Protecting highway bridges against debris flows using lateral berms: a case study of the 2008 and 2011 Cheyang debris flow events, China

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Abstract

Lateral berms are often constructed to protect highway bridges against debris flows in mountainous regions. Currently, different solutions for lateral berm design are debated. The lack of standardization results in the improper design of lateral berms, limiting the mitigating effect. In this paper, a monitoring case of the mitigating effect of a lateral berm is introduced. The lateral berm was constructed through a bridge culvert at the alluvial fan of a debris-flow gully. In September 2008, a debris flow in this gully completely buried the lateral berm. The proposed numerical integral method was used to back analyse the flowing velocity and mud depth in berm. Results supported the speculation that abrupt decreases in mud depth and flow velocity in the lateral berm caused deposits that compressed the effective berm depth and resulted in overtopping flow. Therefore, we suggested reducing the berm width in order to increase the flow velocity in the berm. In June 2011, another debris flow with a smaller magnitude occurred in the gully, and the reconstructed lateral berm reportedly performed well to protect the bridge of Yalu highway. The case studies highlighted that berm width should be one of the main considerations in the berm design.

1. Introduction

Debris flows are major threats to the infrastructure of highways and high-speed railways. In China, for instance, 1036 potential debris flow gullies have been investigated along the well-known Sichuan-to-Tibet road, with nearly 400 debris flow events and 200 million RMB in economic losses recorded (Tang 1986; Yang 1993; Han et al. 2015b). These debris flow events often cause severe damage to the infrastructure of highways. As reported by Liu et al. (2014), the catastrophic Yingxiu debris flow event on 14 August 2010 in the Wenchuan area was responsible for damage to nine bridges and interrupting traffic for two months. Thus, the prevention and mitigation of debris flows are key to ensuring the safety of infrastructure in mountainous regions (Han et al. 2015a; Han et al. 2018).

To protect infrastructures against debris flows in mountainous regions, countermeasures must be used. Commonly used countermeasures include both passive and active measures (VanDine et al. 1997). Passive measures attempt to prevent debris flow by zoning or warnings and evacuation, e.g. early warning systems, proper land use strategies, and improvements to buildings (Han et al. 2017).
Active measures, in contrast, attempt to reduce debris flow hazards by using artificial structures. Discussions of various active measures can be found in several sources in the technical literature (VanDine 1996; Heumader 2000; Huebl and Fiebiger 2005; Prochaska et al. 2008; Lin et al. 2011).

In the structural mitigation system against debris flows, some artificial canals are usually built immediately downslope from the apex of the debris fan and parallel to the desired flow path. These canals are commonly referred to as ‘lateral berms’ (e.g. VanDine 1996; Prochaska et al. 2008), as well as ‘drainage canals’ in China (e.g. Chen et al. 2004; Gao et al. 2010), and ‘training dykes’ in Japan (e.g. Mizuyama 2008; Takahashi 2014). Lateral berms are similar to deflection berms but differ in that lateral berms are used to constrain the lateral movement of debris flow, encourage the debris to travel in a straight path, and thereby direct the flow towards areas of lesser consequence and laterally constrain the natural deposition area (VanDine et al. 1997; Youssef et al. 2014).

To be most effective on debris alluvial fan, orientation and cross-section geometry of lateral berms must be well designed. An idealized lateral berm is able to withstand the debris flow impact. It is widely accepted that lateral berms should be oriented at a sharp angle to flow paths to shift the course of debris flow (e.g. Huebl and Fiebiger 2005; Willingham 2005). A sharp angle between debris flow path and berm orientation helps reduce the impact of debris flow on the berm and consequently minimizes overtopping and erosional damage. Guidelines in Japan, for instance, highlight a key design criterion that the berm should ideally be oriented at less than a 45-degree angle to the expected debris flow attack angle (Ohsumi Works Office 1995).

However, regarding the cross-section geometry of the lateral berm, published guidelines are rather rare, and there appears to be little standardization. The effectiveness of the design is known to depend on debris flow magnitude and composition, channel dimensions, and construction techniques. VanDine (1996) indicated that maximum discharge and flow depth of the debris flow at the location of the structure are the main design consideration for the lateral berm. Prochaska et al. (2008) discussed some key issues in the design of lateral berms, including peak discharge, berm alignment and height, berm top width and side slopes, stability under impact loading, and the ability to pass a range of flow rates.

In general, berm width should be rationally designed according to the maximum discharge, flow depth, and flow velocity. It is commonly suggested that sidewalls of the lateral berm should be designed with a freeboard above the estimated flow depth. The freeboard of the berm has been widely discussed in the previous studies. In the Japanese standard, a 0.6-m freeboard is suggested for discharge less than 200 m$^3$ s$^{-1}$, while 0.8-m freeboard for discharges of 200–500 m$^3$ s$^{-1}$ (Government of Japan 1981). As described in the earlier study by Lister and Morgan (1989), a freeboard of 1.0 m was used in Alberta Creek. A greater freeboard of the berm performs better to prevent overtopping flow due to run-up and superelevation of the flow surface at the bend.

