Debris flow amplification in a moraine terrace and related engineering measures in the Zongzhai Valley, Southeastern Tibetan Plateau

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\textbf{ABSTRACT}

Debris flows can quickly destroy basic facilities in mountainous areas, where suitable land resources are limited and towns are located on gentle slopes. To alleviate the threat of debris flows, two main approaches, based on debris storage or debris-flow excretion, have been proposed in recent decades in China. In August 2015, a debris flow occurred in the Zongzhai Valley for the first time in the last 100 years. Field surveys, section measurements and discharge calculations indicated that the bulking of the debris flow and the sediment entrainment were serious, resulting in the widening and deepening of the channel along the moraine terrace. Therefore, the two traditional mitigation methods appear to be inappropriate for the debris flows in Zongzhai Valley because this region lacks sufficient space for debris storage and economic support for a long drainage canal. This study analyzed the supply mechanism of the bed material and bank sediments along the moraine terrace and found that the bank collapse was mainly controlled by bed scour. Based on a literature review, we determined that the channel bed strength in the terrace should be increased and proposed that shallow dams be constructed to maintain the stability of the channel bed. The parameters of these shallow dams are provided in this article.

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1. Introduction

Debris flows are a common phenomenon in mountainous areas as water mixes with sediments ranging from sand to boulders (e.g., Iverson 1997; Cui et al. 2013; Liu et al. 2016; Deng et al. 2017). Debris flows always originate from high and steep slopes or channels under the effects of a storm (Iverson 1997; Zhou and Tang 2014; Deng et al. 2017), surface runoff (Theule et al. 2012; Kean et al. 2013) or ice...
meltwater (Arenson and Springman 2005; Deng et al. 2017). These flows move along the slope or channel driven by gravitation and deposit in a flatter location, and they are prone to blocking rivers at the confluence with a secondary river (Chen et al. 2015; Liu et al. 2016). Such locations may include towns or villages with a higher social economy and superior basic facilities compared with those in mountainous regions. Debris flows are sudden and ferocious, with the solid volume reaching several millions of cubic metres or more (e.g. Jordan 1995; Procter et al. 2010), and they impinge and bury structures downstream, such as houses, roads and bridges, which can lead to serious injury, death and economic loss. In particular, considerable losses are caused by frequent debris flows after strong earthquakes (Chen et al. 2011; Cui et al. 2013).

To alleviate the loss caused by debris flows, different types of engineering measures have been implemented worldwide, including check dams (Mizuyama 2008; Chen et al. 2015), flexible net dams (Canelli et al. 2012; Volkwein et al. 2015), drainage canals (Takahisa 2008; Brunkal and Santi 2016), debris flow storage basins (Gems et al. 2014) and lateral berms (Qiu et al. 2017). In China, the following engineering measures are applied: Low check dams are used for bed and bank sediment protection, high check dams are used for debris flow storage, grille dams are used for debris flow storage via particle size sorting, and drainage channels are used for debris flows excretion. In practice, a combination of the aforementioned measures has been applied (Zhou et al. 1991). Two main schemes are used to determine the engineering measures of channelized debris flows. The first is focused more on debris flow storage via high check dams, which requires a gentle and wide channel to provide sufficient room for debris storage. The second strengthens debris flow excretion into a secondary river via a downstream drainage channel. Because river blocking could occur if the debris flow discharge is large (Chen et al. 2015; Liu et al. 2016), grille dams are often used in the middle stream to sort solid sediment and decrease debris flow discharge.

At 20:45 on 19 August 2015, debris flows occurred in four branches of the Zongzhai Valley, Nyingchi, Southeastern Tibet. Debris flows passed through the central moraine terrace and induced high entrainment along the channel, resulting in a much wider and deeper channel and debris flows of a much larger magnitude. Selecting between the two previously mentioned engineering mitigation schemes is difficult because of the insufficient room for debris storage along the narrow and steep channel and the expenses involved in constructing a long-distance drainage canal with concrete walls on both sides. However, land resources are limited in mountainous areas of China and worldwide, and many towns and villages are located on moraine terraces, high river terraces or debris flow deposit fans along rivers, where debris flows can greatly amplify when passing through (Berger et al. 2011). This type of amplification should be controlled because debris flows with a larger magnitude could result in higher fatalities as evidenced from a global analysis of debris flows from 1950 to 2011 (Dowling and Santi 2014). In this article, we use debris flows in the Zongzhai Valley as a case study to analyze the evolution of debris flow discharge and the entrainment mechanisms of bed sediment and bank collapse when debris flows pass through a moraine terrace. In addition, we propose a new type of engineering measure that can greatly alleviate bed and bank entrainment.
2. Study area

