Debris-flow mitigation measures and an application case in a small-scale watershed in China

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Abstract

The Wenchuan earthquake in China (May 12, 2008) triggered numerous debris flows, some of which caused serious secondary disasters, such as in Wenjia gully (Sichuan Province) and Sanyanyu gully (Gansu Province). To solve this problem, a planning method for debris-flow mitigation engineering measures was proposed based on watershed and river sediment transport characteristics. This method aids in the selection of engineering measures to effectively prevent secondary disasters and control unconsolidated soil and debris-flow movement from upstream to downstream. Several measures are considered in the proposed method, including check dams and transverse structures built across gullies, which are important engineering measures in debris-flow hazard mitigation. Based on the developed planning method, new types of check dams were proposed, the regulation effect of sediment particle size in slit check dams was qualitatively analyzed, and the design parameters (e.g., deposition slope, deposition length, and dam height) of the check dams were deduced. Moreover, a series of drainage channels was proposed to cross highways and discharge debris flows into the river or debris-flow deposition basin below. Finally, an engineering application case in Xiaogangjian gully, Sichuan Province, China, was examined using the proposed watershed planning method, in which a series of check dams with different orifices sizes was constructed. The engineering application results provide useful data for developing check dams as a restoration tool and hazard mitigation technology in small watersheds.

Keywords: Debris flow; mitigation measures; small-scale watershed; check dam; drainage channel

1. Introduction

Debris flows are sediment movements that can travel several kilometers as a series of surges; they are common on steep terrain and in deep gullies within mountainous areas (Iverson, 1997; Hungr et al., 2001; VanDine and Bovis, 2002; Godt and Coe, 2007; Cui et al., 2013). They can scour channel banks and gully beds, enhancing the debris-flow discharge due to the effects of the blockage and subsequent outbreak process in watersheds (Cui et al., 2013). The Wenchuan earthquake in China (May 12, 2008, Sichuan Province) triggered numerous debris flows, some of which caused serious secondary disasters, such as in Wenjia gully (Sichuan Province) and Sanyanyu gully (Gansu Province) (Zhou et al., 2013; Zhang and Matsushima, 2018). Subsequently, numerous large-scale debris flows occurred during the rainy season from 2008 to 2018, when portions of hillslope deposits were transferred to channel deposits, and the source materials in the channel were carried to the outlet of the watershed. Based on a study of the debris-flow activities along a highway in China, the debris flow volume, runout distance, and deposition width decrease over time due to the decreasing source material volume and a possible change in debris-flow type (Zhang and Zhang, 2017). Whereas 665 debris-flow events per year occurred from 2001 to 2008, the average number of debris-flow events per year reached 1153 from 2009 to 2016 in China (Fig. 1). This trend suggests that debris-flow hazard prevention and mitigation will remain an urgent issue in the coming decades, as stated by Stoffel et al. (2014).

Debris-flow mitigation measures can be classified as structural measures (e.g., check dams, drainage systems, flexible barriers, and debris-flow basins) or nonstructural measures (e.g., warning and evacuation systems, appropriate land use, and building improvements) (Armanini and Larcher, 2001; Takahisa, 2008; Hassanli et al.,

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2009; You et al., 2011; Canelli et al., 2012; Chen et al., 2014; Chen et al., 2015; Liu et al., 2017; Wang et al., 2017; Chen et al., 2018; Wang et al., 2018). Although debris-flow mitigation measures have been constructed in a few watersheds in the Wenchuan earthquake area, China, large-scale debris flows have still occurred, proving that existing mitigation measures are inadequate (Wang et al., 2012; Wang et al., 2013). In addition, the dual impacts of the Lushan earthquake (April 20, 2013, Sichuan Province, China) and the Jiuzhaigou earthquake (August 8, 2017, Sichuan Province, China) are expected to further increase the incidence of debris-flow disasters (Cui et al., 2014; Chen et al., 2018). Therefore, developing new planning methods and techniques based on debris-flow characteristics in this earthquake-stricken region is a critical issue.