Guidelines for determining berm width and flow depth are relatively rare. In practical work, berm width is empirically designed considering the topography at the location of the structure, and flow depth could be subsequently estimated by the Manning–Strickler equation (Osanai et al. 2010). Berm width is a critical parameter that influences the berm performance, and it should be cautiously elaborated. Flow depth is likely to increase in a narrowed berm, thereby reducing the freeboard of the berm and increasing the risk of overtopping. Conversely, although a wide berm reduces the flow depth, the debris may deposit due to slowing velocity. It increases the risk for burying the berm.

In this paper, we introduce a monitoring case to discuss the rational design of the berm width. In this case, a lateral berm was constructed to protect a highway bridge over a debris flow alluvial fan. However, overtopping and burial of the lateral berm were observed after a debris flow event in 2008. We extended the velocity and mud depth analysis methods from our previous study (Han et al. 2015c) to analyse the in-berm behaviour of the debris flow. In the reconstruction work, we redesigned the lateral berm and reduced its width from 26.0 m to 6.5 m, accelerating debris flow in the berm. Reconstruction of the berm was completed in 2010. One year later, another debris flow event with a smaller magnitude occurred in this watershed. Almost all of the debris flow mass was reported to have been directed through the culvert towards areas of low consequence, and the highway bridge was successfully protected.
2. Background

Yalu highway is located in the mountainous region of southwestern Sichuan Province, China (as shown in Figure 1). It has been the focus of multi-year construction on the Chinese national highway network. The region along Yalu highway belongs to the southeastern margin of the Tibetan Plateau. High seismic activity in this region is dominated by the three major active faults distributed in the region, i.e. the Longmenshan, Anninghe, and Xiangshuihe faults (Chen et al. 2012). As a result of frequent tectonic activity and the complex geological and geographical conditions, strong earthquakes have occurred frequently, accompanied by large numbers of landslides and debris flows associated with serious damage (Wang et al. 2007; Chen et al. 2010).

We investigated the geomorphologic conditions along Yalu highway, and divided the study region into two major segments: segment 1 from Ya’an to Shimian over hilly terrain and segment 2 from Shimian to Lugu over highlands and mountainous terrain. During the investigative work, 19 debris flow gullies were explored, with 6 gullies along segment 1 and 13 gullies along segment 2.

To protect the highway’s infrastructure, structural countermeasures were planned to accompany the construction of Yalu highway, including check dams and lateral berms. These countermeasures were expected to obstruct the debris flow path or direct the debris flow to areas of low consequence. However, in the investigation work regarding the mitigation effect of these countermeasures, we found that some of them failed to protect the infrastructure of Yalu highway.

A typical case was reported by Han et al. (2013). As shown in the remote sensing image of Figure 1, a highway bridge crosses the alluvial fan of the Cheyang debris-flow gully (28°40’35.31”N, 102°15’21.24”E). The creek is a tributary of the Anning River, and it has a catchment area of 0.95 km² (95 ha) and high altitudes of ca. 2800–3400 m a.s.l. The gully is 1.6 km in length, with a headwater basin length of approximately 0.5 km. The basin is underlain primarily by quartz sandstone and slate of Triassic age. Because of strong tectonic movements, bedrock in the basin is highly fragmented. Scars are present on the upper slope, and the stability of the slope decreases under extreme conditions, such as earthquakes and heavy rainfall. Debris flow events are reported in this

Figure 1. Schematic illustration of the Yalu highway and the location of Cheyang gully. (The map was provided by Google Map, and the Air photo was downloaded from database of Google Earth.)
watershed every few years. To protect the highway bridge at the alluvial fan, a lateral berm was constructed through the bridge culvert. The original design is shown in Figure 2. The cement mortar berm had a depth of 3.65 m and an open berm width of 26.0 m. The berm had a 23.58% gradient along the path.

When constructing the lateral berm, the channel width was enlarged from its previous 10.0 m to 26.0 m. Based on the perspective that debris flow should decelerate in the berm to reduce abrasions to the concrete structure and to control the discharge of debris, this wide-berm design was expected to direct and reroute the debris flow through the bridge culvert effectively.

However, evidence showed that the enlarged-berm design failed to direct and transport debris flow as expected. On 17 September 2008, a debris flow event occurred after six hours of heavy rainfall. The involved debris mass was $36.6 \times 10^3$ m$^3$ in volume as estimated by the in situ investigation. The bulk density of the debris flow mass was estimated as 17.30 kN m$^{-1}$. As shown in Figure 3(b), the lateral berm was completely buried by the debris flow, and overtopping occurred. This event also delayed highway bridge construction. For this reason, reconstructing the lateral berm with a more reliable design was of utmost importance.

