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A STUDY ON THE PROPERTIES OF THE 12 MAY WENCHUAN EARTHQUAKE-INDUCED DEBRIS FLOW

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ABSTRACT

Debris flows triggered by earthquakes are recognized globally for their huge destructive power. Studies on the development features of debris flow are essential for disaster prevention and mitigation and the results can be used as a scientific basis for assuring public security, preventing debris-flow disasters and reconstructing the afflicted areas by earthquake. Taking the, Niujuan Gully, as the case study area, this paper discusses field observations of the initiation and path of debris flows in the epicentral area of the 12 May, 2008 Wenchuan Earthquake. Based on the natural conditions and debris flow distribution in the study area, a field control network was established to monitor the gully bed, typical slopes and channel sections of different kinds of debris flows that initiated from hillslopes and gullies. We observed debris flows and their change under different rainfall circumstances, surveyed slope, section, channel and gully bed by means of GPS, GPT-3002 total-station instrument and 3D laser scanning system and drew digital topographic maps, sectional maps and profile maps with a 1:50 scale. Based on the observed data, we probed into the erosion laws and development features(including erosion, transportation, deposition, etc) of different kinds of debris flows and analyzed debris flow discharge, erosion-deposition variation and destructive magnitude. The findings provided data support for debris flow risk assessment and monitoring systems.

Key words: *debris- flow, field observation, development feature, Niujuan Gully*

INTRODUCTION

China is among the countries with the most frequent and severe continental earthquake and debris-flow occurrences. Since 1990s the China mainland has experienced many earthquakes and related secondary mountain hazards which were induced by earthquake and named as secondary mountain hazards including debris flows, landslides and rockfalls. These hazards pose tremendous and lasting hazards to life and property. In some afflicted areas these secondary mountain hazards were even more harmful than earthquake itself. The May 12, 2008 Wenchuan Earthquake (Ms=8.0) occurred in the Longmen mountain fault belts at the east edge of Tibetan Plateau and affected more than half of China, with the disaster area covering about 500,000 km^2. The main shock was strong and the intensity at the epicentre reached XI, causing 87,149 dead or missing. The direct economic loss reached 845.14 billion RMB (¥, Chinese money unit and about 6.57 RMB equal to 1 dollar). The earthquake and its continuous aftershocks (more than 30,000 times) severely destroyed the massif of stricken areas and directly triggered large quantities of secondary mountain hazards, including rockfalls, landslides, debris flows, dammed lakes, etc. By means of remote sensing interpretation and field investigation, more than 50,000 sites of rockfalls, landslides, and debris flows and instable slopes were found in 51 severely-afflicted counties, which directly killed more than 20,000 people (Han *et alii*, 2009). The area of potential slope deformation induced by loose massifs reached 150,000 km^2. Because the large number of rockfalls and landslides could carry abundant materials, large-scale debris flows formed due to heavy rainfall, causing more serious soil erosion. With the increasing intensity of stricken-area reconstruction and human activities after earthquake, debris flows will become more and more frequent and serious, lead to massive soil erosion, destroy land and river ecosystem and form an immense threat to the environment, public security, restoration and reconstruction of the afflicted areas. Some research findings exist for the formation and development mechanism of debris flow induced by earthquake in China and abroad (Tamura 1978; Eisbacher & Clague, 1984; Gao & Zhu, 1986; Jiang *et alii*, 1991; Ma & Shi 1996; Li *et alii*, 2001; Liu *et alii*, 2008; Liu *et alii*, 2009). Debris flows in the afflicted areas are widely scattered, form and develop quickly, do great damage and are difficult to monitor, forecast and prevent. Moreover, debris flows develop actively and occur frequently within 5 to 10 years after earthquake (Han *et alii*, 2009). Thus, it is imperative that study on the development and evolution of earthquake-induced debris flow in stricken areas should be strengthened on the basis of existing research achievements and technologies, in order to effectivey mitigate against earthquake-induced debris flows. This paper studies debris flows in the Niujuan Gully, the epicentre of Wenchuan Earthquake, at Yingxiu Township, Wenchuan County, Sichuan province, China. According to debris flow development and movement, the paper identifies earthquake-induced debris flows, explores debris-flow monitoring methodology and data, and analyzes the erosion and sedimentation characteristics of debris flows in the study area and expounds riverbed evolution. The research findings can be used as a scientific basis for preventing debris flows, reconstructing the afflicted areas and assuring key project and public security.

