments basin of debris flow. Its volume is about 2,700,000 m^3 according to the emergency investigation

A volume of 300,000 m^3 of the main slip mass, which comes from the landslides front, participated in forming the debris flow (Tang *et alii*, 2008, 2009). The slope on both sides of the gully is from 28° to 71°, the vegetation covered very well on the right side, but it serious damaged on the left side. According to the interview, the rain was very heavy in many places on September 23rd, 2008. When the debris flow broke out, produced loud noise, the ground vibrated, and flood sharply rise accompanied with slits and stones.

ANALYSIS OF THE FORMATION OF DEBRIS FLOW FOR WEIJIA GULLY

There are many factors affecting debris flow initiation and development. The loose soil, rainfall and micro-topography are the main ones

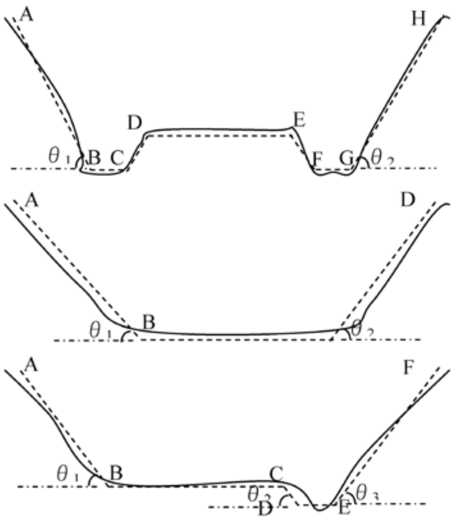

Fig. 6 - Cross sections of Weijia Gully

TOPOGRAPHY

Topography is an important factor in controlling debris flow. There are three types of cross section in Weijia gully (Fig. 6). The source of Weijia gully is at 1350 m, the entrance is about 650 m and the average slope gradient of the channel is 116‰..

PROVENANCE

According to the investigation after the earthquake, loose solid materials are about 2.69×105 m3, the area was about 7.0×104 m^2 Generally there are three ways providing solid materials for the debris flow. (1) Slopes slide and loose solid materials deposit in the channel,

	Number	GPS	Altitude	Values
Trunk gully	1-1	104°26′40.05″E 31°48′29.61″N	843 m	AB=2.15m;BC=7.1m;CD=2.3m; θ_1=45°;θ_2=51°
	2-2	104°26′36.32″E 31°48′26.41″N	867 m	AB=3.7m;BC=11.1m;CD=1.1m; DE=1.7m;EF=2.55m
Left branch gully	3-3	104°26′35.76″E 31°48′25.82″N	873 m	AB=2.5m;BC=2.1m;CD=2.12m; θ_1=71°;θ_2=64°
	4-4	104°26′34.72″E 31°48′25.52″N	890 m	AB=2.8m;BC=1.92m;CD=3.03m;θ_1=50°;θ_2=41°
	5-5	104°26′34.50″E 31°48′25.55″N	905 m	AB=6.5m;BC=2.42m;CD=7.5m; θ_1=72°;θ_2=71°
	6-6	104°26′32.36″E 31°48′26.79″N	921 m	AB=4.5m;BC=1.62m;CD=4.97m;θ_1=44°;θ_2=38°
	7-7	104°26′30.43″E 31°48′25.97″N	937 m	AB=2.1m;BC=2.85m;CD=3.4m; θ_1=45°;θ_2=32°
	8-8	104°26′28.05″E 31°48′26.78″N	979 m	AB=7m;BC=2.54m;CD=7m;θ_1=40°;θ_2=39°
Left branch gully	9-9	104°26′36.45″E 31°48′25.68″N	870 m	AB=3.9m;BC=7.9m;CD=1.8m;θ_1=71°;θ_2=64°
	10-10	104°26′35.96″E 31°48′24.95″N	881 m	AB=1.7m;BC=4.15m;CD=2.38m;θ_1=54°;θ_2=64°
	11-11	104°26′34.67″E 31°48′24.81″N	888 m	AB=5.5m;BC=6.0m;CD=5m; θ_1=31°;θ_2=36°
	12-12	104°26′33.62″E 31°48′24.14″N	899 m	AB=6m;BC=4m;CD=2.9m; θ_1=28°;θ_2=49°
	13-13	104°26′33.51″E 31°48′23.22″N	916 m	AB=3.16m;BC=3.15m;CD=2.7m;θ_1=59°;θ_2=56°
	14-14	104°26′32.93″E 31°48′22.86″N	925 m	AB=3.2m;BC=2.8m;CD=3.05m; θ_1=40°;θ_2=39°
	15-15	104°26′32.35″E 31°48′22.35″N	925 m	AB=5.0m;BC=4.9m;CD=2.3m; θ_1=37°;θ_2=35°
	16-16	104°26′20.81″E 31°48′22.20″N	926 m	AB=1.8m;BC=2.0m;CD=3.6m; θ_1=45°;θ_2=49°
	17-17	104°26′31.59″E 31°48′21.95″N	931 m	AB=2.45m;BC=1m;BG=2.35m; GH=4.5m;θ_1=33°;θ_2=47°

Tab. 1 - Basic values of cross sections

(2) slopes suffer serious erosion due to the continuous heavy rain and result in a great number of clay coming into the channel, (3) cracks and porosity of soil increase because of earthquake. With the infiltration of surface water, Quaternary deposits and weathering layer are also easily imported into the channel.

