Hazard mechanism analysis of Taoguan giant debris flow in Wenchuan earthquake area on 10 July, 2013

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Abstract

The giant debris flow was caused by heavy rainfall in Taoguan gully, in Wenchuan Earthquake area on 10 July, 2013. The authors have done field investigation and experiments to analyze the loose materials, rainfall and terrain conditions of the Taoguan gully, and studied the process of startup flow and deposition of the debris flow. The result shows that the damage of the rock mass triggered by earthquake in the gully is the root cause of such frequent debris flow after the earthquake. Its Mechanism is actually the startup and superposition of loose materials from avalanche and landslides, and deposits on slopes and in the gully. From the development trend, the Taoguan debris flow is now on a high-frequency developmental stage, and the possibility of breakout of large scale debris flows still exist.

Key words: Taoguan gully, debris flow, loose material shattered by earthquake, rainfall, Wenchuan earthquake region

1. Introduction

As one of the major performance of geological disasters, debris flow usually threatens human lives and foundational engineering facilities seriously in a long period after earthquake. According to incomplete statistics, there were 2,333 debris flows breaking out in the Wenchuan earthquake area from 2008 to 2012, tripled with the number before the earthquake from 2003 to 2007 (Huang and Fan, 2013). The strong disturbance on the earth's surface by earthquake changed the forming conditions of debris flow, for instance the loose materials, micro-topography and hydrological conditions has changed (Cui et al, 2010). Tang et al.(2009) contrasted the rainfall data when debris flow break out in Beichuan before and after the earthquake, and found that the cumulative rainfall and the stimulate rainfall intensity reduced by 15%~22% and 5%~31% compared with the data before the earthquake. The rainfall threshold for debris flow to breakout reduced sharply after the earthquake, and the shaking loose effect made water, rock and soil came to coupling state easily, leading to frequent and crowded outbreaks of debris flows (Huang and Fan, 2013). The Wenchuan earthquake produced about 4×10^9 m^3 loose material in the earthquake area, and the average annual sediment of debris flow is about $1.8\times10^8 m^3$, it is speculated that the debris flow will keep active within the next 20 years after the Wenchuan earthquake.

On July 10-11, 2013, the Wenchuan to Yingxiu section of Du (Dujiangyan City) -Wen (Wenchuan City) freeway broke out mass of large debris flow disasters again after "Aug 13th, 2010" and "Aug 19th, 2012" debris flow, which made the Taoguan gully, became the worst-hit area in the section. The debris flow gripped huge amount of solid material along the way after its start, and destroyed 3 check dams and 5 sabo dams, the dams were filled up in most parts of the situation, some dams were even washed out. The debris flow formed an accumulation area whose width is from 80-100m, and the average thickness is 5m in the range of 3km from the accumulation fan. The estimated total amount of the output material is up to $1.1\times10^7 m^3$. Unfortunately, there are about 10 households of enterprise of Wenchuan industrial park in this section, large amount of sediment washed away and buried 8 factories and completely buried a power plant, and threats 696 people's lives and 192 households' belongings, the direct economic losses is up to about 32 million USD (Fig. 1).

Fig.1 Distribution of industrial enterprises and residential areas on depositional segment of Taoguan gully after Wenchuan earthquake

Taoguan gully is one of the most representative large scale debris flow in the upper reaches of the Minjiang River before Wenchuan earthquake according to historical records. In the early morning of May 12, 1890, Taoguan gully broke-out a debris flow and caused to a death of thousands of people among about 300 households, only a few people survived. This event was named "Water-washed Taoguan" in historical records. This area also suffered disasters in 1960, 1982 and 1992 in later years (Wang et al., 2003).

The field investigation and tests of the Taoguan debris flow in "7 July, 2013" and the reveal of the mechanism and develop trend of the debris flow will be useful for a better understanding of the forming mechanism and characteristics of debris flow in earthquake area. They can provide early warning for the earthquake area such as Wenchuan, Lushan and Ludian in southwest China, and can also provide guidance for the design of countermeasures and provide a scientific basis for risk assessment.