The Zongzhai Valley, which is to the south of the downstream Nyang River (a sub-tributary of the Yarlung Zangbo River), has a drainage area of 24.86 km² (Figure 1). The Zongzhai Valley has a southwest–northeast orientation, with its top at the southwestern boundary at 4677 m a.s.l. and a 1.7 km wide outlet to the northeast at 2974 m a.s.l. Two drainage systems are observed in this valley, with streams 1–4 flowing into the western channel and streams 5 and 6 flowing into the eastern channel. Characteristic parameters of each stream are provided in Table 1. As shown in Table 1, the stream branches in the Zongzhai Valley have large gradients; the gentlest (stream 2) has an average gradient of 355°, while the steepest (stream 6) has an average gradient of 588°.

No fault stretching was observed in the valley, and the lithology is divided by the line G-G, with granite to the southwest and gneiss to the northeast (Figure 1). According to remote sensing data, vegetation is dense below 4300 m a.s.l., and only stones and sparse grass are present above this elevation. In general, streams 1 and 6 are wholly covered by dense vegetation, whereas the sources of other streams above 4300 m a.s.l. are bare. According to our field survey, the trees in the valley are coniferous, and most are pine trees, under which grow shrubs and herbs, including bamboo and cuckoo.
Zongzhai Valley is in an area where the Indian monsoon moves to the north above the Yarlung Zangbo River and its tributaries (Gao 2008). According to the observations of the Nyingchi metrological station, which is approximately 8 km to the northwest at an elevation of 3000 m a.s.l., the annual rainfall is approximately 674 mm, and the average temperature is 16 °C during summer and 1.4 °C during winter. The historical glacier movement in this valley was significant, leaving a huge moraine terrace of 2.92 km² in the centre of the valley. The top of the moraine terrace in the western and eastern stream varies and reaches 3775 m a.s.l. between streams 2 and 3, suggesting greater glacier movement in the eastern stream.

Debris flows in Zongzhai occurred in August 2015 in streams 1, 2, 4, 5 and 6. Considering that the debris flows rushed along streams 1 and 6 only a short distance in the moraine terrace, only streams 2, 4 and 5 are included in the analysis. For the middle and downstream of stream 2, the moraine terrace is on the east, and eluvium forms the western boundary (Figure 1). For streams 4 and 5, the middle part of each stream is among the ridges, and the downstream passes through the moraine terrace (Figure 1).

### 3. Data and methods

The Nyang River has a wide valley between 2.5 and 5.5 km in width and with an average gradient of 3%. The majority of local people live in this valley, whereas few live in the mountains. Metrological stations were established in the valley, and the nearest one, Nyingchi metrological station, is 8 km upstream. This station dates to the middle of the last century, and its observations are well documented. After the debris flows, the daily rainfall from the 1st to 20th of August and hourly rainfall on the 19th of August was collected at a 0.1 mm resolution.

#### 3.1. Remote sensing

The study area is on the border of the Tibetan Plateau, and the majority of the valley is difficult to reach because of high altitude; in addition, our view was limited during field surveys because of the dense vegetation. In practice, remote sensing is used to detect the distribution of vegetation and soil sources and the initiation, movement and depositional area of debris flows. To eliminate the impact of clouds, two GF2 remote sensing images (taken by the GaoFen2 optical remote sensing satellite with a resolution of 1.0 m) on sunny days before and after the debris flow event were collected on 11 February 2015 and 19 November 2015, respectively.
3.2. Field survey

(1) Moraine terrace
Remote sensing can detect the boundary between the moraine terrace and the steep slope, although this boundary is occasionally obscure. During the field survey, moraine and eluvium must be carefully identified. A laser range finder was used to measure the surface gradient and the height of the terrace from the top of the moraine terrace to the bare bedrock in the channel. The moraine surface has been changed by rainfall or surface erosion, and the newly uncovered slope surface along the channel caused by the bank collapse during debris flow erosion reflects the particle size distribution of the moraine.

