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DEBRIS FLOWS IN MEIGU COUNTY OF SICHUAN (SW CHINA): GEOMORPHOLOGY AND HAZARDS

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ABSTRACT

A torrential rainstorm on June 1, 2005 in Meigu county of Sichuan province, SW China, resulted in the generation of debris flows from two drainage basins. Map (1:50000 scale) of topography and depositing materials, coupled with the data from meteorological station and field investigation, are used to evaluate the geomorphology and hazard characteristics of debris flows. The return period of debris flows is 20 years and its magnitude is small-moderate scale. Rainstorm and hail with short duration and high intensity in the upper reaches of drainage basins are the triggering factor for debris flows. Unstable side slope in low-middle reaches and a large number of scattered materials in channels provide source materials for debris flows. Grain-size curves of debris flows are multiple peaks. The high clay content, boulder piling up boulder, mud crack show that the debris flows are viscous. Debris flows occurred abruptly, 9 local residents were killed or missed, 8 were injured and great property was lost

Key words: *debris flows, hazard processes, Meigu county*

INTRODUCTION

Debris flows represent a remarkable geomorphologic hazard. They occur in diverse physiographic and climatic environments (Larsen *et alii*, 2006). Three processes of debris-flows initiation have been identified in literatures: infiltration-triggered, runoff-dominated and fire-hose effect (Johnson & Rodine, 1984; Morton, 1989; Iverson *et alii*, 1997; Coe *et alii*, 1997; Cannon *et alii*, 2001; Wilkerson & Schmid, 2003; Griffiths *et alii,* 2004; Godt & Coe, 2007). A lot of studies around the world in recent years showed that the runoff-dominated and fire-hose effect processes are triggered by rainfall especially for short-duration, moderate to high intensity rainstorm or thunderstorm that results in overland flow from unsaturated, consolidated older colluviums, and steep bedrock cliffs (ilkerson & Schmid, 2003; Chen *et alii*, 2006; Godt & Coe, 2007; Morton *et alii*, 2008; Pelfini & Santilli, 2008; Coe *et alii*, 2008; Brayshaw & Hassan, 2009). For the triggering of debris flows, precipitation is an important but not the only critical factor, topography, lithology, erosion, sediment entrainment and vegetal cover are essential for debris flow initiation (Godt & Coe, 2007; Schneider *et alii*, 2010). Rainfall-induced debris flows, therefore, form a wide range of geomorphologic characteristics in onset zones, incised channels and cone deposition and present a hazard that is being increasingly recognized. Many researchers have gone into the prediction of debris flows' occurrence (Bathurst *et alii,* 1997; Giannecchini *et alii*, 2007) and estimation of their magnitude and run-out distance (Hungr *et alii*, 2007; Miller & Burnett, 2008) in order to reduce associated risk.

The purpose of this case study is to document the debris flows activities associated with a 1 June 2005 rainstorm and hail with short-duration and high intensity in Meigu county of Sichuan province, China.

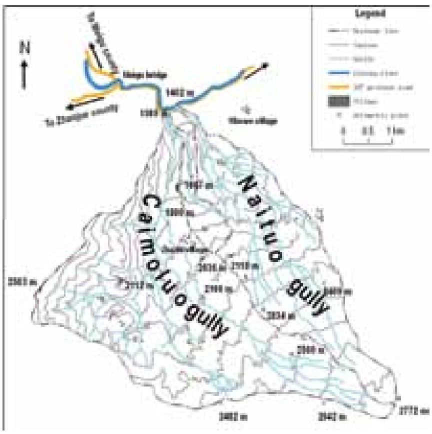

Fig. 1 - Sketch map of the topography of debris flow gullies

At about 1:00 in the morning, debris flows occurred almost at the same time both in Caimoluo gully and Naituo gully near Maluo village in Luoeyigan town in the southeast of Meigu county. During the disaster, 9 local residents were killed or missed, 8 were injured and great property was lost. In this paper, the physical and geologic settings of study area are presented and followed with an analysis of the triggering rainfall. Base on field investigation of topography, lithology, human activity and grain-size analyses of deposition, the initiation processes and geomorphology and hazard characteristics of debris flows were discussed. The objective of this paper is that the baseline information presented hereby can be used in future regional modeling efforts to assess debris flow hazard