GENERAL SETTING

Yingxiu township in the south of Wenchuan county was one of the most severely-afflicted townships by the May 12, 2008 Wenchuan Earthquake. Before the earthquake, Yingxiu Township was the most developed district on heavy industry in Wenchuan County and the vital communication line in the West Sichuan, named as the South Gate of Aba prefecture. However, it was in ruins except for a few severely damaged buildings after the earthquake. Niujuan Gully, the epicentre of the Wenchuan Earthquake, was selected as the study area which is located in 1,500 meters southwest of Yingxiu Town and at the right side of upper valleys of Minjiang River. The study area, with high mountains, steep valleys, intensive cutting, cracked rock mass, complicated geological structures, and developing faults is prone to rockfall, landslide and debris flow. Large-scale rockfalls and landslides supply abundant loose solid materials for debris flows. Once high-intensity rainfall happens, debris flow will occur on large scale. Debris-flow activities become more frequent following the earthquake and have the tendency of occurring in every gully of study area.

STUDY AREA

NATURAL BACKGROUND

The Niujuan Gully is located in the transition zone from Longmen Mountains to Sichuan Basin, which is in the east edge of Tibetan Plateau and within the main fault belt of Longmen Mountains. The study area is dominated by alpine gorges within the coverage of E103°25′12″-103°28′31″ and N31°01′21″-31°03′16″. It is a vital traffic line, close to Wolong panda protection zone and 78 km away from Chengdu city. The terrain in the study area has a general trend of increasing altitude from south to north, with the difference in relative height more than 1833 meters. This area ranges in altitude ranging from 860-2693 meters and contains Alpine peaks and river valleys. The Niujuan Gully has a total drainage area of 10.46 km^2, an altitude ranging from 860-2693m, 5.8 km of main channel length and a main channel mean slope of 3.16 percent The Niujuan Gully includes 6 branch gullies that include Niujinhang gully, Dao gully, Piaochang gully, Qingshui gully, Bai gully and Lianhuaxin gully. Lianhuaxin gully ,as the epicentre of Wenchuan Earthquake, is 3.77 km long with a average gradient of 3.16 percent, with high mountains, steep slopes and deep valleys (Figg. 1 and 2).

The main active fault belt (Yingxiu-Beichuan Fault Belt) of Wenchuan Earthquake originates in Niujuan Gully, goes through Wenchuan, Maoxian to Beichuan county, inclines to the northwest with

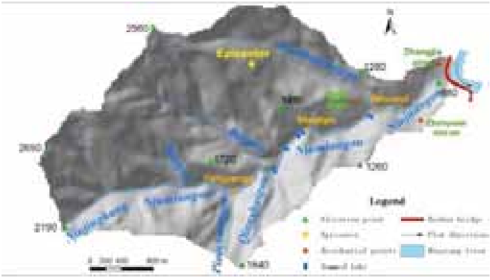

Fig. 1 - Three dimensional digital terrain map of Niujuan Gully

Fig.2 - ADS40 remote sensing image of Niujuan Gully,acquired on May 15, 2008

a strike of 229 degrees and is composed of a series of piezotropy and compression-scissor fractures and folded strata. The geological environment of the study area severely affected by the earthquake is very complex. Moreover, neotectonic movement is very active and the conditions of terrain, strata, lithology, and geological structure have changed greatly. The stratum subjected to rockfall and landslide is widely distributed and consists of heavilyweathered Archaeozoic granodiorite, triassic sandstone of Xujiahe group and surface collapse-landslide clinosol(Han *et alii*, 2009).

