Initiation mechanisms of huge debris flows in the Wenchuan earthquake area

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Abstract

The frequency and the magnitude of the huge debris flows highly increased after the Wenchuan earthquake around the epicenter area in S-W of China. The field investigation reveals that runoff during the rainstorms plays a major role in generating debris flow on the loose deposits, resulted from the debris avalanche during the earthquake. However, the mechanisms of these runoff generated debris flows are not well understood due to the complexity of the initiation process. Especially, it is interesting to explore the huge magnitude of these post-earthquake debris flows. To better understand the initiation mechanism, we performed flume tests to simulate the initiation process in the laboratory. With the help of a 3D laser scanner, the whole processes of the initiation of debris flows were clearly monitored. It was found that the run-off incision caused an accumulation of material down slope, which, after saturation, failed as shallow slides transforming the process in a second stage into debris flows. After this initial phase, the debris flow volume increased rapidly by a chain of subsequent cascading processes starting with collapses of the side walls, damming and breaching leading to a rapid widening of the erosion channel. By comparing the erosion amount, the latter mechanism is much more important than the former one. The latter process is called "damming and breaching effect" in this article. Compared with other erosion processes, the "damming and breaching effect" is found to be the main reason for the initiation and huge magnitude of debris flows in the post-earthquake area.

Keywords: post-earthquake, debris flow, initiation mechanism

1. Introduction

The 2008 Wenchuan Earthquake in SW China in the Sichuan Province generated many landslides, which delivered a huge amount of loose deposits. It caused a dramatic increase in debris flow occurrence in the subsequent years. The mechanism of these debris flows has not yet been completely understood. The mechanism is complex due to the interaction of different processes such as run-off induced gully erosion in initially unsaturated granular deposits, damming and breaching effects caused by the instability of the side wall of the gullies.

Debris flow initiation can be generally subdivided into two mechanisms: 1) Failure of shallow landslides, which transform into debris flows and 2) concentrated run-off (flash floods) erosion in channels filled up with sediments which may be supplied by landslides from the slope. Such debris flows contain a small fine fraction (less than 10-20% silt and clay, tang et al 2011) compared to soils involved in landslide-induced debris flows, and the source materials have a much higher hydraulic conductivity. Tognacca and Bezzola (1997), Cannon et al. (2003) and Berti and Simoni (2005) studied debris flows initiated by channel-bed mobilization, which is only a part of the initiation process of debris flows confined in channels. A framework that describes adequately all the processes involved in the initiation of debris flows is still missing (e.g., Cannon et al., 2001; Berti and Simoni, 2005; Coe et al., 2008a, 2008b). Moreover, the former studies have focused mainly on sediment erosion. More recently, Kean et al (2013) concluded that the debris flow initiation by runoff can be grouped into two categories: mass failure of the channel sediment by sliding along a discrete failure plane and grain-by-grain bulking by hydrodynamic forces. The former initiation process requires a sudden large impulse of sediment to be added to and/or entrained within the water flow, such as from the failure of the sediment-filled bed of the channel or failure of the channel banks caused by channel erosion. The latter process has been motivated by some sediment transport experiments in steep flumes (e.g., Tognacca et al., 2000). In some of these experiments, a debris flow surge is produced by hydrodynamic forces eroding individual particles at the surface rather than by sliding along a failure plane at a certain depth. But there are other mechanisms involved in the initiation process. From field study, several huge erosion gullies were found after the debris flows in Wenchuan earthquake area in southwest of China. These huge erosion gullies make us rethink about the mechanisms and the whole process of the initiation of debris flow. The aim of this paper is to explore the interacting processes involved in the generation of these debris flows. For this purpose, a series of flume tests simulating erosion and incision by run-off water were conducted. By using a laser scanning technique, a sequence of processes related to the initiation of debris flows was monitored with the aim to understand which process plays a major role in the initiation and enlargement of the erosion gully for future prevention and mitigation.