2. The geological environment conditions of the study area

Taoguan gully which locates in Yinxing township in Wenchuan County belongs to the tributary on the left band of the Minjiang River, the area of the basin is 50.8 km^2(Fig 2 and Fig 3). A large number of residential and industrial park located in the accumulation fan of the gully, the Du-Wen freeway and G213 state road across the area in the form of bridge. The Taoguan gully locates in the Jiuding mountain Cathaysian tectonic belt of the southern section of the Longmen mountain Cathaysian tectonic belt in regional condition, it also belongs to the middle zone between Yangtze platform and Sonpan-Ganzi synclinorium. The Maowen fault is the main regional tectonic fracture in the region, whose direction is between 30-45° and the dip angle is between 45-82°. The Jinning period igneous rocks exposes in the strata of the region, and all kinds of Quaternary loose accumulation covers surface of a portion of the slopes.

The Taoguan gully had been deeply cutted and eroded, there are lots of high mountains and steep slopes in the basin. The highest elevation of the basin is 3903m, and the lowest elevation is 1002m, and the relative elevation is 2901m. The gully's shape is as similar as a sector, the main channel's length is about 14.2km and there are lots of ditches in the gully. The main gully's average inclination is 197‰, and the slope gradually decrease from 421‰ in the source of the gully to 61‰ in the accumulation fan of the gully. The cross section of the valley type conversion from "V" in the upstream to "U" in the downstream. The valley's slope is so steep that the water flowing fast and fluctuate rapidly.

The climate of the Taoguan gully belongs to north subtropical humid climate which has little and uneven rainfall. The average annual precipitation is 1253.1mm, the maximum annual precipitation is 1688mm (in 1964) and the minimum annual precipitation is 836.7mm (in 1974). The largest continuous 4 months (from June to September) precipitation is 853.2mm which accounting for 68.2% of the annual rainfall. According to the "Rain and flood calculation manual of small basin in Sichuan Province", Taoguan gully's maximum precipitation in 10min is 10mm, 20mm in 1hour and 90mm in 24hours.

Fig.2 Geographic location map of Taoguan debris flow

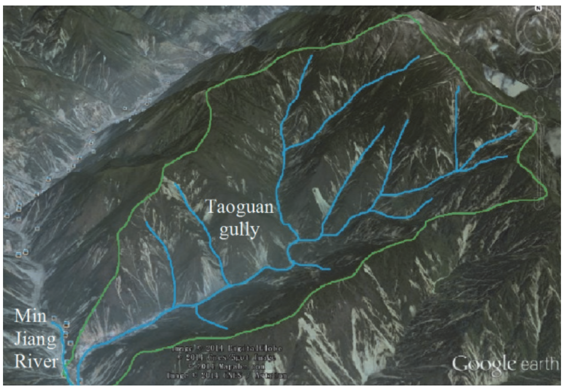

Fig.3 Schematic diagram of Taoguan debris flow basin (citation from Google Earth)

Taoguan gully has broken out many debris flows in 1890, 1960, 1982 and 1992 according to relevant data. Before "the 12 May" Wenchuan earthquake in 2008, the loose materials in the basin main was mainly comprised of the deposits distributed in slopes and ditches, there are rarely channel blockings and the loose material is hard to startup. But the earthquake induced lots of avalanches and landslides in the basin, it is estimated that there are $2.799\times10^8 m^3$ loose materials in the gully by field investigation in July 2013. For example, there is a landslide (whose volume is about $4.2\times10^5 m^3$) induced by earthquake blocked the channel and formed a quake lake at a distance of 6km from the accumulation fan. These avalanches and landslide loose materials provide sufficient sources to the outbreak of debris flow subsequently.

3. Analysis of the forming conditions of the Taoguan debris on July 10th, 2013

A large number of avalanches and landslides which induced by earthquake in the basin provide lots of loose material for the outbreak of debris flow. This is the most significant feature of the forming condition of debris flow in earthquake area.

3.1 Rainfall condition

The rainfall data that was measured in Mianci town weather station in Wenchuan before and after the debris flow show that the precipitation in the region is heavy on 8 to 10 July, 2013. The accumulative precipitation is 67.3mm in the first two days and the precipitation on 10th is up to 104mm in north slope, The Taoguan gully is near it and locates in the south of the mountain. Since the rainfall usually increases with the altitude, it can be inferred that the accumulative precipitation in the Taoguan gully is more than 67.3mm and the stimulating precipitation is more than 104mm in 10th.