3. Methodology

We observed the redesign work on the lateral berm of the Cheyang gully. Over-enlargement of the channel while constructing the lateral berm was speculated to be the reason for the countermeasure failure. The abrupt drop in flow velocity in the berm significantly reduced the transport capacity and caused a blockage in the berm. In this case, therefore, the concentration and acceleration of debris flow using a narrowed berm appeared to be a more rational solution.

To support our speculation, the mud depth and flow velocity in the berm were first analysed. Numerical integral methods perform well with the irregular domain of integration. We used the
Riemann integral method as demonstrated in our previous studies to solve the issue of the complex bed surface in natural river channels.

(1) Estimating peak discharge of debris flow

The first step of this method is to estimate the peak discharge, \( Q \). We used the method illustrated by Chen and Chuang (2014). The peak discharge of debris flow is proportional to the water flow peak discharge, \( Q_w \), fed by rainfall in the watershed catchment.

\[
Q = \left(1 - c_V\right)^{-1} Q_w,
\]

where \( c_V \) is the volumetric sediment concentration of debris flow mass and is commonly no more than 0.65, according to Wrachien and Mambretti (2011), and often ranges from 0.48 to 0.55, according to Chen and Chuang (2014).

The water flow peak discharge \( Q_w \) can be estimated as follows:

\[
Q_w = CIA/t_c,
\]

where \( C \) is the runoff coefficient, which ranges from 0.7 to 0.9, as recommended by SWCB (2005); \( I \) denotes the maximum hourly rainfall intensity (mm h\(^{-1}\)); \( A \) is the watershed area (ha); and \( t_c \) is the so-called concentration time as a function of watershed characteristics. According to Tropeano et al. (1996) and Berti et al. (1999),

\[
t_c = \frac{4A^{0.5} + 1.5L}{0.8(H_m - H_0)^{0.5}},
\]

where \( L \) is the headwater basin length, \( H_m \) is the average basin elevation, \( A \) is the watershed area (km\(^2\)), and \( H_0 \) is the basin outlet elevation. Equations (1)–(3) indicate that debris flow peak discharge is regarded as the amplification of water flow discharge due to the involvement of a large amount of solid debris.

(2) Mathematically reproducing the cross-section of lateral berm
The second step is to describe the cross-section of the lateral berm from a mathematical perspective. We used the numerical integral method in previous studies (Han et al. 2015c). An inclined polyline defined by a series of vertices replicates the concrete bottom, and an interpolation is made between two neighbouring vertices (Figure 4). To obtain solutions as close to the desired integral solution as possible, the reproduced bed surface between two vertices is partitioned using linear interpolation with a small increment of $\Delta x$ (Figure 4). In this way, the cross-section is partitioned into $m$ segments.

(3) **Iterative solution of mud depth in berm and velocity distribution**

Assuming a horizontal flow surface $H_{\text{dummy}}$, the mud depth $h$ at the segment $i$ can be expressed as

$$h(i) = H_{\text{dummy}} - Z(i).$$

The mud depth is also partitioned with an increment of $\Delta y$. In this way, Equation (4) can be rewritten in the following discretized form:

$$Q_{\text{dummy}} = \sum_{i=1}^{n} \sum_{j=1}^{m} v(i,j) \Delta x \Delta y.$$  

Equation (5) implies that the peak discharge $Q$ equates the summation of the discharge in each sub-cross-section. For simplification, we assume that the velocity profile through depth follows a uniform law:

$$v(i,j) = v(i),$$

where $v(i)$ is the mean velocity at the segment $i$. The Manning–Strickler equation can be used to determine that

$$v(i) = \frac{1}{n_c} \frac{h(i)^{\frac{3}{2}}}{S^\frac{1}{2}}$$

Figure 4. Reproducing the cross-section of the lateral berm using the numerical integral method. (a) A typical cross-section of a lateral berm. (b) Linear interpolation of the individual segment between two turning points. $H$ and $Z$ are the relative elevation of the flow and concrete bottom, respectively; $h$ denotes flow depth, and $\Delta x$ denotes interpolation resolution.
In this way, Equation (5) can be reduced to

$$Q_{\text{dummy}} = \sum_{i=1}^{n} v(i)h(i)\Delta x.$$  \hspace{1cm} (8)

To estimate the unknown flow surface, an iteration algorithm is proposed. Generally, we initially assume a flow surface $H_{\text{dummy}}$ and increase the flow surface gradually with a small increment of $\Delta h$ in each iterative step. Given this flow surface, a dummy peak discharge, $Q_{\text{dummy}}$, can be obtained by using the numerical integral method. When the obtained dummy peak discharge $Q_{\text{dummy}}$ satisfies the following terminate condition (Equation (9)), the preliminary flow surface $H$ is determined as $H_{\text{dummy}}$:

$$\frac{|Q_{\text{dummy}} - Q|}{Q} \leq \varepsilon$$  \hspace{1cm} (9)