(2) Section measurement
Measurements were conducted using a laser range finder with a precision of 0.1 m. Measurements of sections and channel gradients were included. Because the distribution of the debris flow velocity of the channel section at the bend is uneven, section measurements were not conducted at the bend. The section should be smooth without embossments, trunks or other blockages that could promote splashes of the debris flows. In addition, the location of the channel bed and debris flow surface could be clearly distinguished. The location of the channel bed was determined using the following rules: (1) the bedrock of the channel bed is bare, with remnants of runoff erosion, and (2) boulders of the channel bed are rounded and grooved by runoff. Debris flows could entrain the sediment and leave remnants of slurry along the boundary during its passage. For the section, the upper remnants had not been changed by runoff or debris flows, and the mixture of remnants with fine particles, leaves and dead wood is significantly different from the slope eluvium. The channel gradient is the averaged value of the channel measured 5 metres downstream or upstream away from the channel section, and local rises by sole boulders should be eliminated.

(3) Sediment supply
The channel section morphology after a debris flow can be obtained via section measurements, and in-person interviews with local herdsmen can provide additional information about the channel prior to the debris flows. During the field survey, the herdsmen were invited to walk along the channel and provide an estimate of the width and location of the channel by determining certain references, such as trees or larger boulders. The moraine and eluvium on both sides of the channel were once covered by thick vegetation, and the newly formed scar of the channel bank was analyzed to determine the particle size distribution of the material. In our field survey, samples of debris flow deposits were collected to determine the particle size distribution. Because the surface deposits had been changed by rain or surface runoff, the first 10 cm was removed, and the underneath sediments smaller than 60 mm were collected.

3.3. Debris flow discharge
The debris flow discharge can be calculated using the section area and the debris flow velocity as follows:
where \( Q_c \) is the discharge of debris flow through the section, \( m^3/s \); \( A_c \) is the section area through which the debris flow passes, \( m^2 \); and \( V_c \) is the debris flow velocity, \( m/s \).

Debris flows always have the fastest velocity at their surface and the slowest velocity at their bed. Because the internal velocity is difficult to calculate, the surface velocity is often applied. Based on the field observations of debris flow velocities in southwestern China, the following formula that has been widely used in debris flow mitigation was used:

\[
V_c = \frac{1}{\sqrt{\gamma_s \varphi}} \left( 1 + \frac{1}{n} R_c^{2/3} I_c^{1/2} \right)
\]  

(2)

\[
\varphi = (\gamma_s - \gamma_w)(\gamma_s - \gamma_c)
\]  

(3)

where \( V_c \) is the debris flow velocity, \( m/s \); \( n \) is the roughness coefficient and is determined from an assignment table based on the debris flow fluid characteristics and channel conditions (Fei and Shu 2004); \( R_c \) is the hydraulic radius of the debris flow, \( m \), and \( R_c = \chi / A_c \), where \( \chi \) is the wetted boundary of the section, \( m \); \( I_c \) is the channel gradient based on field measurements; \( \varphi \) is the correction coefficient; \( \gamma_s \) is the specific gravity of the solid material, \( g/cm^3 \); \( \gamma_w \) is the unit weight of water, \( \gamma_w = 1 g/cm^3 \); and \( \gamma_c \) is the unit weight of the debris flow, \( g/cm^3 \).

Sample testing is a good method to determine debris flow density. However, it is difficult to collect samples because debris flow observations are limited; in addition, only a small proportion of debris flows are witnessed by local people. Debris flows have not been observed in the Zongzhai Valley, and local people maintain limited knowledge of debris flows, which increases the difficulty of determining the state of the debris flows. Normally, the information maintained by debris flow deposits, such as the particle size distribution can be applied to deduce the debris flow density (Chen et al. 2003; Yu 2009). Using data from a large number of debris flow samples from southwestern China, Yu (2009) proposed a new method of calculating the debris flow density based on the contents of particles smaller than 0.05mm and larger than 2mm, as follows:

\[
\gamma_c = P_{0.05}^{0.35} P_2 \gamma_v + \gamma_x
\]  

(4)

where \( P_{0.05} \) is the content of particles smaller than 0.05mm, \( P_2 \) is the content of particles larger than 2mm, and \( \gamma_v \) and \( \gamma_x \) are the correction coefficients for 2.0 and 1.4 g/cm\(^3\), respectively.