The study area is typical of subtropical moist climates and is one of the most rainy areas in West Sichuan with multi-annual mean rainfall 1253.1 mm, annual maximum rainfall 1688 mm, and daily maximum rainfall 269.8 mm. Moreover, precipitation of study area mainly concentrates in June to September, which accounts for 68.2 percent of the annual rainfall. The climate is warm and humid, characterized by raininess, flood and clear seasons. The Niujuan Gully is part of Minjiang River system, which is 50-120m wide, has a large drop height in gully bed, contains plentiful groundwater storage and abundant water yield, and its branches and tributary gullies have a dendritic shape. The Wenchuan Earthquake triggered 5 landslide-dammed lakes in Niujuan Gully. The water supply is mainly recharged from rainfall during flood period and from snowmelt runoff and groundwater during drought season. In the study area, large quantities of secondary mountain hazards were induced by the intensive main earthquake and aftershocks. In the rainy season, debris flows occurred more frequently and caused large-scale soil erosion and damage to the ecological environment of study area. By means of remote sensing interpretation and field investigation, it was estimated that the area of soil erosion in Niujuan Gully was about 3.52 km^2, which accounts for 33.7% of the total study area. All of the soil erosion in the study area was due to gravity driven processes and the total soil erosion reached 201,000,000 kg/a

SOCIO-ECONOMIC BACKGROUND

There were 2 townships, 3 villages and 5 villager teams (a part of village and the smallest administrative unit), that is, 2 villager teams of Zhangjiaping village, Yingxiu Township as well as 2 villager teams of Caijiagang village and 1 villager team of Hejiashan village, Xuankou Township. Most of the people in study area consist of a rural population of Han Chinese and Tibetan people. Wenchuan Earthquake did fatal socio-economic damage to the study area. Before earthquake, Zhangjiaping village had two villager teams, 105 households, 389 people, with one acre of farmland acreage per person. The annual per capita income was ¥6000-7000, and on livestock consisted of about 5 pigs per household and more than 1800 sheep. However, the earthquake caused 52 deaths, and 120 injuries, collapsed houses, destroyed homes and arable lands, and only 90 sheep survived. Caijiagang village had two villager teams, 68 households and 279 persons before the earthquake, with 0.5 acres of farmland per person, an annual per capital income of ¥1000, an average of 2 pigs and 5 chooks per household and more than 300 sheep. The earthquake caused 16 deaths and, 48 injuries, destroyed more than 100 acres of farmland, killed about 10 percent of the livestock, and collapsed houses and schools.

DEBRIS FLOWS IN STUDY AREA

The study area was the epicentre of Wenchuan Earthquake and it was severely affected by intense ground motion which caused mountains to collapse, the earth to fracture and rock-soil mass to crack, and greatly changed geologic environment of study area. The earthquake triggered exceptionally serious secondary mountain hazards including ground fracture, collapse, landslide and debris flow. Additionally, the earthquake and secondary mountain hazards created abundant loosely consolidated materials and landslides formed 5 dammed lakes in the mid-lower reaches of Niujuan Gully, which potentially induced large-scale debris flows due to intense rainfall during the rainy season. Seven large-scale debris flows occurred on 2008-5-12, 2008-6-27, 2008-9-29, 2008-10-14, 2009-8- 22, 2010-7-15 and 2010-8-14. The first large-scale debris flow occurred during the Wenchuan Earthquake at 14:28 pm, May 12, 2008. The earthquake accelerated a landmass at 1.5g in the Lianhuaxin gully, 1km to the northwest of mouth of Niujuan Gully. Then the disturbed landmass and landslides turned into high-speed debris flows, which traveled more than 70 m/s, increased in size by a factor of four, and formed a remarkable path that travelled 3.2 km long and 700m vertical. In the mid-lower reaches of Lianhuaxin gully, from Feiyuzui waterfall to the mouth of Niujuan Gully, the debris-flow deposit was composed of riprap rocks mingled with clastic soils and had a volume greater than 4,000,000 m^3 that was approximately 1,100 m long, 80-100 m wide in channel bed and 40- 60 m thick. In the upper reaches of Lianhuaxin gully, from Feiyuzui waterfall to the effusive site, the debris-flow deposit was mainly composed of fine grained sediment mixed with gravels and had a volume greater than 3,500,000 m^3 that was approximately 2,100 m long, 50-80 m wide in channel bed and 20-40 m thick. Thus, abundant solid materials provided large quantities of source material for rainstorm-induced debris flows. The 6th large-scale debris flow occurred on July 15, 2010. It was triggered by intense rainstorm with 132 mm rainfall in 45 minutes. The maximum discharge of this debris flow was 12,173 m^3/s, the velocity reached 9.7 m/s, 600,000 m^3 of material were transported and channel deposits were about 420,000 m^3. The biggest particle diameter is 9.3 meters, with a volume of 421 m^3 and a weight of approximately 1,120,000 kg in the channel bed. The largest particle diameter in the debris flow fan was 6.8 meters, with a volume of 165 m^3 and a weight of 438,000kg. The geologic conditions, tremendous influence of Wenchuan Earthquake and intense rainfall were the main factors causing debris flows in study area.