This paper presents a new planning method for debris-flow hazard prevention and mitigation measures, and describes several corresponding engineering technologies. The proposed debris-flow hazard prevention and mitigation method was tested based on several medium-sized debris flows, and a related case study of a small, steep watershed is described. The results indicate that this method is effective in regulating debris-flow hazards; therefore, this planning method and related engineering technologies may provide a new process for debris-flow hazard mitigation.

Fig. 1 Debris-flow events in China from 2001 to 2016

2. Debris-flow hazard mitigation engineering planning method and new technologies

2.1. Planning method

The early planning method for debris-flow hazard mitigation engineering, in 1980s in China, is primarily based on the target objects intended to be protected, which is effective for small debris flows, but not large debris flows. For instance, several large debris flows have exited the gully in which they originated and blocked the river below, such as in Wenjia gully (Sichuan Province) and Sanyanyu gully (Gansu Province). Therefore, the planning method requires reconsideration for large debris flows. Based on the calculation method of the debris flow block the main river (He, 2003) and to make full use of the sediment transport capacity of rivers, Chen et al. (2015) proposed the use of cascade check dams and deposition basins to regulate the scale of debris flows in gullies. Figure 2 shows the specific implementation process of the new planning method for debris-flow mitigation engineering measures, which includes consideration of the debris-flow peak discharge with a design standard ($Q_{\text{Total}}$), the debris-flow peak discharge through the drainage channel ($Q_{\text{Drainage}}$), the debris-flow peak discharge requiring blockage by check dams ($Q_{\text{Block}}$), and the debris-flow peak discharge that must be accommodated by the deposition basin ($Q_{\text{Deposition}}$). The primary steps in designing a mitigation system include the determination of $Q_{\text{Total}}$ based on the design standard and rainfall data, as well as the transport capacity of nearby rivers based on river discharge data, followed by the determination of $Q_{\text{Drainage}}$. Why we consider the drainage channel discharge capacity and the sediment transport capacity of the river, the reason is that the river can be blocked when the debris flow discharge into the river is large than the sediment transport capacity of the river. Based on the block condition of the river, the better process can be selected according to the flow chart in Figure 2. The relation between the debris-flow peak discharge with a design standard and the total volume $Q$ of a debris flow is $Q = 19TQ_r/72$, $T$ stands for the debris flow duration time and $Q_r$ stands for the debris-flow peak discharge.
2.2. New debris-flow hazard-mitigation technologies

To better apply the proposed planning method, a large number of check dams and drainage channels were researched and developed. Several types of structures are described in the following sections.

2.2.1 Cascade check dams with orifices of various sizes

A series of open check dams with rectangular orifices with various sizes can be used to block and separation debris particles and the interval spaces of the orifices was calculated by the debris flow impact force. When debris flows enter the circulation area, water and stones are separated. The mean particle size gradually becomes smaller further downstream, thereby decreasing the impact forces of large stones. Such structures can achieve a uniform distribution of debris flow materials along the length of the debris flow. As such, this method makes use of both the siltation and hazard mitigation functions of check dams. Cascade check dams have completely prevented debris flows (Liu et al., 2017); therefore, they have an important hazard mitigation function. Since cascade check dams have the advantage of reducing debris flow particles with sequentially decreasing orifice sizes, regulating the debris-flow peak discharge, this method is expected to have major impacts on the mitigation and treatment of large-scale debris flows.

2.2.2 Debris-flow blocking structure with piles

Blocking structures can be constructed from both rectangular and T-shaped piles arranged in a staggered formation (shown in Fig. 4). In these structures, the horizontal coupling beam is made of reinforced concrete with a rectangular cross-section. Such structures can block stones, while having minimal effects on flow efficiency. The rectangular pile structure in the first row is relatively strong, and mainly blocks large stones; the T-shaped piles in
the second row are used to form a soil arch effect. Overall, this enables the pile structure to block debris and form a dam. Debris-flow blocking structures with two rows of piles at equal intervals can block large stones while discharging smaller particles, protecting downstream buildings from the impact forces of large debris. Meanwhile, the T-shaped piles improve the stability of the structure. Compared with gravity retaining check dams, the pile spacing can be easily adjusted, reducing the project budget without affecting the function. Finally, the structure is relatively convenient, economical, and practical to construct in the poverty-stricken area.