In Equation (9), $\varepsilon$ is a manipulated parameter used to control the accuracy of the calculation; here, a value of 0.01 is adopted. The iteration algorithm stops only when Equation (9) is satisfied. Otherwise, the $H_{\text{dummy}}$ will increase by a small increment of $\Delta h$ in the next step, and the iteration algorithm continues. The iterative solution of flow surface $H$ is subsequently used to analyse the velocity distribution across the berm. The lateral distribution is estimated by Equation (7), and the vertical distribution is estimated by the profile law proposed by Johnson et al. (2012) because of its best fit to laboratory experiments (Han et al. 2015c):

$$v(i,j) = \nabla (i) \left( \alpha + 2(1 - \alpha) \frac{j}{h(i)} \right),$$  \hspace{1cm} (10)

where $\alpha$ is a parameter controlling the amount of shear within the bulk of the flow; here, $\alpha = 0.5$ is suggested (Iverson 2012). $j$ denotes the vertical location through flow depth.

Equations (4–10) are used to estimate the flow depth $h$ and flow velocity $v$ in the berm. The design of the lateral berm follows these two principles:

- The berm should not over-decelerate flow velocity because deposition can cause blockage.
- The flow depth in the berm should not exceed the height of sidewalls because of the potential for overflowing.

The proposed approach was implemented in code. We programmed the core function of the approach in a MATLAB environment. MATLAB was chosen because of its powerful capacity for matrix operations and visualization features. Prior to starting the program, the controlling parameters and the shape of the cross-section must be input into separate text files in ASCII format. The program reads these files, reproduces the concrete bottom of the berm, and then iteratively searches for an approximation of the flow surface. The final determined flow surface is used to calculate the flow depth across the cross-section and can be subsequently displayed with the help of the visualization function embedded in the MATLAB environment.

4. Solution and effect

(1) Determination of peak discharge

The peak discharge of the 2008 Cheyang debris flow event was back-analysed, and detailed data used in the calculations are listed in Table 1. The calculated peak discharge of that event was $57.16 \text{ m}^3 \text{ s}^{-1}$. In checking the calculation results, we also investigated the residual evidence of the event in situ. The
residual mud line on the bank was approximately 3.0 m in height, which indicated that the area of the debris flow cross-section was 12.0–18.0 m². The flow velocity was witnessed by local residents as approximately walking speed, i.e. 3.0–5.0 m s⁻¹. Consequently, the peak discharge was estimated to range from 36.0 m³ s⁻¹ to 90.0 m³ s⁻¹, which is consistent with the theoretical calculation based on geomorphological and precipitation conditions. In a comprehensive consideration, an approximation of 60.0 m³ s⁻¹ is used to back-analyse the event.

(2) Estimating in-berm velocity

For the performance of the lateral berm, the slope of the berm was designed to be 23.58%. Because the berm’s bottom was constructed of sleek concrete, the roughness, \( n_c \), could be small; thus, \( n_c = 0.18 \) in the berm was used. Guideline for determining the roughness could be found in Li et al. (2016). The numerical integral method described above was used to determine the mud depth and velocity in the concrete berm (Figure 5). The results revealed that flow depth decreased to 1.16 m and that the mean velocity abruptly decreased to 2.97 m s⁻¹ when the debris flow mass entered the concrete berm. The greatly decreased velocity therefore limited the mass transport capacity, thus causing the boulders and debris to deposit gradually. The deposits accumulated, compressing the effective depth of the berm and subsequently resulting in overtopping flow. This theoretical analysis supports the speculation that the inappropriate deceleration solution resulted in overtopping during the 2008 Cheyang debris flow event.

![Figure 5. Calculated mud depth and flow velocity distribution in the lateral berm. The upper figure is the suggested solution, and the lower figure is the previous design.](image-url)
To address the overtopping issue, we optimized this lateral berm design for the local administration. The optimization was based on the acceleration solution. We tested the performance of a narrowed cross-section 6.5-m wide. The results in Figure 5 show that the flow depth and mean flow velocity both increased. The narrowed lateral berm is supposed to keep debris travelling, thereby preventing depositing and overtopping flow. For this reason, we suggested reducing the width of the lateral berm from 26.0 m to 6.5 m.