DEBRIS FLOW MONITORING

MONITORING AIMS

According to the distribution and motion features of debris flows in study area, different slopes, properties and types of debris flow material and main gullies were selected as monitored objectives. Combined with the natural environmental background of the study area, a network of field observation locations and monitoring stations were set up. We used modern surveying and mapping technologies to observe the distribution and motion characteristics of debris flows, changes to the gully and channel bed geometry, to draw large-scale digital topographic maps, and to create a three-dimension digital elevation model. Based on these data collected, we could study the erosion, movement, transportation, and material of the debris flow, explore into debris-flow characteristics and channel evolution, quantitatively analyze the debris-flow path and deposit, and to estimate the mechanism of debris-flow transport and channel evolution. These findings can provide scientific basis for comprehensive studies on earthquakeinduced debris flows, for quantitative assessments of debris-flow erosion and deposition, and for disaster mitigation and risk management.

MONITORING METHODS

Debris flows are not only characterized by being dense and having high velocity, large discharge, short duration and wide range of particles, but also by the ability to transport sediment and erode and deposit material. Therefore, debris flows can carry large quantities of sediment into channel in very short time, which causes river channels that have evolved for a long period to suddenly change (Cui *et alii*, 2006). In this research, the zone where debris flows initiated from Lianhuaxin gully to the mouth of Niujuan Gully was selected as the monitoring objective. The GPS monitoring control network, traverse control network, levelling network and debris-flow observing sections were established within the 1,300 m by 110 m debris-flow path and include the debris-flow initiation zone, transport zone and deposition zone (Fig. 3). Different types of slope and gully debris flows were selected and monitoring stations were set up along the channel bed and debris-flow slopes. Global position system, GPT-3002 total station, SDL30M precise level gauge, 3D laser scanning system and other surveying instruments were utilized to survey the slopes, sections, gully, and

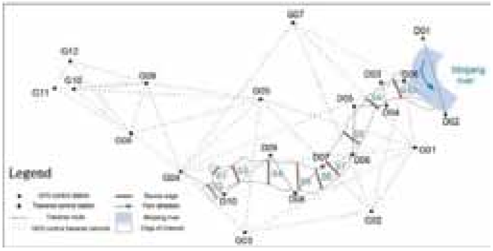

Fig. 3 - Layout of field monitoring control network, stations and sections of study area

	Horizontal	Vertical
RTK positioning accuracy	±(1cm+1ppm)	±(2cm+1ppm)
Post static processing accuracy	±(2.5mm+1ppm)	±(5mm+1ppm)

Tab. 1 - Accuracy index to GPS

Instrument	Accuracy	Measurement range(km/p)
GPT-3002 total-station	±(2mm+2ppm·D)	3.0/1P
GPT-3002 total-station	±3mm+2PPMD/NP	0.25/NP

Tab.2 - Accuracy index to GPT-3002

ISO :	20 im + 25 im/m
Accuracy :	maximum 50 μm (0.002 in)
Depth of field(scan) :	30 cm (12 in)
Z-axis resolution :	0.1 mm (0.004 in)

Tab. 3 - Accuracy index to 3D laser scanning system

channel bed of the debris flows at each monitoring station and for different triggering rainstorms. The methods for monitoring debris flow included 3-5 year long-term observation, quarterly regular observation and emergency observation for debris flow occurrences. According to field observation data, 1:50 scale digital topographic maps, profile maps and cross sections were drawn to study the features of debris-flow erosion, initiation, transport and deposition and to probe into erosion-sediment change and activities of the gully bed. The technological procedure for monitoring debris flow is indicated in Figure 4 and corresponding accuracy index is indicated in Tables 1,2,3.

