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Application and design of an efficient siphon dewatering system for debris flow mitigation: A case study of a small catchment in Zhejiang Province, China

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ABSTRACT

Excessive water in a channel is an important factor that triggers channelized debris flows. In this study, we propose a new system for the separation of water and sediment and drainage in order to drain water away from channels and reduce the potential for debris flows. The main component of the system contains a siphon drainage pool covered with an inclined perforated plate and siphon drainage pipes. The inclined perforated plate can separate sediment from the water, and the siphon drainage pipe can drain flood water quickly. To test the effectiveness of the new structure, a field experiment was developed and tested in a small catchment in which debris flow was an issue. The experimental results showed that the drainage pool effectively decreased the maximum depth of the flow in the triggering area, thereby avoiding the occurrence of debris flow. To set the optimize design parameters of the pool, three main design parameters were evaluated, i.e., peak discharge during storms, separation ability of drainage pool, and the maximum depth of surface flow in the triggering areas. The peak discharge was obtained by using the NAM model and a rational formula, and the NAM model provided more accurate results. The results of the calculation of the separated ratio showed large runoff volumes and a lower separated ratio. The results of the NAM model were used to simulate the maximum depth of flow using the FLO-2D model.

1. Introduction

Debris flows are natural, geo-hazard phenomena in mountainous regions, and they consist of sediments and water that move as a continuous fluid driven by gravity. Many debris flow hazards can produce catastrophic consequences, such as the debris flow that occurred in Zhouqu County in China (Wang, 2013). This large-scale debris flow destroyed > 200 buildings and killed approximately 1700 people. Therefore, it is apparent that avoiding or mitigating debris flows is an important issue for both the government and the public. Debris flows are commonly triggered by a combination of three essential factors, i.e., sufficient loose solid materials, water runoff, and a steep terrain. Among these three environmental factors, water runoff is the only one that can change drastically in a comparatively short time, and the stability of the deposits of debris within channels is related closely to the flow of surface water (Zhou et al., 2015; Gregoretti and Fontana, 2008). The quantity of runoff water that is discharged has been proven to be the major factor in triggering debris flows (Gregoretti, 2000). Therefore, decreasing the quantity of runoff water discharged over a given amount of time is an effective measure in decreasing the severity of debris flows in gullies during storms.

Currently, two types of mitigation measures are generally recognized, i.e., active measures and passive measures (Hungr et al., 1987). Active measures focus on the hazard, while passive measures focus on the potential damage. The various measures can be categorized in various ways, including: (1) work to restrict the occurrence of debris flows (e.g., stabilizing the slopes of hills), (2) structures to prevent, retain, or diminish debris flows (e.g., check dams), (3) work to control the directions of the flows (e.g. training dikes), and (4) work to provide areas for deposits to be accumulated (e.g., forest dispersion zones and sedimentation basins). Zhuang et al. (2013) examined the various processes that can initiate debris flows in order to identify suitable mitigation strategies. There are three main mitigation measures that can be used to prevent and control channelized debris flows, i.e., debris flow dams, bypasses, and drainage canals. Drainage canals often are constructed in alluvial fans to prevent debris flows from destroying buildings that have been built there. You et al. (2012) proposed a method for designing the optimal cross-section of a drainage channel for debris flow. Wang et al. (2017) proposed three baffle shapes to study velocity reduction and energy dissipation. The influences of debris flow

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density, baffle shape, and row spacing were investigated. In British Columbia in Canada, rigid liners, such as concrete or grouted riprap liners, have been used to prevent erosion and help ensure that channels continue to operate as planned (Hungr et al., 1987). However, some debris flows can produce such severe erosion effects that channels can be destroyed. The main types of debris dams are the closed and open types (Xie et al., 2014). Initially, debris dams were designed as closed dams to impound and block debris flows, and the open dams, which separate water from the debris flow, were developed later. Such open dams reduce the volume and mass discharged by a debris flow by trapping coarse sediments and allowing water and fine sediments to pass through the structure. The open dams have been divided into three different types, i.e., (1) the vertical rigid type (Chen et al., 2015), (2) the vertical flexible type (Canelli et al., 2012; Brighenti et al., 2013), and (3) the horizontal type (Brunkal and Santi, 2016; Gonda, 2009; Kim et al., 2012). However, over time or during a significant debris flow event, open dams have been known to lose their water–sediment separation function due to blockage by sediment and other debris. In order to solve this problem, Xie et al. (2017) proposed a new herringbone structure to separate coarse sediment from debris flow. It consists of a draining dyke, a herringbone water-sediment separation grid, an outflow channel and deposit fields. Another possible measure that can be implemented is to allow the flooding to bypass the excessive accumulation of sediment to avoid along specific channel reaches. For example, in the "St. Julien" torrent in France, a channel that was 202 m long and had a cross section of 44 m^2 was designed to bypass the "Mont Denis" landslide. Debris and water were directed into the artificial channel by transverse structures (Jakob et al., 2005). But the movement of the debris and water in a bypass channel are driven mainly by gravity, and, gradually, sufficient sediment will be deposited to inevitably block the channel.