Obviously, the rainfall that induced the debris flow which broke out in "7.10th" ought to be heavy, long lasting and intense. According to previous research (Tan et al., 1992), the critical rainfall of debris flow in Longmen mountain area is 80-100mm and the rainfall in one hour is 30-50mm. The rainfall condition could be completely satisfied compare to the precipitation in Taoguan gully.

3.2 Loose materials condition

The field investigation found that there are 100 sites of avalanches and landslides triggered by earthquake in Taoguan debris flow basin (Fig. 4 and Table 1), there are about $4.75\times10^7m^3$ loose materials that provided by the avalanches and landslides in the basin and it is estimated that 29.5% ($1.4\times10^7m^3$) of them could start up. There are $1.856\times10^8m^3$ of loose materials provided by sediment provenances distribute among 18 channels and branches in the basin in addition, $1.46\times10^7m^3$ (7.9%) loose materials among them could start up. Besides, there are $4.68\times10^7m^3$ loose materials that provided from 32 slopes and $1.28\times10^7m^3$ (27.3%) among them could start up. The total volume of the loose materials is about $2.80\times10^8m^3$, 14.8% ($4.14\times10^7m^3$) among them could start up. It is also found that a kind of loose material that should pay attention to the loose rock mass was shattered by earthquake, which is distributed in the primary and secondary parts of the watershed. This kind of rock mass can't be classified in to the loose material in general, but parts of the shattered rock mass eroded and started to participated in the debris flow indeed.

Viewed from the distribution of material resources, there is no concentrated trend obviously, for the material usually distributed in each branch gully and the main gully. Overall, the material resources of the upper and lower Taoguan gully is more than that in the Gaoyan gully whose has a volume of 5.86 million m³. The volume of loose materials in the upper Taoguan gully is 7.92 million m³, while it in the whole gully is 14.21 million m³.

The loose material resources especially the avalanche and landslide deposits increased a lot after the earthquake. The loose material causes blockage to the gully, which increases the potential startup volume of sediment source in gully. These provided an advantage for the burst of the mega Taoguan debris flow on 10 July.

3.3 Terrian condition

The shape of Taoguan debris flow in plain view is approximately like a banana leaf about 50.86 km² in area. The branch gully is well developed, and the longitudinal gradient of gully is up to 197‰. The area of upstream water zone whose has an area of 21 km² takes 41% of the total area of the valley, and it scatters in the upstream of Lannitang gully(bottom elevation above 2300m), the upper and middle reaches of the Dahongyan gully(bottom elevation above is 2330m), the upper and lower Feishuiya gully(the intersection and bottom elevation above is 2400m), the upper and middle reaches of the Tongpengzi gully(bottom elevation above is 2400 m) and the upper reaches of the Gaoyanwo gully(bottom elevation above is 2650 m). This area has a large longitudinal gradient about 350‰~550‰ generally, and the valley here is like a narrow "V" in shape, which provides favorable terrain conditions for the surface runoff and the startup of debris flow. The longitudinal gradient of middle reache is relatively steep, and the form of valley turns from the shape of "V" to "U", the width of bottom usually up to 30~100m. The gradient of both sides of the slope is steep, part of the section (such as the Lannitang downstream) presenting steep cliffs, which provides favorable deformation space for avalanche and landslide.

Table 1 Statistics about different types of loose materials in Taoguan debris flow basin

Kinds of materials	Total materials /million m³	Dynamic reserves / million m³, Ratio of total materials（％）	Basic characteristics
Avalanche and landslide	4.75	1.40, 29.5	Up to 100 points in all kinds of size along the gully, in which 12 points are over 0.1 million m³
Overland deposits	4.68	1.28, 27.3	The deposits early distribute on the slope and along the gully channel, and the causes of the formation are various.
channel deposits	18.56	1.46, 7.9	The deposits distribute along the gully channel early and recently
Total	27.99	4.14, 14.8	Estimate dynamic reserves according to the natural repose angle, erosion modulus of slope and the depth of erosion of the gully

Because of the down-cutting and washing, steep terrain provides a good dynamic condition for the flood's strongly erosion on the slope and loose debris on gully bed. The length of downstream valley is about 4 km, gully width increasing obviously up to 60~130m with a "U" shape, the longitudinal gradient is between 60~90‰, which is conducive to balance and priority to siltation.