![Debris-flow blocking structure with piles](image1)

**Fig. 4 Debris-flow blocking structure with piles**

### 2.2.3 Drainage channel with prefabricated reinforced concrete boxes

The drainage channel with prefabricated reinforced concrete boxes described herein represents a new type of debris flow drainage channel, which is shown in Fig. 5. In this design, the prefabricated reinforced concrete boxes can be used to construct the sidewall or as an energy dissipation section by filling with stones. The side walls, which can be either vertical or inclined, can be constructed from masonry, concrete, reinforced concrete, or prefabricated, reinforced concrete boxes. The ground sill was constructed by reinforced concrete. The energy dissipation section is located between the upstream and downstream sections of the channel slab, and stones are used to fill the structure. Different structural forms, such as a steel cable network can be used to avoid scouring damage, can be used as the slab of the energy dissipation section, and a concrete lining layer can be used to protect the bottom from scouring. Debris flows can flow through the top open surface as they pass through the structure. Some of the energy is dissipated via strong interactions between the debris flow and stones. In addition, the impact energy of the debris flow can be absorbed by the soft foundation, and exchange between the debris flow and bottom soil can be inhibited, controlling the erosion of the channel slab by the debris flow. Ultimately, this structure can achieve a balance between the reduction in the potential energy and the dissipated energy.

![Schematic diagram of a drainage channel with prefabricated reinforced concrete boxes](image2)

**Fig. 5 Schematic diagram of a drainage channel with prefabricated reinforced concrete boxes**

### 2.2.4 Drainage channel with a step-pool configuration

Drainage channels with a step-pool configuration are composed of sidewalls, a channel slab (i.e., step section), upstream and downstream ground sills, and a pool section (Fig. 6). The step section includes the upstream ground-sill, the downstream ground-sill, and a concrete slab that connects the upstream and downstream ground-sills. The pool section is located between two adjacent ground-sills and is filled with stones. Debris-flow energy can be dissipated via interactions between the debris flow and stones. In addition, debris-flow impact energy can be absorbed by the soft foundation, and exchange between the debris flow and bottom soil can be prevented to control erosion of the channel slab. Figure 6 shows the structural
characteristics of a drainage channel with a step-pool configuration. The sidewalls can be vertical or inclined, and different structural forms can be used in the pool sections. Additionally, steel cable networks, soft foundations, or concrete lining layers can be used in the pool bottom to protect against bottom scouring.

![Fig. 6 Schematic diagram of a drainage channel with a step-pool](image)

3. Engineering application case

3.1. Research area

The small-scale watershed of Xiaogangjian gully is located in the central Longmen Mountains area (31°02′N, 104°07′E). The area of this gully is 1.36 km², the main channel of the gully is 2,590 m long, and the longitudinal gradient is 412‰. The altitude of the catchment ranges from 810 to 1,987 m, representing an elevation difference of 1,177 m. The area with slope gradients equal to or greater than 25° measures approximately 1.16 km². The slopes in this catchment are mostly steep with large longitudinal gradients, favoring the concentration of stormwater runoff, making the area prone to debris flows.

![Fig. 7 Location of Xiaogangjian gully](image)

The Wenchuan earthquake induced numerous landslides and avalanches in this gully, with total deposits of 80 × 10⁴ m³. Ten debris flows occurred between May 12, 2008, and September 5, 2011, and caused a radical change to the landscape, particularly the outlet of the gully. The total volume of solid materials that exited the gully was estimated to be 50 × 10⁴ m³, including materials from the old accumulation platform (40 × 10⁴ m³) and those from
the collapse upstream \((10 \times 10^4 \text{ m}^3)\). An area of \(3 \times 10^4 \text{ m}^2\) was directly affected by the debris flow in the gully outlet, including the road below the gully. Major hazards included the blockage and siltation of the main road and river channel, the formation of a dammed lake, the inundation of the upstream road, and the rise in the downstream river bed due to high-intensity sedimentation, which resulted in the burial of the road downstream. For example, the road was buried by a debris flow that occurred on July 26, 2010, interrupting traffic for 18 days. Another large-scale debris flow occurred on August 13, 2010, and blocked the road at the gully outlet to form a dammed lake that flooded the upstream road, interrupting traffic until August 20, 2010.