MONITORING CONTENTS

GULLY MONITORING

Two debris flows that occurred on August 22, 2009 and July 15, 2010 were monitored. Scanning was done using a 3D laser scanning system and concentrated on monitoring sediment level, flow depth and accumulating scope and volume of debris flows in the deposition zone of the main gully. By means of a GPT-3002 total station instrument, 1:50 scale digital topography

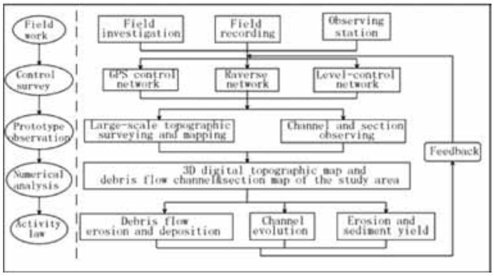

Fig. 4 - Technological procedure of monitoring debris flow

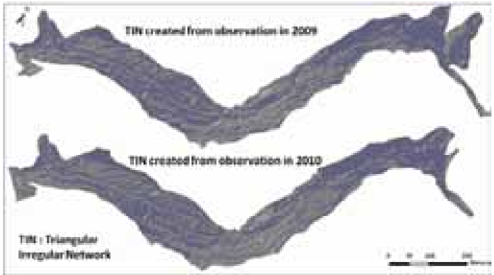

Fig. 5 - Digital elevation models from observed data of two debris flows on August 22, 2009 and July 15, 2010

was surveyed and mapped on gullies and their two side slopes at 0.2m observing intervals. Then the above observation data were input into geographic information system (ArcGIS 9.2 issued by ESRI comp.) to create a high-resolution digital elevation model (Fig. 5). By spatial overlay analysis, we can monitor the erosion and sedimentation of debris flows in the deposition zone and the evolution features of gully bed and even determine the influence of debris flows on topographic features of gullies and the sediment-transport capacities.

SECTION MONITORING

According to the motion features, gully location, gully bed slope and gully width variation of debris flow, 10 channel sections were installed and 28 field stations for observation were selected. Sectionpositioned points were marked out respectively in the upper, middle and lower reaches of the debris-flow gully. By utilizing a GPT-3002 total station instrument, field observations were conducted on sections of gully bed at 0.3 m intervals. The digital profile of every observed section in the gully bed was created from the observed data. By contrast with the two series of debris-flow gully profiles on August 22, 2009 and July 15, 2010, we monitored gully bed variation at every observed

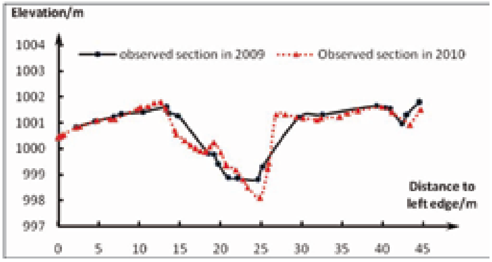

Fig. 6 - Chart of debris-flow erosion and sediment at S1 section

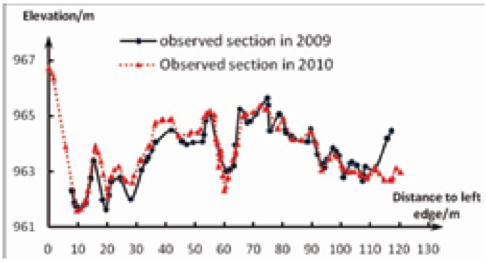

Fig. 7 - Chart of debris-flow erosion and sediment at S4 section

section, analyzed the erosion, sedimentation, and development of gully, and explored the role of the debris flow on the topographic evolution of the gully.

RESULTS AND ANALYSIS

GULLY EROSION AND SEDIMENTATION

Earthquake-induced debris flows showed erosion and deposition in the mid-lower reaches of gully, which changed the debris-flow paths and gully topography. It is necessary to note that the erosion and deposition of debris flow in different zones along the upper, middle and lower reaches of gully is complicated and varies for each section. According to continuous observations of 10 selected sections in Niujuan Gully, we calculated the parameters of debris-flow erosion and deposition within a certain section of gully at a certain time and further discuss erosion-deposition features of the upper, middle and lower reaches of gully.