4. Forming mechanism of "7.10" debris flow

4.1 Characteristics of outbreak and movement of the "7.10" debris flow

According to field investigation, at 4 to 5 a.m on 10 July, 2013, debris flow firstly broke out under the cross of Lianghekou. To 6 a.m, No. 1 branch of Taoguan Gully firstly buried the water plant locates in the upside of industrial park, blocking the main valley, making the main gully back silting and buried hydropower station. After the barrier dam broken, the debris flow flowed down through 2 km factory district, to the nearest Zhongyang silicon industry Shunxin at 8 a.m. on 10 July, continuing flow down 500 m to the residential area at 8 to 9 a.m. on 10 July. The duration of the first stage of debris flow below the cross of the Lianghekou is about 2 to 3 hours.

According to the sections of mud marks, the peak flow of the debris flow was about 430 m^3/s. At 10 to 11 a.m. on 10 July, massive debris flow going through the cross of Lianghekou locates in the middle of the gully (second wave), arrived at the factory at 12 noon. According to mud marks of the Lianghekou, the peak flow of the debris flow was about 280 m^3/s.

From the above, although there is a gap between two wave of the debris flow, it shows that the Taoguangou debris flow on 10 July has characteristics of long duration, the different peak propulsion and gustiness flow. Taoguangou debris flow is bounded by the cross of Lianghekou, and the outbreak time of the section below Lianghekou was earlier than the section above Lianghekou.

In addition, the main gully of Taoguan debris flow is long, and along the supply resource lies numerous with multiple barrier dam. Besides the upstream and downstream started up respectively because of the block of the cross of Lianghekou. So the debris flow lasted long and rushed out with huge scale, forming catastrophic mudslides, buryed the corporations and the residential construction in the period of about 3 km range of the export, threatened Dujiangyan-Wenchuan freeway and G213 state road (Fig. 4 and Fig. 5).

Fig.4 Destroyed workshop(2013-08-16)

Fig.5 Bare pier washed by debris flow under a bridge on Dujiangyan-Wenchuan freeway

4.2 Dynamic characteristics of "the 10 July, 2013"debris flow

The important indicators of dynamic characteristics of debris flow include density, velocity, discharge and the total amount of rushed out once, that are also the important parameters for the prevention and cure measurement of project (Tang et al., 2009 and Zhang et al., 1996). The average density of "7.10" is 1.736 t/m^3, adopting the method of mixing weighing on site, and it belongs to the transitional partial viscous debris flow.

Table 2 Calculation results of velocity and discharge of "the 10 July" debris flow on different part by modified flood discharge method

Number of section	Solid density (t/m^3)	Sediment correction coefficient Φ	Roughness coefficient $1/n$	Mud mark (m)	Longit -udinal Grade I_c	Velocity (m • s^{-1})	Peak discharge (m^3 • s^{-1})		Discharge of debris flow (m^3 • s^{-1})	
							5%	2%	5%	2%
No. 1-1' section (export)	2.65	0.88	15.0	2.40	0.08	4.16	201.98	232.22	569.89	655.21
No. 2-2' section (middle)	2.65	0.88	10.0	3.40	0.11	4.07	65.19	74.94	261.00	300.08

Table 3 Calculation results of the total run-off volume of "the 10 July" debris flow

Design frequency (%)	5	2
Design maximum flood discharge (m^3 • s^{-1})	201.98	232.22
Peak discharge of debris flow (m^3 • s^{-1})	569.89	655.21
Amount of debris flow rushed out once	1.0833	1.2454
Amount of solid once (million m^3)	0.5029	0.5782

By measuring the section area with typical residual mud mark and the corresponding longitudinal grade, using the rain flood correction method combined with blockage of loose materials source (factor of blockage is 1.5), according to the formula, the velocity and discharge can be obtained in the typical section of middle circulation area and export areas (Table 2). According to the results of mud mark survey method, the rainfall frequency of debris flow here is once in 20 years. Considering the outbreak time of "the 10 July" debris flow lasted about 2 hours, the amount rushed out once Wc and the total solid Ws at the export can be obtained based on formula (Table 3).