RAINFALL

Rainfall is another major factor inducing the debris flow. On the one side, the surface of slopes became unstable after the rainfall, and it easily caused landslides; on the other side, the deposits along the channel are washed out by the conflux, which made the loose solid materials come into the channel continuously. According to the statistical analysis of the rainfall data in this area, some characteristics can be obtained. (1) Rainfall is abundant. The annual mean rainfall is 929.6 mm; the maximum annual rainfall is 2340 mm (in 1967). (2) Rainfall is concentrated. The rainfall from June to September amounts to about 70% of the annual value. The maximum monthly rainfall is in August, which can be up to 280.8 mm. (3) The intensity of rainfall is strong. The maximum monthly rainfall is 977.6 mm; the maximum daily rainfall is 179.6 mm, and the maximum hourly rainfall is up to 42 mm from 2000 to 2009. Especially during September 23 to 24, 2008, the rainfall reached 272.7 mm in the study area, the maximum hourly rainfall was 41 mm. It could not infiltrate the soil in short time. Therefore, abundant rainfall provides dynamic conditions for the debris flow.

DYNAMIC CHARACTERISTICS OF DEBRIS FLOW IN WEIJIA GULLY

Based on field investigation and making an analogy of the dynamic characteristics in the history, debris flow of Weijia gully is analyzed.

THE VELOCITY OF DEBRIS FLOW

Formulas in calculating the velocity are mostly empirical, which should combine the regional characteristics. The dry density of soil in Weijia gully is 1.59 g/cm3, fine particle content is between 1.68% and 2.36%, the water content is between 30% and 50%. So, density of debris flow is between 2.06 and 2.38 g/cm3, it belongs to viscous fluid. The formula used in this paper is recommended by the institute of Railway Academy of Science and Southwest Academyof Science. (Kang *et alii,* 2004)

$$v_c = \frac{1}{\alpha} m_c H^{2/3} I^{1/2}$$

Where

$$\alpha = [\frac{\rho_H(\rho_c - 1)}{\rho_H - \rho_c} + 1]^{1/2} = [\rho_H \phi + 1]^{1/2}$$

ν_c is velocity (m/s),ρ_H is solids density (g/cm3), m_c is density of debris flow (g/cm^3), c m is external resistance coefficient m_c= 75 $H^{-0.425}$ cm , H is average soil depth of cross-sections; I is soil surface slope generally using vertical slope (‰); α is internal resistance coefficient,$\alpha= [\rho_H \Phi + 1]^{1/2}$ is correction factor.

According to emergency investigation, the peak discharge was up to 260 m^3/s and velocity was 4.1 m/s (Tang *et alii*, 2008, 2009). And the calculated value was 4.2 m/s.

THE DISCHARGE OF DEBRIS FLOW

Discharge not only reflects the intensity but also determines the engineering structures. Discharge is usually calculated by two methods, one is rainstorm method, and the other is morphological investigation method. Based on the climate characteristics of Weijia gully, rainstorm method is used to calculate the discharge. First of all, assuming that debris flow and storm occurred at the same time and the same frequency, then calculating the flood discharge by the hydrology method, at last, choosing the blockage coefficient, the discharge can be calculated. The formulas are as follows, theparameters and results are in Table 3.

$$Q_c = (1+\phi)Q_p \cdot D_c$$

$$Q_p = 0.278\psi i F = 0.278\psi \frac{S_p}{\tau^n} F$$

Parameters	Values
ρ_H (g/cm^3)	2.6
ρ_c (g/cm^3)	2.1
H (m)	1.5
I (‰)	116
m_c	63.13
ϕ	2.2
α	6.72
v_c (m/s)	4.2

Tab. 2 - The basic parameters and results of velocity calculation of debris flow occurred on 24th September

Where i is the maximum mean rainstorm intensity, mm/h,

$$i = \frac{S_p}{\tau^n}, \quad S_p = H_{1/6p} \times (1/6)^{(n-1)}, \quad \tau = [(1-n) \times S_p / \mu]^{1/n},$$

$$\psi = 1 - \frac{\mu}{S_n}\tau^n, \quad H_{tp} = K_p \times H_t \quad (t = 1/6, 1, 6, 24), \text{ if } t = 1/6,$$

n= 1.285 lg($H_{1/6\,p}$ / $H_{1/p}$), θ is the feature coefficient of the drainage basin,