2. The post-earthquake debris flows in the SW of China

A total of 72 gully debris flows were induced by the most serious rainfall event on the 24th of September 2008 in Beichuan County, close to the earthquake epicenter, causing 42 casualties (Tang et al., 2009). The position of these debris was shown in Figure 1. In addition, a heavy rainstorm on the 13th–14th of August 2010 near the town of Yingxiu, located at the epicenter of the Wenchuan earthquake, triggered many landslides and channelized debris flows. On the 13th of August 2010, numerous debris flows occurred along the Qingping section of the Mianyuan River, (Tang et al 2012, Xu et al 2012). The Wenjia gully debris flow located in the Qingping section of the Mianyuan River was the largest one among these debris flows. The loose source material of this debris flow was deposited by a rock avalanche, which occurred during the Wenchuan Earthquake. The high energy of the rock avalanche was able to entrain the shallow, loose, soil material along its flow path increasing the amount of fines in the deposited material with a total volume of more than 70 million m^3. On the 13th of August 2010, a heavy rainfall generated in the gully a huge amount of the surface runoff. The intensive runoff produced the debris flow and a huge erosion channel. The incision of the material was caused by gully erosion. The widening of the gully must be caused by slope instability, looking at the hollow shaped slope forms which are traced by the slumping. However the complete insight in the sequence of processes leading to the initiation of debris flows and the formation of this huge erosion gully are not clear. The flume tests were conducted to simulate the whole initiation process and special attention was paid to study the formation of huge gully.

3. The experiment set-up and test procedures

3.1 Numerals

The flume was instrumented in order to obtain the hydrological changes and the deformation in the deposits during the initiation process. The equipment was described in details in Hu et al. (2014). The materials for the flume tests were collected at the top of the so called 1300 platform in the Wenjia gully, which formed the loose source material for the debris flow. There is a difference in grain-size distribution between the in situ materials taken from different locations.

4. Test resutls

About 10 tests were carried out with different slopes varying from 12 to 35 degrees, which provoked the same initiation process. Tests with a slope of 28 degrees were selected for the presentation of this process. Two tests were carried out with the same initial conditions of a 28-degree slope and a runoff discharge of 0.0003 m3/s. One test was stopped several times to obtain 3D scanning of the erosion channels. Another one was carried out without any pause to obtain the erosion curve during the initiation of the debris flow. A study of the videos of these two tests shows that the pauses did not change the initiation mechanism nor the process.

The 3D scanner results are shown in Figure 1. The development process of the debris flow can be divided into 6 stages.

Stage I : a small gully was formed at the top of the slope due to runoff surface erosion. The wash-out particles were deposited in the lower part, as shown in Figure 1a. This is due to the decrease of the seepage force. Most of the run-off water infiltrated into this slope deposit, decreasing the shear force of the remaining runoff water which consequently entrained only some fine particles. At this stage, no debris flow was initiated (Figure 1a).

Stage II: The water continued to infiltrate into the slope deposits. The finest particles were washed out due to the seepage force of the infiltrated water. According to a laser particle size distribution analyzer these particles appeared to be smaller than

0.05mm. The washing out of the fine particles decreased the density and hence the shear strength of the deposited material and made the material more sensitive to static liquefaction. After about 5 minutes from the beginning of the test, a complete fluidization of the deposited soil mass occurred and the mass transferred into a debris flow. A gully was formed at the toe of the slope due to this fluidization process, as show in Figure 1(b).

Stage Ⅲ: The erosion gully continued to be deepened and widened due to the sediment erosion and entrainment. (Figure 1(c)).

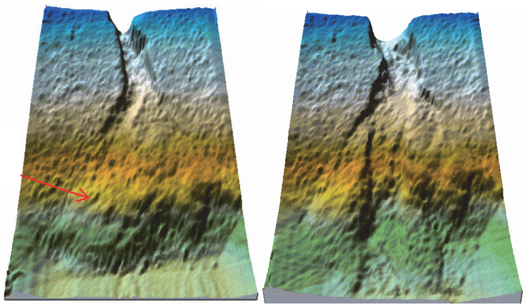
Stage Ⅳ: As a result of continued water infiltration and seepage into the soil, both sides of the erosion gully became unstable and small landslides were initiated and the gully was dammed by the landslide debris (Figure 1(d))

Stage Ⅴ: There was a quick rise of water level behind the landslide dam, which became quickly saturated. After about 20 seconds, the landslide dam breached by combination of overtopping and internal erosion. The debris from the breached landslide dam transferred into a larger debris flow. The process in stage four and stage five is called "damming and breaching" in this article. This process increased largely the volume of the debris flow and widened and deepened the erosion gully as shown in Figure 1(e).