According to the accumulation area and its average thickness of the "the 10 July" debris flow in industrial park of the export, and the size rushed out from the export to the Minjiang river, the amount of debris flow rushed out once could be determined, which equals to 1.1 million m^3. Compared with the results in Table 2, it also shows that the amount rushed out equals to the size rushed out of the rainfall every 20 years.

4.3 Mechanism analysis of "7.10" debris flow

According to the "Wenchuan county" records, the basin of the Taoguan gully belongs to non-torrential rain areas, the main characteristics of rainfall is cloudy and autumnal rain. Before the 12 may Wenchuan earthquake in 2008, the basin was covered well with vegetation, and gully bed mainly consists of coarse gravel with little sand and clay, which belongs to typical gravel bed of mountains, with highly gravel roundness, and the bed material is relatively stable, and is difficult to be restarted by debris flow, so there is little possibility to occur massive debris flow. In fact, the Taoguan Gully is just like that before the earthquake, and the torrential gully is the main feature.

After the Wenchuan earthquake, avalanches and landslide induced by the earthquake forming very rich loose materials in the trench, which changed the geological conditions in the gully. So the formation mechanism of the Taoguangou debris flow occurred frequently related to the increasing loose materials sharply besides its terrain conditions and continuous rainfall. In terms of the disaster mechanism, combining with the field investigations, the starter mechanisms of the Taoguangou flow can be summarized as the following four modes:

(1) The shattered-relaxed rock mass in the watershed area collapses and slides headward (Fig. 6);

(2) The rainfall acted on the surface of slope forms runoff, leading to erosion and avalanche of loose materials on the surface of slope, supplied by way of overland flow (Fig. 7);

(3) Avalanches and landslides in the 12 May Wenchuan earthquake in 2008 eroded by water flow added to slough and supply (Fig. 8);

(4) The materials resource in the valley was undercutted and supplied by quickly gathered water and debris flow started by materials resource of three parts above..

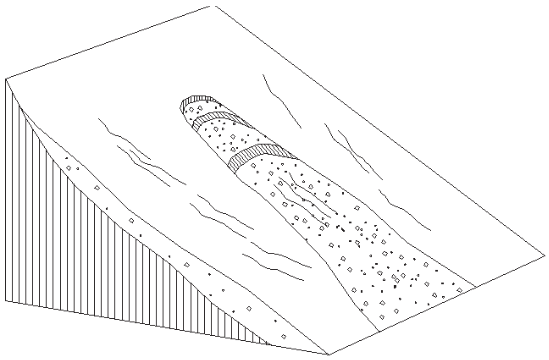

Fig.6 The startup mode of retrogressive erosion avalanche of shattered rock mass

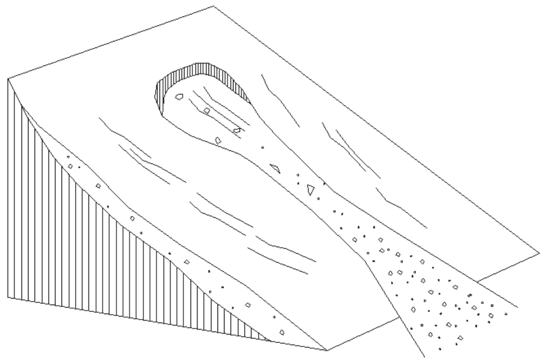

Fig.7 The startup mode of debris flow on slope formed by loose materials

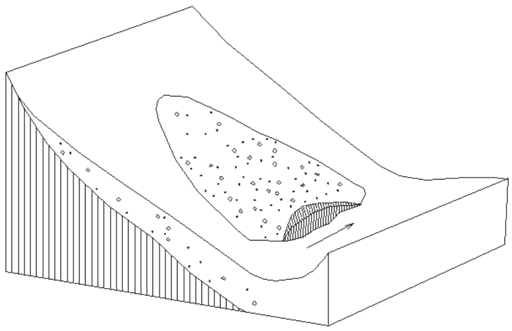

Fig.8 The startup mode of side erosion and toe cut of seismic avalanche and landslide source