STUDY AREA

The Caimoluo gully and Naituo gully that we surveyed for this study are located in the right bank of Liutong river, they are ranked the first-branch trenches. Liutong river is the first tributary of Jinsha river. The distance between both gullies is 0.5 km. Base on the Global Position System (GPS), Caimoluo gully is positioned at 28°06.394′N, 103°01.681′E and Naituo gully is positioned at 28°06.461′N, 103°01.859′E. Both gullies belong to Maluo village of Luoeyigan town, which is the boundary between Meigu and Zhaojue county (Figure 1).

Caimoluo and Naituo drainage basins are situated in the north and south trending tectonic belt between Sichuan province and Yunnan province which is characteristic of widespread folds and faults. The rocks are weathered intensively and the joints are developed well. The outcrop consists of Jurassic purple rock, Triassic limestone and purple rock, Ordovician red sand-shale stone (Editorial Committee of Zhaojue County - Annals of Sichuan Province, 1999). Both drainage basins are on the east limb of an anticline along Kangding and Yunnan, and being eroded intensely by the water system of Jinsha river. Elevations in the study area range from about 1000 m to 3000 m with large relief.

The climate of study area is typically of plateau climate, with dry-cold winter and wet-warm summer. According to the climatic regionalization, this area belongs to Yalongjiang temperate zone in the west of Sichuan province with mean annual temperature of 11.4°C and mean annual rainfall of 814.4 mm. The southwest monsoon prevails during mid-May to mid-October. Because of the thermal influence, frequent rainstorms usually fall in the night with high intensity during the rainy season.

The soils distributed in the study area mainly include paddy soil, moisture soil, yellow-brown soil. There are thick soil-layer and abundant heat-water, the soil fertility is rich. Local residents usually plant rice, corn, cabbage, garlic and so on. They can reap twice a year in their fields. Unfortunately, the increasingly human disturbances such as grazing and deforestation have severely depleted the forest cover in Caimoluo and Naituo drainage basins. As a result, there are no extensive tree covers except a few scattered small shrubs and herbaceous plants. Water loss and soil erosion are serious in study area.

DEBRIS FLOW INITIATION PROCESSES

Field observation indicates that the debris flow initiation process is similar with a process called "fire-hose effect" (Johnson & Rodine, 1984), when overland flow of water resulting from intense rainfall reaches the base of bedrock slopes, it mobilized the solid material and eroded deep gullies into the heads of the deposits. Base on the field investigations of rainfall, geomorphology, stratum lithology, geologic structure and human activity, the debris flow initiation processes can be described in four aspects.

INTENSE RAINFALL AND HAIL

The hydrometeorologic conditions for debris flow initiation may vary widely. Rainfall intensity, accumulated rain during the storm event and antecedent pre-

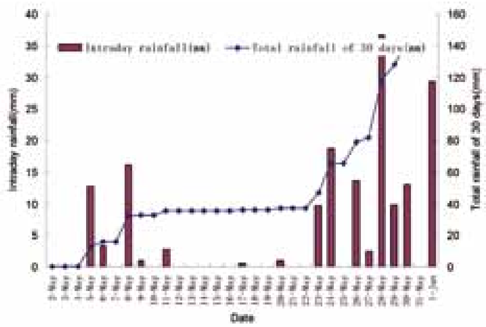

Fig. 2 - Daily and cumulative rainfall during May 2005 recorded at Meigu county station