(3) Evaluating surface abrasion of concrete structures

Highly concentrated debris flow transports large boulders at high velocity. It is extremely erosive to the bottoms and sides of the berm (Banihabib and Iranpoor 2015). Two types of abrasions to the concrete bottom can be categorized, i.e. friction abrasion (Horszczaruk 2004; Liu et al. 2006; Banihabib and Elahi 2009; Zou et al. 2016) and impact abrasion (Liu et al. 2012; Banihabib and Iranpoor 2015) as shown in Figure 6. Both types of concrete abrasion were found in the lateral berm during the 2008 event (Figure 7). As such, it is important to check the surface abrasions of the concrete bottom. To evaluate the surface abrasion of concrete structures, an index of $E_R$ is often used. It represents the abrasion ratio, and is defined as the unit weight loss after abrasion.

\[
E_R = \frac{m_1 - m_2}{tB},
\]

where $m_1$ and $m_2$ denote the concrete weights before and after abrasion, $t$ denotes the abrasion duration, and $B$ is the abrasion area. $E_R$ is given in kg/(h·m²), and a higher value signifies weaker tested
concrete abrasion resistance. Previous studies focused on measuring $E_R$ via laboratory experiments, and in Table 2, we summarize the measurements obtained in some of these studies. However, most previous studies explored the concrete abrasion ratio by sand-water or water flows, which are understood to be much less abrasive and erosive than debris flows. Chen et al. (2004) suggested that the concrete bottom erosion rate by debris flows is approximately $4.35 \times 10^{-5} \text{ cm s}^{-1}$, which equates to $4.35 \text{ kg/(h\cdot m}^2)$. Abrasion by debris flows may be 5–10 times larger than that by sand-water flows (Liu et al. 2006; Liu et al. 2012).

Owing to the small amount of knowledge on concrete abrasions by debris flows, we must compromise and assume that the Cheyang debris flow had the same abrasive capacity as the debris flow presented by Chen et al. (2004). This means that the 0.35-m thick concrete bottom in the original design permits 212-h abrasion by debris flow. We also suggest increasing the stiffness of the berm bottom via some enhancement, such as using a metal cover with a metal halter on the concrete bottom of the lateral berm in Chen et al. (2014).

(4) Effect

The suggested solution was approved by the local administration and expert committee, and as shown in Figure 8, reconstruction work on the lateral berm was finished in May 2010. One year later, on 16 June 2011, another debris flow event occurred. The inundated area was estimated as 38,720 m$^2$, with the averaged deposition depth commonly around 0.7–0.9 m. As such, the actual mass volume of the 2011 event approximated 27,104–34,848 m$^3$, obviously smaller than the 2008

### Table 2. Abrasion ratios as revealed by different experiments.

| Abrasion type                                | $E_R$(kg/(h·m$^2$)) | Conditions                                                                 |
|----------------------------------------------|----------------------|-----------------------------------------------------------------------------|
| Comprehensive abrasion by debris flow (Chen et al. 2004) | 4.35                 | C30 (w/c = 0.32), sand content = 1314 kg/m$^3$, boulder diameter = 6.31 mm   |
| Impact abrasion by water-borne sand (Liu et al. 2006)    | 0.59–0.90            | C50 (w/c = 0.5), water content = 160 kg/m$^3$, boulder diameter ranges from 5 mm–25 mm |
|                                                     | 0.32–0.35            | C28 (w/c = 0.28), water content = 140 kg/m$^3$, boulder diameter ranges from 5 mm–25 mm |
| Friction abrasion by sand-water flow (Gao et al. 2014)   | 0.03–0.06            | w/c = 0.35, water flow with low sand content                                |
| Impact abrasion by sand-water flow (Liu et al. 2012)     | 0.42–1.15            | w/c = 0.50, sand content = 340 kg/m$^3$, impact angle ranges from 90°–45°   |
|                                                     | 0.40–0.93            | w/c = 0.36, sand content = 340 kg/m$^3$, impact angle ranges from 90°–45°   |
|                                                     | 0.27–0.57            | w/c = 0.28, sand content = 340 kg m$^{-1}$, impact angle ranges from 90°–45° |

Note: $E_R$ denotes the abrasion ratio. w/c denotes water/cement ratio. C30, C28, and C50 represent different concrete types in reference to the water/cement ratio.

Figure 8. Redesigned cross-section of the debris flow lateral berm. The mud depth in the berm is estimated by the presented approach. The berm was reconstructed in May 2010 with the suggested improvements.
event. Although the challenge by the event with a smaller magnitude was certainly reduced, the improvement of the mitigation effect of the reconstructed berm was observed. As shown in Figure 9, most of the boulders and debris mass were successfully directed through the highway bridge culvert towards the alluvial fan, and very little debris left in the berm. This observation also supports our overall finding in the study.