EROSION AND DEPOSITION IN THE UPPER REACHES OF GULLY

Section S1 (abbreviated to S1) was selected to analyze the erosion and deposition features of the debris flow in the upper reaches of gully. As shown from Figure 6, in 2009, S1 was eroded and deposited to a moderate extent with net erosion .The left side, middle part and right side of section S1 were eroded to a width of 10 m and to an average depth of 1.9 m with a maximum depth of 2.1 m. The left side and right side exhibited lesser deposition, with accumulated sediment thickness of 0.4 m. In 2010, erosion and deposition occurred at S1 with net erosion. The left side and middle part of S1 continued to be cut downward in a “V” shape with a maximum erosion depth of 3.4 m and the gulch widened further about 4m. The middle-left side and middle-right part exist smallamplitude sedimentation with the average relative sediment thickness 0.9 m, with the maximum sediment thickness being 1.3 m deep. By comparison of observations in both 2009 and 2010’s at S1, the earthquake-induced debris flows carried tremendous amounts of loosely consolidated materials, violently eroded and deposited material in the upper reaches and have the general trend of erosion. Furthermore, the magnitude of debris-flow erosion and deposition increases as debris flow activity and scale increase in 2010.

EROSION AND SEDIMENTATION IN THE MIDDLE REACHES OF GULLY

Section S4 (abbreviated to S4) was selected to analyze the erosion and sedimentation features of debris flow in the middle reaches of gully. As shown from figure 7, in 2009, material was eroded and deposited at S4 to a moderate extent with erosion. The left and middle parts of section S4 exhibited intense downward cutting and erosion with a maximum erosion depth of 2.6 m. The right side of S4 was also eroded with a maximum erosion depth of 1.2 m. The middle-right part and right side of S4 were dominated by moderate deposition with an average accumulated deposit thickness of 0.8 m. In 2010, material at S4 was eroded and deposited to larger extent and still displayed net erosion. The middle part and right side of S4 suffered more intense erosion and continued to be downward cut into a “V” shape with a maximum erosion depth of 2.1 m. The middle-right part of S4 also exhibited smaller-amplitude erosion with an average relative erosion depth of 0.3 m; while the left edge of S1 extended outward 8.1 m and up to 4.4 m of material was deposited. From these observations we can deduce that the magnitude of erosion and deposition is controlled by the scale, discharge, and velocity of debris flow. Small-scale debris flows result in lesser erosion and deposition. On the same scale, the erosion and sedimentation of debris flow in the middle gully is larger than that in the upper reaches of gully.

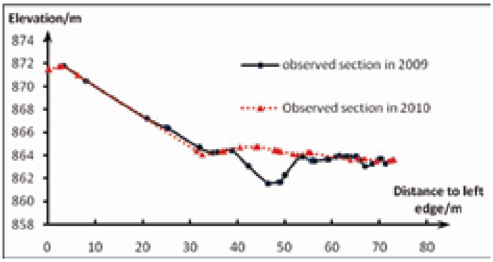

Fig. 8 - Chart of debris-flow erosion and sediment at S9 section

EROSION AND SEDIMENTATION IN THE LOWER REACHES OF GULLY

Section S9 (abbreviated to S9) was selected to analyze the erosion and deposition features of the debris flow in the lower reaches of the gully. As shown from figure 8, in 2009, material in S9 was eroded and deposited to a large extent with net deposition. The left side of section S9 was characterized by significant deposition with maximum deposition thickness of 5.9 m. The middle part of S9 suffered from sharp erosion and produced a gulch with an average erosion depth of 2.2 m and a maximum erosion depth of 4.5 m. The right part of the gully also showed erosion with an average erosion depth of 1.8 m. In 2010, the magnitude of debris-flow deposition in the lower reaches of the gully increased with the scale of the debris flow. The left and middle parts of section S9 exhibit deposition with an average relative deposit thickness of 0.8 m and a maximum relative deposit thickness of 3.8 m. The magnitude of erosion on the right side also increases with debris-flow magnitude with the accumulated erosion depth of 0.4 m. The result shows that the erosion and deposition in the lower part of gully is most affected by the magnitude of the debris flow. When debris flows occurs on a small-scale, erosion and deposition magnitude are also small and for large-scale debris flows, the magnitude of erosion and deposition is large. Generally, the debris flow had a trend of deposition. In addition, at S9, when the debris flow traveled along one side of channel, sediment accumulated in the middle of the gully, heightening the channel bed and pushing successive debris flow material to the opposite side. This action eroded the gully bank and transferred the channel bed to the opposite bank to form an inclined channel bed with one bank higher than the other.