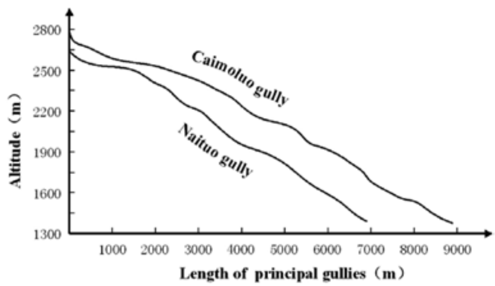

Fig. 3 - Longitudinal profile of the debris flow gully beds

Parameter	Caimoluo gully	Naituo gully
Drainage basin area (km^2)	16.5	8.2
Main channel length (km)	8.2	7.04
Ratio of unstable channel (%)	76.7	69
Incision density (km/km^2)	2.31	3.3
Maximum elevation of the drainage basin (m)	2772	2772
Minimum elevation of the drainage basin (m)	1389	1402
Relative relief (m)	1383	1370
Slope gradient (%)	169	195

Tab. 1 - Morphometric characteristics of both gullies

cipitation are important factors for triggering debris flows (Campbell, 1975). Rainstorm with short duration and high intensity is crucial for the debris flow occurrence within study area. At about 10 o'clock in the night of May 31, hails suddenly struck the upper reach of Caimoluo and Naituo drainage basins. An hour later, heavy rain fell also mixed with hail, the flux of both gullies increased rapidly. Heavy rain kept on about two hours before debris flows occurred. According to the records from meteorological station of Meigu county, on June 1 debris flows occurred, the daily rainfall amount is 29.3 mm and during the past 30 days from May 2 to May 31 before debris flows occurred, the total rainfall was 140.8 mm (Fig. 2).

Rainstorm runoff formed in the upper reach of both gullies, eroded solid materials in the channels and deposits piled up in the lower valley slopes. When slope became saturation, the stability lowered and a series of collapses began to occur, then a great deal of solid material such as gravels, loose soil was engulfed by the floodwater. As a result, at about 1 o'clock on the dawn of June 1, debris flows were triggered.

A shorter gully without name between Caimoluo gully and Naituo gully is worthy to be mentioned whose main channel length is 2.77 km. Base on field investigation, it was found that the unconsolidated materials and topographic are all similar to the study gullies. But there was no debris flow occurrence on June 1. The reason may be that there was not enough rainfall in its drainage basin, especially in the upper reach, because of its shorter length and smaller drainage area. This can be regard as evidence that it was the intense rainfall and hail provided enough water for the debris flows of Caimoluo gully and Naituo gully. In a word, the rainfall and hail with short duration and high intensity was important reason why debris flows occurred.

TOPOGRAPHIC AND GEOMORPHOLOGIC CONDITION

According to on-site measurement by GPS and the topographic map with the scale 1:50000 (Fig. 1; Fig. 3), the topographic and geomorphologic data of Caimoluo gully and Naituo gully can be obtained (Tab. 1). It can be seen that the topography and geomorphology of Caimoluo gully and Naituo gully have two favorable conditions. For one thing, this topographic configuration is conducive to a rapid concentration of runoff, and when combined with intense rains, it can lead to high peak discharge and erosion rates. For another thing, it provides potential energy for debris flows.

STRATUM LITHOLOGY AND GEOLOGIC STRUCTURE CONDITION

The strata in Caimoluo and Naituo drainage basins are mainly Jurassic purple rock, Triassic grey rock and purple rock, Ordovician red sand-shale stone. Though the lithology on both sides of Caimoluo

Fig. 4 - Loose materials on the right slope of Caimoluo gully

Fig. 5 - Landslide surface cracks on the right slope of Naituo gully

gully is the same as that of Naituo gully, the slope characteristic and the supply mode of solid materials are different. The bedrock on left bank of both gullies is exposed, whereas the rocks and soils on the right bank usually fall into the channels in the way of collapse because of the well-developed vertical joints (Fig. 4). For example, a large-scale landslide is located on the right bank in the middle reach of Naituo gully, potato and walnut have been cultivated on the landslide. There are a lot of cracks which are about tens of centimeters width on the landslide (Fig. 5). More and more solid materials fall into the channel in the way of collapse and slide. Therefore, the cracked strata, lithology, as well as geologic structure in Caimoluo and Naituo drainage basins contribute to the debris flow occurrences by providing source materials

UNREASONABLE HUMAN ACTIVITIES

Tens of villages distribute in Caimoluo and Naituo drainage basins such as Yibowo village, Zhazhi village, Naituo village. Local residents mainly live by farming and grazing. Because study area is situate at the district boundary between Meigu and Zhaojue county, the cultural and educational level fall behind and local residents hardly have any protection consciousness for the ecological environment.