5. Discussion

(1) Sensitivity to the peak discharge

As demonstrated in VanDine (1996), the maximum discharge is the main design consideration for lateral berms. To evaluate the influence of discharge, we tested different values ($Q$ ranges from 10 to 110 m$^3$ s$^{-1}$) and compared the results to reveal the sensitivity to $Q$. Figure 10 shows that both flow depth and velocity significantly increase with the discharge $Q$. As demonstrated in Section 4, a freeboard of 1.28 m remains for the back-analysed discharge of 60 m$^3$ s$^{-1}$. The satisfactory freeboard provides space for preventing overtopping due to superelevation and run-up. Such reliability of the lateral berm may be under threat because freeboard reduction with the increase of peak discharge is obvious. In the extreme situation of the sensitivity test in Figure 10, the freeboard of the berm exhausts when peak discharge extends upward to 110 m$^3$ s$^{-1}$. In this context, the sensitivity analysis suggests a maximum discharge of 110 m$^3$ s$^{-1}$ for the reconstructed lateral berm.

(2) 'Deceleration solution' and 'acceleration solution' for the lateral berm design

Currently, two conflicting solutions for the design of lateral berm exist: the ‘deceleration solution’, which dissipates debris flow energy but entails a risk of overtopping flow, and the ‘acceleration solution’, which maintains debris flow energy but results in freeboard reducing and structural abrasion.

‘Deceleration solution’ stresses the function of rerouting debris flows and the durability of the berm structure. Highly concentrated debris flows can transport large boulders at high velocities and
are extremely erosive to the bottoms and sides of the berm. To prevent abrasions to the concrete structure, some early studies suggested decelerating debris flows in the berms by enlarging the width of the berms or using submerged sill on the bottom, such as with Dongchuan-type berms in China (Huang et al. 2009). However, Gao et al. (2010) indicated that such lateral berms do not perform well because heavy in-berm deposition often occurs.

In contrast to the ‘deceleration solution’, some recent studies (e.g. Prochaska et al. 2008; Pierson et al. 2014) recommended a second type, the ‘acceleration solution’. These authors suggested that the lateral berm must be sufficiently smooth, steep, and narrow to maintain the flow depth needed to prevent in-channel deposition, implying that debris flows should maintain velocity or even accelerate in the berm. However, consequently, debris flows become more erosive, and the bottom and sides of the lateral berm must be revetted by concrete or stone masonry (Youssef et al. 2014). Meanwhile, the debris flow depth is likely to increase in a narrow berm, thereby increasing the risk of overtopping. If sidewalls of the berm are overtopped, the rapid erosion of back side of the berm can quickly cause their failure (Paguican et al. 2009).

Based on the previous studies above, we summarize the pros and cons of both the solutions in Figure 11. Nevertheless, owing to the lack of convincing evidence and theoretical support, a rational comparison of the two solutions is scientifically challenging. In the investigated case as described in this paper, we have found that the reconstructed lateral berm using ‘acceleration solution’ performs better. Through the rational estimation of flow depth and erosion in the berm, risk for overtopping and structure abrasion can be minimized. The case study in this paper also makes a supplement for

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**Figure 10.** Sensitivity analysis of flow depth and velocity in the lateral berm against different peak discharge.
the system of design consideration for lateral berms. It is suggested that for the either solution, berm width should be one of the main design considerations except of maximum discharge and flow depth in VanDine (1996).

(3) Limitations and ongoing work

Some limitations still exist in the current study. First, the proposed method in this paper represents an alternative solution for evaluating the flow velocity and the mud depth of debris flows in lateral berms. However, strong phase separation in debris flow, which is an important feature of debris flows as substantiated by Pudasaini and Fischer (2016), could not be taken into account. Phase separation mechanically results in a solid-dominated front surge of debris flow, leading to a varying velocity profile through depth. Such effect owing to the phase separation has to be simplified by the velocity profile law in Equation (10), and a fitting parameter \( \alpha \) is introduced, which turns the method into a semi-empirical law. Second, the mitigation effect of the ‘acceleration solution’-based lateral berm still requests long-term monitoring and evaluation. Especially that the 2011 event was smaller than the 2008 event in magnitude. Although the reconstructed berm performed well because very little deposits left in the berm, the advantage of the ‘acceleration solution’ will be more convincing when undergoing a debris flow event with a comparable or much greater magnitude. As such, our ongoing work focuses on improving the method presented here by considering the two-phase model of debris flow, as well as collecting the data for supporting our conclusions.

6. Conclusion

In this paper, we introduce a monitoring case to discuss the rational design of lateral berms. We used the proposed numerical integral method in our previous study to analyse the mud depth and flow velocity distribution in the berm and found that the abrupt decrease in flow velocity from the natural channel to the concrete berm significantly reduced the transport capacity, thereby causing deposits in the berm. For the reconstruction, we suggested the acceleration solution and reduced the berm width from 26.0 m to 6.5 m. The reduction of the berm width increased the mean flow velocity from 2.97 to 4.84 m s\(^{-1}\), and guaranteed a 1.24-m freeboard of the berm. The redesigned lateral berm was supposed to reduce the risks of debris deposition and overtopping flows. Reconstruction of the berm was completed in 2010, and the berm successfully transported a subsequent debris flow with a smaller magnitude in 2011. We suggest using the lateral berm based on the acceleration solution with an enhanced bottom to direct debris flows and protect highway bridge infrastructure.
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References

Banihabib ME, Elahi M. 2009. Empirical equation for abrasion of stilling basin caused by impact of sediment. In: Starrett S, editor. World Environmental and Water Resources Congress 2009: Great Rivers. Kansas City (MO): American Society of Civil Engineers; p. 3481–3490.