3.2. Debris-flow mitigation engineering measures in Xiaogangjian gully

To protect lives, properties, and the road, as well as create favorable conditions for a healthy economy and environment and for construction and development in the nearby town, a debris-flow mitigation project in Xiaogangjian gully was carried out in 2011. The design standard of the debris flow mitigation measure was to resist rainstorm-induced debris flows with a 20-year return period. Geological, geomorphological, hydrological, and meteorological conditions were considered in the project design.

3.2.1 Systematic planning of the debris flow mitigation project

Based on the planning method for debris-flow hazard mitigation engineering, the debris-flow discharge into the river through the drainage channel is large than the sediment transport capacity of the main river, then the river can be blocked by the debris flow. Thus, the maximum debris-flow discharge into the river through the drainage channel should not exceed the threshold of \(Q_{\text{Drainage}} > 17.5 \text{ m}^3/\text{s}\). Based on the hydrology of the small basin, the debris-flow peak discharge with a 20-year return period, \(Q_{\text{Total}}\), was 90.3 \text{ m}^3/\text{s}. Because \(Q_{\text{Total}} > Q_{\text{Drainage}}\), a drainage channel alone would be insufficient in this gully.

A series of check dams with orifices of various sizes was used to raise the erosion base level and stabilize the inner bank slope. Based on an analysis of the geological and geomorphological conditions, it was determined that three check dams should be built in the gully. Based on a slope stability analysis, these dams could mitigate a peak discharge of \(Q_{\text{Block}} = 31.3 \text{ m}^3/\text{s}\). Because \(Q_{\text{Total}} > Q_{\text{Drainage}} + Q_{\text{Block}}\), a debris flow basin was added to accommodate additional debris flow peak discharge. To avoid blocking the river, the debris flow basin should be capable of accepting a peak discharge of \(Q_{\text{Deposit}} = Q_{\text{Total}} - Q_{\text{Drainage}} - Q_{\text{Block}} = 90.3 - 17.5 - 31.1 = 41.7 \text{ m}^3/\text{s}\).

In summary, the design of the engineering project based on the debris flow peak discharge and the total volume of a single debris flow event is as follows: the peak discharge, \(Q_{\text{Drainage}}\), of the debris flow that can drain into the main river is 17.5 \text{ m}^3/\text{s}; the reduction in peak discharge, \(Q_{\text{Block}}\), that can be produced by check dams is 31.1 \text{ m}^3/\text{s}; the peak discharge, \(Q_{\text{Deposit}}\), that can be accepted by the debris flow basin is 41.7 \text{ m}^3/\text{s}, with a minimum volume of 26,414 \text{ m}^3; which can be calculated by the empirical formula \(Q = 19TQ^7/2\) for the debris flow duration time and \(Q_{D}\) stands for the debris-flow peak discharge.

3.2.2 Application of the drainage channel

Three check dams with orifices of various sizes were constructed in Xiaogangjian gully to mitigate debris flows (Fig. 8). In downstream succession, the sequence of dams is as follows: the first dam is 12.5 m high with 7 orifices, the sizes of the orifices are 0.8 \times 5.0 m and 0.8 \times 3.5 m (width \times height); the second dam is 11.5 m high with 7 orifices, the sizes of the orifices are 0.8 \times 4.5 m and 0.8 \times 3.0 m (width \times height); the third dam is 12.5 m high with 10 orifices, the sizes of the orifices are 0.8 \times 3.0 m, 0.8 \times 2.5 m and 0.8 \times 1.0 m (width \times height). To protect the highway at the gully outlet, a drainage channel with prefabricated reinforced concrete boxes was constructed to enable discharge of the debris flow into a debris flow basin (Chen et al., 2015). The steps in designing the drainage channel are as follows.