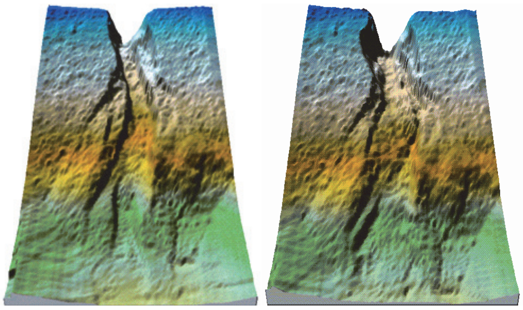
Stage Ⅵ: "The process of damming and breaching" continued and contributed to the enlargement of the erosion gully. Sediment erosion also played a role, however much less than the " damming and breaching" . Finally, a large erosion channel was created, as shown in Figure 1(f).

By comparing the digital map of different erosion stages with the initial slope topography, an isopath map for the different stages was obtained as shown in Figure 5. Positive contour numbers mean cumulative deposition with the units of centimeter and negative numbers means cumulative erosion with respect to the initial slope surface. The change in topography from Figure 1(a) to Figure 1(b) was caused by the shallow landslide of the deposited material at the toe of the slope. From Figure 1(b) to 1(c), the topographic change was caused mainly by the bed and side erosion. From Figure 1(d) to 1€, it was caused by the breaching of the dammed materials. From 1(e) to 1(f), it was caused mainly by the continuous "damming and breaching effect" and partly by bed erosion.

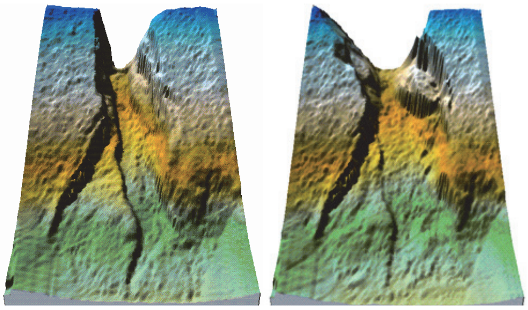
The above observations show that damming, breaching and fluidization of the loose deposits generated peaks in the solid concentration and played a key role in the initiation and the development of the debris flows.



(a) Stage Ⅰ (b) Stage Ⅱ



(c) Stage Ⅲ (d) StageⅣ



(e) Stage Ⅴ (f) StageⅥ

Figure 1 Digital Elevation Model (DEM) for initiation of debris flow. (a) Stage Ⅰ: Superficial erosion and deposition of loose material. (b). stage Ⅱ. Shallow landslide in the deposited materials and initiation of debris flow. (c) Stage Ⅲ: bed erosion. (d). stage Ⅳ: instability of the side wall of the erosion channel and damming. (e). stage Ⅴ. Breaching of the dammed material and enlargement of thechannel. (f).stage Ⅵ. Continuous breaching and damming effect and enlargement of the channel.

5. Conclusions

The "damming and breaching effect" highlighted by our experiments shows again the complexity of the processes related to the supply of material for the initiation and development of debris flows and the big challenge to model these processes.The long chain of processes showed by the flume tests with runoff erosion (lateral erosion and incision), slope failure, damming and breaching and in addition bed failure (not simulated in our experiments) was usually simplified by equations taking into account only a part of these processes (among others Berti and Simoni(2005), Iverson et al (2011) Tognacca, et al (2000) Cui et al. (2013), Kean et al (2013)) or by simplifying the supply of material to debris flow with erosion rates related to flow velocity and flow height (Eglit and Demidov 2005, McDougall and Hungr 2005, Van Asch et al. 2014).

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