$$\theta = \frac{L}{I^{1/3} \times F^{1/4}}$$

m is the confluence coefficient, $m = 0.221\,\theta^{0.204}$, is the runoff yield coefficient ,$\mu = 3.6F^{-0.19}$. According to the contour map of rainstorm of Sichuan (P = 5%), $H_{1/6\,p}$ (the designation rainstorm) can be calculated, then, $H_{1/6}$ (the maximum 10 minutes rainstorm) and H_1 (the maximum 1 hour rainstorm) can be looked up in the $H_{1/6}$ and H_1 contour map respectively, $C_{V1/6}$ (the variation coefficient of the maximum 10minutes rainstorm) and C_{V1} (the variation coefficient of the maximum 1 hour rainstorm) also can be looked up in the $C_{V\,1/6}$ and C_{V1} contour map, different $C_{V1/6}$ and $C_s = 3.5\,C_{V1/6}$, C_{V1} and $C_s = 3.5\,C_{V1}$ correspond to different K_p , which can be looked up in the coefficient table of Pearson3 curve. Q_c is the flux of debris flow when the frequency is P, m^3/s, Q_p is the flux of flood, m^3/s, Φ is sediment correction coefficient of debris, ρ_c is the density of debris flow, g/cm^3, ρ_w is the density of water, g/cm^3, D_c is the blockage coefficient, when the channels block weakly, D_c takes from 1.1 to 1.4; when block generally, D c is 1.5 to 1.9; when block seriously, D_c is 2.0 to 2.5 when channels block very seriously, D_c is 2.6 to 3.0. (Wang, 1996; The Department of Water Resources of Sichuan, 1984)

Parameters	Values
drainage area F (km^2)	0.52
length L(km)	1.5
gradient I (‰)	116
correction factor ϕ	2.2
feature coefficient θ	3.622
confluence coefficient m	0.294
Runoff producing coefficient μ	4.076
Design frequency P/%	5
Water strength S_p /(mm/h)	141.933
Concentration time τ_0 (ψ =1)	1.377
Peak runoff coefficient ψ	0.970
Peak flux Q_p /(m^3/s)	19.26
Blockage coefficient D_c	3.0
Discharge Q_c / (m^3/s)	184

Tab. 3 - Parameters and results of discharge calculation

The peak discharge of debris flow is 184 m^3/s. For the Weijia gully, the channels are very narrow, so it is difficult to discharge such a large flux of debris flow and it certainly causes great damage.

DEBRIS FLOW VOLUME AND SEDIMENT DISCHARGE

Debris flow volume can be calculated assuming that debris flow and storm occurred at the same time. According to the investigation of the latest debris flow occurred on September 24th, 2008, the local residents told that debris flow broke out at 5:00 am and lasted more than 60 minutes. So sediment discharge was calculated as follows. Debris flow volume W_c is

$$W_c = 19 \cdot T \cdot Q_c / 72$$

Sediment discharge W_s is

$$W_s = \frac{\rho_c - \rho_w}{\rho_H - \rho_w} W_c$$

Considering duration of debris flow is 60 min and flux equal to 184 m^3/s, debris flow volume can be calculated as 18,848 m^3 and sediment discharge is 12,958 m^3.

IMPULSIVE FORCE OF DEBRIS FLOW

The calculation of impulsive force contains two aspects, one is for the fluid and the other is for the single rock. Many methods can be used to calculate the force, but most of them are modified by some theoretical formulas. Only the whole impact force is calculated because huge rock is rare in Weijia gully.

$$\delta = \frac{\lambda \gamma_c V_c^{\,2}}{g} \sin\alpha$$

where δ is dynamic pressure of debris fluid (Pa), g is gravity acceleration, 9.8 m/s^2, α is the angle between the thrust face and impulsive force of debris flow (°), λ is shape coefficient, square is 1.47, rectangle is 1.33, circle is 1.00. Taking α =80°, λ =1.47, δ can be calculated as 5.3×10^4 Pa.

DISCUSSION AND CONCLUDING REMARKS

Due to the strong motion resulting from the earthquake, a large number of landslides induced and abundant unconsolidate materials generated for debris flows. Debris flows will be a major hazard in the Wenchuan earthquake area for many years. Therefore, field investigation and dynamic analysis for debris flow is a critical element for post-earthquake reconstruction. A case study of debris flow in Weijia gully shows that:

The rainstorm method was applied to calculate the debris-flow discharge. The peak discharge was calculated as 184 m^3/s, with error of 29.2% compared to the measured value. So the rainstorm method should be modified. The theoretical formula was applied to calculate the velocity. The results show that the velocity is about 4.2 m/s. The error between the calculated value and the field-measured value is 2.44%, indicating that the result calculated by the formula is acceptable.

Abundant rainfall provides dynamic conditions for the debris flow. The total of the loose mass generated by the landslides reaches about 2.69×105 m^3, which provides abundant material for debris flows for a long time. The great changes of river basin constitute the conditional combination of the debris flow formation. Therefore, the intensity of post-earthquake debris flow increases rapidly and debris flow became one of the most serious risk sources after the Wenchuan earthquake.

Debris flow is a multi-phase mixture of solid, liquid and gas, it is difficult to obtain dynamic characteristics of debris-flow quantitatively. In the future, the calculation method should be developed by coupling the loose soil supply process and the rainfall process together which may yield more accurate result.

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