Fig.9 The No.5 dam was filled up again after the reinforcement and restoration in 2004(2014-7-14)

From starting mechanism of the debris flow, the first three parts are the main reasons, accounted for about 75% of the started quantity of material resources of debris flow

Visibly, the earthquake damage to rock-soil mass is the root of the frequent outbreaks of debris flow after earthquake. The plague mechanism is the startup and overlays of each other of avalanche, landslide deposits, overland deposits, and channel deposits. As long as the started material resources are controlled effectively, such as slope protection, blocked dam and so on, the occurrence and development of debris flow should be effectively controlled.

4.4 Analysis of development trend about debris flow

According to the geological exploration data, the quantity of mass provenances of the Taoguan Gully remains 27.99 million m^3 after “the 10 July” debris flow in 2013, except the dynamo-relaxed rock mass shattered by earthquake at the secondary watershed and primary watershed. The sources activated in “the 10 July” debris flow mainly silt at the section at upper reaches and lower reaches of the cross of Lianghekou, The quantity solid materials that flowed into the Minjiang river in the previous debris flow is so limited that possibility of debris flow is very large under the condition of rainstorm. In fact, the original dam(No.3, No.5) reinforced and heightened, have been silt up at the time of “9 July” local rainstorm in 2014 (Fig. 9), all of the factors above have illustrated that this debris flow is very likely to occur.

Debris flow disaster, which happened in the main disaster area of Wenchuan, Mianzhu, Beichuan in Sichuan province in six years from 2008, has showed they will continue arise frequency in the next 5 years, with the greater active intensity in some gullies. The Taoguan Gully is a typical representation, and it has great possibility to generate debris flow disaster under the action of general rainfall and flood with large catchment area and extremely rich loose materials.

5. Conclusion

(1) Induced by The Wenchuan earthquake, there are amount of deposits accumulated after rockfall or landslide in Taoguan ditch catchment. In addition, many

dynamo-relaxed rock masses shattered by earthquake at the Secondary watershed provide the main material resources of debris flow. After “the 10 July” debris flow in 2013, the quantity of loose provenances has reached 27.99 million m^3 in volume, in which there are 4.14 million m^3 dynamic reserves except the dynamo-relaxed rock mass shattered by earthquake at the secondary watershed. According to the startup dynamics of debris flow, we can divide it into three forms under the consideration of supply patterns of the loose materials: 1) Dynamo-relaxed rock and earth mass supply the debris flow in a model of retrogressive erosion at rainfall condition; 2) The avalanche and slide origins directly involve in the supply because of the lateral erosion by flooding; 3) gully bed deposits supply for erosion of flood and debris flow. The upper three supply patterns interact with each other.

(2) Another controlling factor of occurrence of debris flow happened in earthquake zones is rainfall conditions, performing at the interaction of the antecedent accumulation rainfall and active rainfall at this time. The rainfall conditions of the debris flow happened on 10 July in the Taoguan gully has the characteristics of heavy volume and long duration. The antecedent precipitation before the outbreak of debris flow is greater than 67.3 mm, and the active rainfall is greater than 104mm. The characteristics as heavy rainfall and long duration of the antecedent rainfall lead the loose deposits to stay in water-saturated state and easily start. As the active rainfall is heavy, floods move together with solid matters and this further drives the material resource on gully bed starting to form debris flow.

(3) In 2013, materials of "the 10 July" debris flow rushed out of were about 1.1 million m^3, which only took 3.9 % of the total materials, while accounted for 26.6% of dynamic reserves. Especially in the downstream and middle channel large accumulations of debris flow silted, and the blocking condition in channel is still serious. So if the cumulative rainfall before and the provocative rainfall intensity are appropriate, possibility the occurrence of debris flow would be greatly. The debris flow will be break out frequently in the next 5 years.

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