Banihabib ME, Iranpoor M. 2015. Determination of the abrasion of aprons of dams by debris flow. Int J Mater Struct Integrity. 9(4):262–271.

Berti M, Genevois R, Simoni A, Tecca PR. 1999. Field observations of a debris flow event in the Dolomites. Geomorphology. 29:265–274.

Chen HK, Tang HM, Wu SF. 2004. Research on abrasion of debris flow to high-speed drainage structure. Appl Math Mech. 25(11):1150–1156.

Chen JC, Chhuang MR. 2014. Discharge of landslide-induced debris flows: case studies of Typhoon Morakot in southern Taiwan. Nat Hazards Earth Syst Sci. 14(7):1719–1730.

Chen JG, Chen XQ, Wang T, Zou YH, Zhong W. 2014. Types and causes of debris flow damage to drainage channels in the Wenchuan earthquake area. J Mt Sci. 11(6):1406–1419.

Chen XL, Zhou BG, Ran HL, Yamamoto Y, Hyodo M. 2010. Geohazards induced by the Wenchuan earthquake. London: Taylor & Francis Group; p. 2010.

Chen XL, Zhou Q, Ran H, Dong R. 2012. Earthquake-triggered landslides in southwest China. Nat Hazards Earth Syst Sci. 12:351–363.

Gao Q, Chen XQ, Zhao WY. 2010. [A review: design of debris flow drainage canal]. J Geol Hazard Control. 21(2):1–7. Chinese.

Gao YH, Zhu YD, Fu ZQ, Wu LJ, Zhang JZ. 2014. Wear-resistant performance of reinforcing hydraulic concrete with igneous rock fiber. J Hydroelectric Eng. 33(5):177.

Government of Japan. 1981. A guide of counter measures against debris flow disasters. Sabo Div, Public Works Res Inst, Min Constr, Jap Civil Eng J. 23(6–11):186.

Han Z, Chen GQ, Li YG, He Y. 2015a. Assessing entrainment of bed material in a debris-flow event: a theoretical approach incorporating Monte Carlo method. Earth Surf Process Landforms. 40:1877–1890.

Han Z, Chen GQ, Li YG, Kasama K. 2013. An optimized method for run-out volume estimation of seismic debris flow. In: Chen GQ, editor. Proceedings of the 48th Japan National Conference on Geotechnical Engineering; Jul 23, Toyama, Japan. p. 1937–1938.

Han Z, Chen GQ, Li YG, Tang C, Xu LR, He Y, Huang X, Wang W. 2015b. Numerical simulation of debris-flow behavior incorporating a dynamic method for estimating the entrainment. Eng Geol. 190:52–64.

Han Z, Chen GQ, Li YG, Wang W, Zhang H. 2015c. Exploring the velocity distribution of debris flows: an iteration algorithm based approach for complex cross-sections. Geomorphology. 241:72–82.

Han Z, Li YG, Huang JL, Chen GQ, Xu LR, Tang C, Zhang H, Shang YH. 2017. Numerical simulation for run-out extent of debris flows using improved cellular automaton model. Bull Eng Geol Environ. 76(3):961–974.

Han Z, Wang WD, Li YG, Huang JL, Su B, Tang C, Chen GQ, Qu X. 2018. An integrated method for rapid estimation of the valley incision by debris flows. Eng Geol. 232:34–45.

Heumader J. 2000. Technical debris-flow countermeasures in Austria--a review. In: Wieczorek G. F, Naeser ND, editors. Proceedings of the Second International Conference on Debris-flow Hazards Mitigation, Taipei, Taiwan, Aug 16–18, 2000. Rotterdam: AA Balkema. p. 553–564.

Horszczaruk E. 2004. The model of abrasive wear of concrete in hydraulic structures. Wear. 256:787–796.
Huang H, Ma D, Wang X. 2009. [Experimental study on the relationships between the velocity of debris flow and structure of the Dongchuan debris flow channel]. J Mountain Sci. 27(5):551–556. Chinese.

Huebl J, Fiebiger G. 2005. Debris-flow mitigation measures. In: Jakob M, Hungr O, editors. Debris-flow hazards and related phenomena. Berlin: Springer; p. 445–487.

Iverson RM. 2012. Elementary theory of bed-sediment entrainment by debris flows and avalanches. J Geophys Res. 117:F03006.

Johnson CG, Kokelaar BP, Iverson RM, Logan M, LaHusen RG, Gray JMNT. 2012. Grain-size segregation and levee formation in geophysical mass flows. J Geophys Res. 117:F01032.