4. Results and discussion

4.1. Distribution of sediments

(1) Sediments in the mountains

According to the remote sensing and field survey data, the moraine is the source, and the eluvium on the slope and channel bank collapsed along the moraine terrace. Based on remote sensing, the moraine in the source area is
mainly distributed in the upstream of streams 2 and 3; these areas are flatter areas, and there is a low possibility of the moraine forming debris flows. Eluvium is distributed on the slope where the vegetation is dense with trees, shrubs and herbs. The bedrock of the slope is slightly covered by eluvium, as indicated by the erosion scars on the slope of stream 2 due to concentrated runoff during rainstorms. Because the vegetation is dense and the eluvium is shallow, the eluvium should be of high humus content. In streams 4 and 5, a shallow gravel landslide is distributed in the middle stream. In the terrace area, bank collapse of the moraine provides abundant sediment.

(2) Background of the moraine terrace
The moraine terrace is located in the north part of the valley (Figure 1) and covers an area of approximately 2.92 km², although distinguishing the moraine from the eluvium is somewhat difficult. The thickness of the moraine terrace varies, with a larger thickness in the upper terrace and a smaller thickness in the lower terrace. In the upper terrace, the terrace can exceed 50 m; for example, the terrace is approximately 60 m deep at section S2-1. In the lower terrace, the borehole at the elevation of 2947 m (Figure 1) shows that the underground layer is composed predominantly of gravel soil, followed by sand and clay. The moraine terrace is wide in the north and narrower to the south. In the south, the moraine terrace is gradually divided into two branches. Along streams 2 and 3, the moraine terrace is much longer, and it reaches an altitude of approximately 3770 m a.s.l., whereas in streams 4 and 5, the moraine terrace is shorter in length and reaches only approximately 3400 m a.s.l.

The moraine terrace can be divided into four parts according to the surface gradient. The top part is between 3770 and 3600 m a.s.l. It presents an average surface gradient greater than 37%, and it is covered by large glacial erratic boulders and tall trees. The second part is between 3600 and 3380 m a.s.l. and presents an average surface gradient between 28% and 37%, and it is covered by a mixture of large glacial erratic boulders, gravels and silt and shrubs. The third part is between 3600 and 3380 m a.s.l. and has an average surface gradient between 20% and 28%, and it has far fewer glacial erratic boulders and more gravel and silt. Moreover, tree felling was significant and widely distributed, leaving stumps, shrubs and herbs. The lowest part is no higher than 3220 m a.s.l. and presents an average surface gradient between 14% and 20%. The surface seems to have been greatly changed by runoff because the silt content is decreasing, while the content of sand and gravel is increasing. Judging by the new scar of the channel bank after the debris flows, the composition of the moraine terrace ranges from small silt particles to larger boulders, whereas larger boulders in the eluvium are not as common.

4.2. Triggering of the rainfall process
At the beginning of August 2015, rainfall occurred occasionally; the maximum daily rainfall reached 20.5 mm (Figure 2a). During the latter half of the month, more continuous rainfall occurred. On the 16th, the daily rainfall reached 19.6 mm, and over the next 2 days, it reached 27.3 mm and 20.9 mm (Figure 2a). In summary, the 3-day precipitation before the debris flows reached 67.8 mm.
On the 19th, only occasional drizzle occurred before dawn, with a maximum hourly rainfall of only 1.9 mm/h. After dawn, the rain stopped and then restarted until 14:00. After a flurry for a short time, the rain began to increase rapidly (Figure 2b) and reached 10.3 mm/h at approximately 18:00. At 20:45, debris flows rushed out from the Zongzhai Valley and lasted for nearly 1 hour. The debris flows from the western stream blocked Highway S306 through the culvert, and debris flows through the eastern stream blocked the Nyingchi-Lhasa highway. In summary, the accumulated rainfall before the debris flows reached 51.5 mm at an average hourly rainfall intensity of 6.91 mm/h. After the debris flows, the rain intensity began to decrease and quickly reached less than 2 mm/h.