Fig. 6 - Serious blocking in the gully bed of Caimoluo gully

The deforestation and farming activities are increasingly serious, which result in the number of trees and bushes is less and less in two drainage basins. As a result, the soils are eroded seriously and the ecological environment is deteriorative increasingly. It is just these unreasonable human activities that accelerate the debris flows occurrence.

Moreover, the houses of local residents and other infrastructures such as electricity and communication facilities were built near debris flows gullies where is the best prone to be destroyed when debris flows dashed out. Therefore, the unreasonable distribution of buildings and constructions is also one important reason why the loss caused by debris flows was so disastrous.

DEBRIS FLOWS CHARACTERISTICS

DRAINAGE BASIN CHARACTERISTICS

A classic debris flow landform includes well-defined starting zones, incised channels, levees, and cone deposits (Zimmermann, 1987). The mid-section consists of a steep, confined channel with relatively steep sidewalls, and often a fan or cone at the lower end where the gully intersects a valley floor (Brayshaw & Hassan, 2009). The ease of identifying gullies, however, is offset by the more complex nature of debris flows frequency and magnitude. For example, some debris flows channels have a U-shaped profile with a flat channel floor and nearly vertical walls, and are flanked by debris-flow levees. While some channels have steep-sided ridge-like levees produced by material tumbled from flows that had a convex upper surface that was higher than the channel walls (Morton *et alii,* 2008).

Both Caimoluo gully and Naituo gully can be obviously divided into source area, transportation area and deposition area, the debris flows are typical gully-type. As to the transportation area, both banks of that

Parameter	Caimoluo gully	Naituo gully
Maximum width of mud trace (m)	14	8
Maximum height of mud trace (m)	2.5	2
Maximum cross section area (m^2)	35	16
Channel gradient (%)	165	219
Velocity of debris flows (m/s)	11.6	10.5
Discharge of debris flows (m^3/s)	404.7	168.7

Tab.2 - Mud trace and dynamic parameters in both gullies

are unstable, especially for the right one. The channels are jammed badly with abundance of solid materials (Fig. 6). As seen in Figure 6, the sidewall of channel exhibits extensive areas of freshly exposed where we can see the red soil, steep to near vertical walls. And there likely was less than 0.5 m material mantle on the surface, which is one of reasons why the solid materials are loose. Therefore, one clear characteristic of drainage basin is that the transportation area is also an important supply source of solid materials, which provide lots of loose materials for debris flows so as to increase the magnitude and damage ability.

As showed in some studies, the channel gradient was the first significant parameter, with steeper channels being more likely to produce debris flow (Cannon *et alii*, 2001; Brayshaw & Hassan, 2009). The mean channel gradients (in degrees and percent slope) for failures that did result in a debris flow were 29±6° and 57±13% (Brayshaw & Hassan, 2009). In Caimoluo gully and Naituo gully, there are steep slope gradient which are 169% and 195% respectively (Figure 3) and perennial flow water in channels, the velocity are 1.3 m/s and 0.4 m/s respectively, the flow are 0.2 m^3/s and 0.02 m^3/s respectively.

RETURN PERIOD CHARACTERISTICS

The occurrence of debris flows is closely connected with many factors, such as topography, geology, soil, vegetation, precipitation, as well as human activities. Some authors think that debris flows events in the high mountain environment cannot be easily correlated with daily precipitation data, it can be assumed that the debris flows are triggered by 20-30 mm of rainfall, probably concentrated in a short time, such as a few hours (Wilkerson & Schmid, 2003).