(1) Based on field measurements, the drainage channel slope is approximately \(i = 35\%\), and the length of the channel is 105 m. The cross-section is rectangular, the width of the channel is \(B = 6\) m, and the height of the sidewall is 3.5 m. According to the construction material, the roughness coefficient is approximately \(n_0 = 0.02\). Based on the velocity characteristics of the scour resistance of the reinforced concrete materials, the admissible velocity in the drainage channel ranges from 2.7 to 8 m/s.

(2) Assuming that the width and length of the energy dissipation section are \(b = 3.0\) m and \(L = 15\) m, respectively, the mean diameter of the filled stones is \(D = 0.4\) m. The roughness coefficient of the energy dissipation structure section can be calculated using the equation proposed by Chen et al. (2018).

(3) The debris-flow velocity can be obtained by substituting the parameters into the Manning equation. During
the design process, the relationship between the debris flow depth and the mean diameter of the filled stones is \( h = 4D \).

(4) The calculated debris-flow velocity and the admissible velocity in the first step are compared to determine whether the parameters are reasonable. If not, the design parameters can be adjusted, and the computational process repeated.

Ultimately, for design parameters of \( i = 0.35, b = B = 6.0 \text{ m}, L = 25.0 \text{ m}, \text{ and } D = 0.3 \text{ m} \), the roughness coefficient of the energy dissipation structure section is \( n = 0.109 \). The calculated debris flow velocity is 4.9 m/s, which meets the permissible velocity limit for the drainage channel.

3.3. Effect of the debris flow mitigation project in Xiaogangjian gully

The debris-flow mitigation project was completed in May 2012. From August 13 to 18, 2012, seven debris flows were triggered in the gully with a total flow volume to \( 23.2 \times 10^4 \text{ m}^3 \). The mitigation project was designed by the rainstorm with a 20-year return period in this steep and rich source materials gully, thus, the highway was effectively protected by the mitigation engineering and the debris flows did not cause a disaster. This outcome indicates that the debris flow mitigation strategy used in this gully is effective and that the construction of the mitigation system is feasible. In general, strategies for controlling debris flows using a combination of check dams, drainage channels, and debris flow deposition basins are effective (Chen et al., 2015). However, the design standard of the mitigation measures should be improved if the areas to be protected are particularly important. To ensure the longevity of the debris flow mitigation system, the following measures must be taken. During the construction, the construction quality should be inspected. After the debris flow mitigation measures are installed, their operation and maintenance, such as dredging to maintain the capacity of the check dams and repairing abrasion of the drainage channel, must be performed in a timely fashion.

![Image](image_url)

Fig. 8 Application of the debris-flow mitigation structures in Xiaogangjian gully, Sichuan Province, China

4. Conclusion

Avalanches and landslides caused by the Wenchuan earthquake in the Longmen Mountains region provided an abundant source of loose slope material for debris flows. Based on the large-scale debris-flow characteristics of the Wenchuan earthquake, a new planning method for debris-flow mitigation measures in small-scale watersheds was proposed, and new techniques for the planning and designing were suggested. A drainage channel constructed of prefabricated reinforced concrete boxes was developed and applied in a practical engineering case. In the case application in Xiaogangjian gully, a series of check dams with orifices with various sizes was constructed to promote the settling of debris-flow particles of various sizes and separate water from stone along the length of the gully channel. The impact forces of debris flows can be effectively reduced using this method. Moreover, this method can uniformly distribute debris flow materials among the group of check dams, more fully enabling the siltation and hazard mitigation functions of check dams. The results support the application of the new debris-flow
mitigation measure and new planning method to small-scale watersheds, which can not only effectively protect roadways and minimize losses by debris flows in China, but also it can apply to debris-flow-prone regions worldwide.

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References