Section S9 (abbreviated to S9) was selected to analyze the erosion and deposition features of the debris flow in the lower reaches of the gully. As shown from figure 8, in 2009, material in S9 was eroded and deposited to a large extent with net deposition. The left side of section S9 was characterized by significant deposition with maximum deposition thickness of 5.9 m. The middle part of S9 suffered from sharp erosion and produced a gulch with an average erosion depth of 2.2 m and a maximum erosion depth of 4.5 m. The right part of the gully also showed erosion with an average erosion depth of 1.8 m. In 2010, the magnitude of debris-flow deposition in the lower reaches of the gully increased with the scale of the debris flow. The left and middle parts of section S9 exhibit deposition with an average relative deposit thickness of 0.8 m and a maximum relative deposit thickness of 3.8 m. The magnitude of erosion on the right side also increases with debris-flow magnitude with the accumulated erosion depth of 0.4 m. The result shows that the erosion and deposition in the lower part of gully is most affected by the magnitude of the debris flow. When debris flows occurs on a small-scale, erosion and deposition magnitude are also small and for large-scale debris flows, the magnitude of erosion and deposition is large. Generally, the debris flow had a trend of deposition. In addition, at S9, when the debris flow traveled along one side of channel, sediment accumulated in the middle of the gully, heightening the channel bed and pushing successive debris flow material to the opposite side. This action eroded the gully bank and transferred the channel bed to the opposite bank to form an inclined channel bed with one bank higher than the other.

GULLY BED EVOLUTION

EROSION AND DEPOSIT OF GULLY BED

In alpine gorge areas, earthquake-induced debris flows that carry abundant loosely consolidated materials will be triggered by intense rainfall and have strong kinetic energy and intense erosion and deposition. Therefore, such debris flows often remarkably change the topographic features of gully and gully bed, lead to gully erosion and deposition, and cause the gully to change its course. The August 22, 2009 debris flow was large scale event that rapidly moved along the middle to left side of the gully bed and eroded the gully to be 5.2 m wide and 2.6 m deep. Meanwhile, large quantities of loosely consolidated materials with 0.12-0.35 m grain size were produced from this debris flow and deposited in different parts of the gully and gully bed. Accompanied by a flash flood, the July 15,

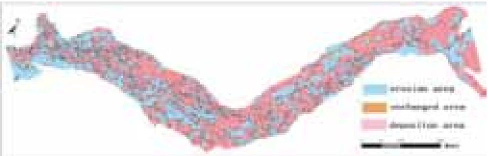

Fig. 9 - Gully erosion and sedimentation caused by debris flows in 2009 and 2010

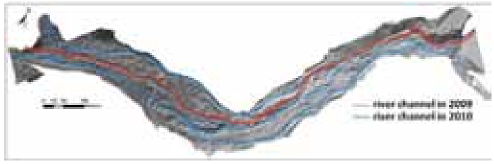

Fig. 10 - The evolution of gully channel configuration caused by debris flows in 2009 and 2010

2010 debris flow was a larger scale event that more intensely eroded and deposited material. By drawing a comparison between debris-flow observations made in 2009 and those in 2010, we can obtain the following results (Fig. 9).

With the increasing amplitude and scale of the debris flow in 2010, the gully bed was eroded more significantly. The area of gully erosion amounted to 55,989 m^2, which accounted for 76.54 percent of the gully bed area. The total volume of loosely consolidated materials eroded from the gully reached 78,919 m^3 and the mean erosion depth was 1.41 m. In parts of gully bed, the maximum local erosion volume was 10,379 m^3 and the maximum mean erosion depth was 2.54 m. In general, the whole gully was eroded to different degrees, but the upper and middle reaches of gully were the most eroded.