According to the past documented record, a large-magnitude debris flow ever occurred in 1982 in Caimoluo gully. So we can infer that Caimoluo gully is an lower-frequency debris flow gully, its return period is 20 years approximately. What's more, the loose soil and gravels have been sliding and collapsing on both sidewalls of Caimoluo gully and Naituo gully after debris flows occurred. And the solid materials from both banks fall into the channels constantly and continually. Fractured bedrocks on the sidewalls provide abundant material for the development of debris flows. As a result, both banks in channels were eroded seriously and the riverbed was blocked badly. When the next heavy rainstorm is coming, another debris flow may occur because of the blocking and flood overflowing in the channels. Thus, the debris flows have the further development tendency.

DYNAMICAL CHARACTERISTICS

Base on the on-site survey of mud trace which is a strong evidence of dynamic characteristic, some indexes such as the maximum width and height of mud trace, the maximum area of the cross section and slope gradient were measured (Tab. 2). According to the improved formula which is adopted to calculate debris flow velocity of Dongchuan, China (Chen *et alii*, 1983):

$$V_C=(M_c/a)R^{2/3}I^{1/2} \quad (1)$$

where V_C is debris flows velocity (m/s). MC is channel roughness coefficient. a is collision coefficient, for viscous debris flow, a=0.01~0.02; for turbulent debris flow, a=0.02~0.03. R is hydraulic radius (m). I is channel gradient. The velocity and flow of debris flows in both gullies are calculated respectively. The results are showed in Table 2.

DEPOSITING CHARACTERISTICS

Debris flows have powerful carrying ability and a great deal of large volumes of boulders, gravel, sand and clay can be carried down to the lower reach of gully. Deposits piled up in the gully mouth are called "debris fans" (White, 1981; Madole *et alii*, 1998).

In the study area, plenty of clay, sand, gravels and even boulders were piled up on the gully month, thus two deposition fans were formed. The length, width, and gradient of the fans were measured with equipments and accordingly the volume of run-out deposits was calculated. The results are showed in Table 3. Much of the debris volume reaching the gully mouth comes from materials entrained in channels, the size

Parameter	Caimoluo gully	Naituo gully
Length of deposition fans (m)	210	110
Width of deposition fans (m)	130	90
Gradient of deposition fans (°)	4	5
Volume of deposition fans (m^3)	10.16×10^4	2.44×10^4

Tab. 3 - Deposition fans characteristics in both gullies

Fig. 7 - Large boulder carried by the debris flow in Caimoluo gully

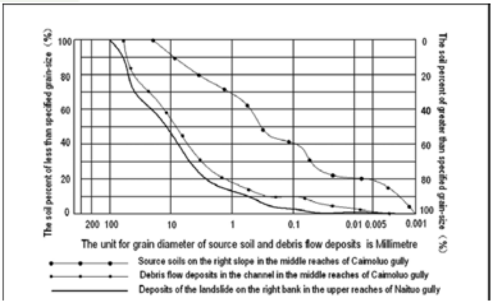

Fig. 8 - Grain-size curve of source soil and debris flow deposits in study area

range from clay to boulder. Huge boulders were carried to near gully mouth by debris flows. The size of the largest one is about 4.5×4×3 m^3 (Fig. 7) in Caimoluo gully and that is about 4×3×1.7 m^3 in Naituo gully.

Debris flow deposits are on unsorted and stratified. Depositing geomorphology mainly are gravel islands, lateral accumulation mounds in channel and surge deposits, fan-shaped gravel deposits on the toe. Other micro-topography could be seen such as the boulder piling up boulder, mud crack, which demonstrate that the debris flows are viscous.