To date, most debris-flow mitigation methods focus on reducing the existing risk to an acceptable level. Once a debris flow occurs that involves strong erosion, powerful impact force, and high velocity, it is difficult to reduce the damage of the debris flow efficiently or effectively. Therefore, we should pay more attention to techniques that can be used to eliminate the conditions that trigger debris flows. The amount of runoff is an important factor in triggering channelized debris flows, and reducing the runoff can be an effective way to prevent or reduce the runoff in a channel. But water in current drainage systems is driven mainly by gravity, and many of them cannot drain the large quantities of water quickly enough. It could be of great significance to determine a new, more-effective approach for separating sediment efficiently and for draining water more quickly.

In this paper, we propose a new dewatering system for the mitigation of debris flows. The system is implemented in a small catchment to verify its mitigation effects and to explore the design parameters of the dewatering system. There are three design parameters that we would like to optimize, i.e., the peak discharge during storms, the water separation ability (i.e., how much flood water can seep into the pool during different amounts of runoff), and the water-depth threshold that will trigger debris flows, and we calculated these three parameters in this paper. By implementing the new dewatering system in the field, we also acquired the appropriate design parameters required for the dewatering system to deal effectively with storms of different intensities.

2. Establishment of the siphon drainage system

The siphon drainage pool is the main part of the system, and it must be located in the water collection area of the debris flow (Fig. 1) so that it can collect the most flood water in the channels to avoid allowing the flood water to encounter loose materials in the triggering area, possibly causing a debris flow. The pool consisted mainly of an inclined, perforated plate and siphon drainage pipes (Figs. 2, 3). The inclined perforated plate is made of metal plate with many apertures that allow water to seep quickly into the pool while separating the big particles of

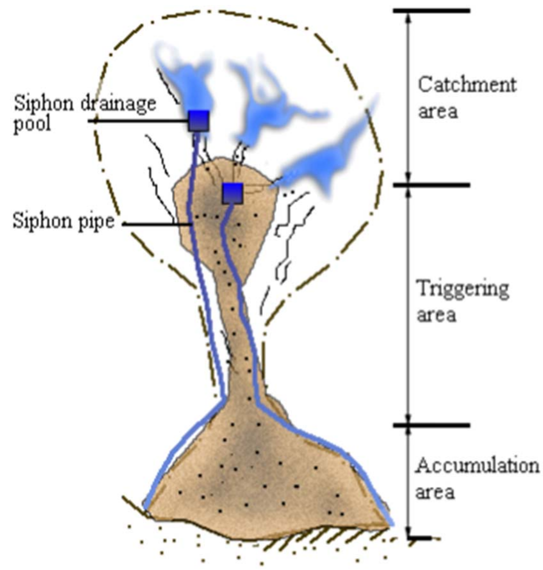

Fig. 1. Schematic diagram of controlling debris flow using a siphon drainage pool.

sediment from the water. The inclination angle should be large enough, usually > 45°, to prevent the sediment from depositing on the plate. We also installed some beams as supporting structures to prevent the big particles from destroying the perforated metal plate. The flood water that seeped into the drainage pool was drained quickly via siphon drainage, which has been used draining water from slopes because of its powerful water delivery capacity (Cai et al., 2014, 2015). During the siphoning process, the velocity of flow varies with changes in the water levels. When flood water passes through the siphon drainage pool, part of the flood water will seep into drainage pool through the perforated plate. Once the water-level in the pool reaches the peak point of the siphon drainage pipe (i.e., the control water level), the siphon drainage will begin to work, and the flood water that seeps into the pool will be quickly drained via siphon drainage and convey to safe places downstream (where there are no loose materials). After most of the water in the pool has been drained and the water-level is below the control water level, siphon drainage will cease. Once the water-level of the collected flood water reaches the peak point of the pipe, the drainage works again, and this process is repeated as the water level changes. The siphon drainage pipe can drain water quickly due to its very large water delivery capacity (Wang et al., 2016). Simultaneously, the high velocity water flow and pumping effect caused by siphon drainage could entrain slight amounts of sediment in the water, and this avoids depositing the sediment in the pool (Zhang et al., 2015b). Since most flood water can be delivered by siphon drainage pipes to the safe places, the amount of flood water in the channel can be controlled such that its level is below the threshold all the time.

3. An illustrative case study

3.1. Description of the study area

In order to test the effectiveness of the new dewatering structure, a field experiment was developed, and tests were conducted in a small catchment that often suffered debris flow. Fig. 4 shows that the catchment was located in Fenghua City, Zhejiang Province. The basin had a trumpet shape that was prone to concentrate surface flows into channels. Fig. 5 is the geological map of the study area. Table 1 provides the morphological characteristics of the catchment. The only road that connects Lingjiao Village of about 50 citizens to the outside world is located downstream of the catchment, and it is very vulnerable to the occurrence of debris flows (Wei et al., 2017).

Loose, solid materials are distributed extensively in various