With the increasing magnitude of debris flows in 2010, the magnitude of debris-flow deposition increased. The area of gully bed deposition amounted to 10,121 m^2, which accounted for 13.84 percent of the gully bed area. The total volume of loosely consolidated material deposited in the gully reached 15,143 m^3 and the mean deposit thickness was 1.57 m. In parts of gully bed, the maximum local deposit volume was 9,827 m^3 and the maximum mean deposition thickness was 3.34 m. In general, variability exists in the amount of deposition in the whole gully, but the two sides and lower reaches of gully exhibited the most deposition.

There were still fragmentary unchangeable parts of gully without debris-flow erosion and sedimentation and its total acreage amounted to 7,041 $m^{2,}$ accounting for 9.62 percent of the total area of gully bed

GULLY-BED CONFIGURATION

When the debris flow travelled through a gully, it considerably changed the gully-bed and channel configuration (Fig. 10). However, the evolution of channel configuration was affected by water and sediment conditions of main gully, debris-flow magnitude and velocity, gully bending characteristics and gully-bed boundary conditions. Under different circumstances, the channel of the gully may take different shapes, including a single channel as a debrisflow route, double channels with two debris-flow routes and wandering channels with multiple debris-flow routes.

On August 22, 2009, the heavy rainstorm occurred at Niujuan Gully, caused a flood and triggered large-scale debris flows. The flood was retained by 5 dammed lakes in the upper-middle reaches of main channel. Short of flood action and influence, the debris flow occurred on a large scale, was limited to the narrow and steep channel, ran rapidly and accelerated continuously. When entering into the channel bed of main gully, the debris flow eroded and deposited material in the main channel under immense tractive forces of loose solid substance and created a single channel configuration. On July 15, 2010, an exceptional rainstorm happened at the study area, formed a flash flood, and triggered a larger-scale debris flow. The flash flood destroyed 2 dammed lakes in the upper reaches of main gully and caused a catastrophic flood. This flash flood and debris flow massively eroded and deposited material along the channel bed and created a wandering channel configuration..

DISCUSSION AND CONCLUDING REMARKS

The preliminary study on the features of earthquake-induced debris flow suggests a number of conclusions that can be summarized as follows:

Special geologic conditions including topogography, geology, climate, hydrology, land use, vegetable and so on, tremendous influence of violent earthquake, and intense rainfall are the main factors that contribute to debris flow occurrence. Debrisflow initiation and gully evolution can be successfully monitored using modern surveying and mapping technologies, including GPS, GIS, total station, 3D laser scanning system and spatial analysis.

Earthquake-induced debris flows are characterized by intense erosion and deposition and the magnitude of erosion and deposition has a close bearing on debris-flow scale, gully location and channel configuration. Erosion and deposition occurs in the upper reaches of the gully with a general trend of mid-small scale erosion. Deposition and erosion occurs in the middle reaches of gully with a general trend of deposition. Erosion and deposition occur in the lower reaches of the gully with a tendency of strong deposition. Meanwhile, the magnitude of erosion and deposition along the gully become larger with the magnitude of the debris flow.

The channel and gully-bed configuration is changed remarkably and influenced by water-sediment conditions of the main gully, debris flow magnitude and velocity, gully bending characteristics and gully-bed boundary conditions. Different sized debris flows have different effects on the channel and gully bed, and create different gully configurations. Large-scale viscous debris flows, bearing less water, produces the sole channel configuration and the channel bed has a general tendency towards deposition. Under the action of great flood, non-cohesive debris flow often generate wandering multi-route channels and the channel bed has a general tendency of intense erosion and sedimentation, even with hundreds of thousands cubic meters of sediment at a scene.

The most active and frequent debris flows occur withinfive to ten years following an earthquake. Therefore, in order to understand and prevent debris flows, it is imperative to study the initiation and characteristics of earthquake-induced debris flows and to make field monitoring measurements and risk assessments of debris flows.

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