Grain samples are source soils derived from right slope, in-channel debris flow accumulation in the middle reach of Caimoluo gully, landslide earth derived from right bank in the lower reach of Naituo gully, all these were collected and tested by geo-technology in the laboratory. Under the preconditions that the water content accounts for 10% and the density is 1.65g/cm3, the test results of the source soils from Caimoluo gully are as follows: internal frictional angle 31.3º, cohesive force 12 $Kp_{a,}$ liquefaction limit of the viscous grains 33.2%, plasticity limit 19.8% and the plasticity index 13.4. The peak of grain-size distribution curve leaned to right. According to soil texture classification published by the United States Department of Agriculture (Brady, 1974), the weight content of fine silt (0.005—0.002 mm) and clay (<0.002 mm) accounts for 19.3% (Fig. 8). As to the in-channel debris flows accumulation in the middle reach of Caimoluo gully, under the preconditions that the water content accounts for 7.7% and the density is 1.62g/cm^3, the test results are as follows: the internal frictional angle 38.2º, cohesive force 12 Kp_a. The weight content of fine silt (0.005-0.002 mm) and clay (<0.002 mm) is 2.2% and the grain-size distribution curve has three typical peaks appearing on the percentage content of silt, sand and gravel respectively (Fig. 8). The landslide lying in the right bank of the lower reach of Naituo gully was induced by debris flows, and it also provides a great deal of solid materials for debris flows. According to the geotechnical testing on the accumulation of the landslide front, on the precondition that the water content accounts for 7.4% and the density is 1.76g/cm3, the internal frictional angle and cohesive force are 35.8º and 5 Kp_a respectively. The grain-size distribution curve has only one peak (Fig. 8).

DISASTER CHARACTERISTICS

Disaster characteristics of debris flows in Meigu county can be summarized as follows. Firstly, they are different from those of most rainstorm-induced debris flows. There was almost no precedent precipitation the day before debris flows occurred in locality. The debris flows were triggered by rains and hails which fell only two hours earlier before debris flows occurred. Secondly, some large boulders from the upper reach of both drainage basins can be seen on the fans. Thus, it can be inferred that the transport distance of debris flows are as many as several kilometers (Fig. 9). Some trees' rinds were decorticated by debris flows (Fig. 10). So it is clear that the destructive energy of debris flows is powerful. Last but not least, the disaster occurred at midnight and kept on less than half an hour, however, 9 local residents were killed or missed, 8 were injured and great property was lost, as well as buildings, farms,

Fig. 9 - Large boulders carried by the debris flow in Naituogully

Fig. 10 - Big trees debarked by the debris flow in Naituo gully

Fig. 11 - Destroyed house by the debris flow

Fig. 12 - Destroyed communication facilities by debris flow

roads, bridges, communication facilities and hydropower facilities were damaged seriously (Fig. 11 and 12), vegetal cover and surface soil on the slopes and in the channels were washed away by flood, which result in the ecological environment further deteriorated.

CONCLUSIONS AND SUGGESTIONS

Debris flows are significant hazards in mountainous areas, especially in southwestern China. The debris flows in Meigu county were triggered by short-duration heavy rainstorm and hail, the topography, lithology and human activity also play an important role in debris flow initiation. In both gullies, the details of debris flow characteristics can be obtained by a series of field investigation. Multiple evidences such as boulder piling up boulder, mud crack and clay content demonstrate that they are viscous debris flows. The viscous debris flows broke out rapidly and violently, so it has destroyed the houses, farms, roads, bridges, communication facilities and even lead to loss of human life. This is a catastrophe caused by natural hazard, whereas could arose high attention for the whole society.

Historically, debris flows ever occurred in Caimoluo gully and Naituo gully, there are distinct fans trace on the mouth of both gullies and the trail of transport and deposition in the channels. Local residents have little consciousness of the hazards, though they taken precautions against natural disaster, for example, they built a floodwall with the height of 2 meter, unfortunately, the floodwall did not take effect during this catastrophe. Therefore, some technological and civil engineering measurements should be taken into account in order to mitigate debris flows hazards in Meigu county.

Several suggestions can be adopted in the study area from this study case. Firstly, the important interaction between human and natural environment indicates that local residents should improve protection consciousness for the ecological environment, excessive deforestation and farming must be prevented. Secondly, local residents can move out of the dangerous area of the debris flows and the infrastructures should be put in the safe region with finance support by governments. Thirdly, the meteorological monitoring in areas prone to debris flows activity could help predict debris flow hazards. Fourthly, a variety of geomorphic methods, including repeat photography, dendrogeomorphology, lichenometry, plant succession, and stratigraphic analyses, could be employed in the study of debris flows so as to understand the mechanism and process of debris flows better.

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