Li YG, Tang C, Han Z, Huan J, Xu L, He Y, Chen G, et al. 2016. Estimating the mud depth of debris flow in a natural river channel: a theoretical approach and its engineering application. Environ Earth Sci. 75(8):722.

Lin JY, Yang MD, Lin BR, Lin PS. 2011. Risk assessment of debris flows in Songhe Stream, Taiwan. Eng Geol. 123(1–2):100–112.

Lister DR, Morgan GC. 1989. Debris torrents along Howe Sound, British Columbia. Field Trip Excursion Guidebook, Conference XX, International Erosion Control Association, Vancouver, BC.

Liu JF, You Y, Chen XQ, Liu JK, Chen XZ. 2014. Characteristics and hazard prediction of large-scale debris flow of Xiaojia Gully in Yingxiu Town, Sichuan Province, China. Eng Geol. 180:55–67.

Liu YW, Cho SW, Hsu TH. 2012. Impact abrasion of hydraulic structures concrete. J Marine Sci Technol. 20(3):253–258.

Liu YW, Yen T, Hsu TH. 2006. Abrasion erosion of concrete by water-borne sand. Cement Concrete Res. 36:1814–1820.

Mizuyama T. 2008. Structural countermeasures for debris flow disasters. Int J Erosion Control Eng. 1(2):38–43.

Ohsumi Works Office. 1995. Debris flow at Sakurajima, Kyushu regional construction bureau, ministry of construction, Japan, Vol. 2, pp. 81.

Osanai N, Mizuno H, Mizuyama T. 2010. Design standard of control structures against Debris flow in Japan. J Disasters Res. 5(3):307–314.

Paguican EMR, Lagmay AMF, Rodolfo KS, Rodolfo RS, Tengonciang AMP, Lapus MR, Balisatan EG, Obille EC Jr. 2009. Extreme rainfall-induced lahars and dike breaching, Mayon Volcano, Philippines. Bull Volcanol. 71:845–857.

Pierson T, Wood N, Driedger C. 2014. Reducing risk from lahar hazards: concepts, case studies, and roles for scientists. J Appl Volcanol. 3(16):1–25.

Prochaska A, Santi P, Higgins J. 2008. Debris basin and lateral berm design for fire-related debris-flow mitigation. Environ Eng Geosci. 14(4):297–313.

Pudasaini SP, Fischer JT. 2016. A mechanical model for phase-separation in debris flow. arXiv preprint arXiv: 1610.03649.

[SWCB]Soil and Water Conservation Bureau. 2005. [Technical handbook of soil and water conservation, soil and water conservation bureau (SWCB), Taiwan]. Chinese.

Takahashi T. 2014. Debris flow: mechanics, prediction, and countermeasures. Leiden: CRC Press/Balkema.

Tang WP. 1986. Research on the debris flow distribution characteristics and their activities in China. J Railway Eng. 4:96–100.

Tropeano D, Casagrande A, Luino F, Cescon F. 1996. [Processi di mud-debris flow in Val Cenischia (Alpi Graie) – Osservazioni nel bacino del T. Marderello]. Quaderni di studi edocumentazione dell’Associazione Georisorse a Ambiente. 20:5–31. Italian.

VanDine DF. 1996. Debris flow control structures for forest engineering: ministry of forests research program. Working paper 22, pp. 68. 08/1996, Victoria, British Columbia.

VanDine DF, Hungr O, Lister R, Chatwin SC. 1997. Channelized debris flow mitigation structures in British Columbia, Canada. In: Chen CL, editor. Debris-flow hazards mitigation: mechanics, prediction, and assessment. New York: American Society of Civil Engineers; p. 606–615.

Wang HB, Sassa K, Xu WY. 2007. Analysis of a spatial distribution of landslides triggered by the 2004 Chuetsu earthquakes of Niigata Prefecture, Japan. Nat Hazard. 41:43–60.

Willingham WF. 2005. The army corps of engineers’ short-term response to the eruption of Mount St. Helens. Oregon Hist Quart. 106:174–203.

Wracchin D, Mambretti S. 2011. Assessment of debris flow magnitude in small catchments of the Lombardy Alps: the Val Gola case study. Agr Sci. 2:9–15.

Yang JC. 1993. [Topographical features and related evolution in China]. Beijing: Ocean Press, Inc. Chinese.

Youssef AM, Pradhan B, Maerz NH. 2014. Debris flow impact assessment caused by 14 April 2012 rainfall along the Al-Hada Highway, Kingdom of Saudi Arabia using high-resolution satellite imagery. Arab J Geosci. 7:2591–2602.

Zou JF, Xia ZQ, Dan HC. 2016. Theoretical solutions for displacement and stress of a circular opening reinforced by grouted rock bolt. Geomech Eng. 11(3):439–455.