These debris flows occurred hours after the storm because long-duration high-intensity rainfall is prone to generate large surface runoff (Zhuang et al. 2009; Stoffel et al. 2011). An interesting phenomenon occurred in which the rainfall intensity decreased once the debris flows started, which leads to the following question: if the rainfall intensity had declined much earlier, would the debris flows have been generated? The debris flows in the Zongzhai Valley are of low frequency, with no debris flows documented over the last several decades; however, debris flows are frequently reported in the nearby Parlung Zangbo basin (Jiang 2002; Liu et al. 2013; Deng et al. 2018; Wei et al. 2018). In recent decades, debris flows have occurred for the first time in the Tuomo and Zenong valleys, which are 150 km away in the middle stream of the Parlung Zangbo (Deng et al. 2018), suggesting a regional rainfall process with rare high rainfall intensities and totals.

4.3. Discharge of debris flows

(1) Debris flow density

In streams 2, 4 and 5, samples of the debris flow deposits were collected. The samples were first sent to the laboratory to determine the particle size
distribution and calculate the debris flow density. Because subsurface flows among
the boulders can transport fine particles and change the particle distribution, debris
flow deposits were collected where fewer boulders have aggregated. The surface
layer, which has been changed by rainfall and surface runoff, was first removed,
and then the unchanged sediments underneath were collected. A sifter and
Malvern particle analyzer were combined to complete the test, and the particle size
distribution curve is shown in Figure 3. According to Figure 3, Equation (4) was
applied to calculate the debris flow density as given in Table 2.

(2) Discharge of debris flows
Section measurements are used to calculate the discharge of debris flows and
show the evolution of discharge among different sections and the subsequent
amplification of debris flow magnitude. To show changes in the debris flow
magnitude along the moraine terrace, two measured sections should be set
above and downstream of the moraine terrace, and other sections between
them that exhibit the amplification process should also be included. As stream
2 stretches a long distance along the moraine terrace to a high altitude that is
difficult to reach, the highest measured section (S21) (Figure 1) is on the
moraine terrace; however, the moraine terrace between streams 4 and 5 is
much lower, and the highest measured section in streams 4 and 5 (S41 in
stream 4 and S51 in stream 5; Figure 1) is above the moraine terrace. After the
confluence of stream 4 with stream 3, the addition of water flows from stream
3 will dilute the debris flows, thereby changing the debris flow entrainment to
set the lowest section above the confluence. For the other two streams, the
channel bank becomes gradually lower downstream as the debris flow magni-
tude increases and the debris flow begins to cross the banks and deposits; thus,
the two lowest measured sections are still on the moraine terrace. In general,
four sections are observed in stream 2, three sections are observed in stream 4,
and four sections are observed in stream 5 (Figure 4). Combining the density of
debris flows with Equations (2) and (3), the debris flow flux at each section can be obtained (Table 3).

To show the evolution of discharge along the moraine terrace, we attempted to plot the change in discharge with distance. However, S41 and S51 are above the moraine terrace and the discharge of streams 4 and 5 at the boundary with the moraine terrace cannot be obtained directly; instead, the discharge was calculated through a linear relationship based on the adjacent two sections. Based on this method, the discharge at the boundary for streams 4 and 5 is 20.22 and 28.0 m$^3$/s (Figure 5), respectively. The change in discharge along the moraine terrace is plotted in Figure 5. The findings suggest that the discharge in the three streams along the moraine terrace experienced sharp amplification. The discharge values may contain error because erosion and deposition may have affected the section morphology; however, the amplification tendency is certain.

### 4.4. Evolution of channels on the moraine terrace

According to the remote sensing image taken on 11 February 2015, vegetation on the moraine terrace was dense, and the channels were covered by thick branches and leaves, which increased the difficulty of recognizing the channels and determining their widths. However, the remote image taken on 19 November 2015 suggests that the widths of the deposits in streams 2 and 5 were approximately 8 and 6 m in stream 4 after the debris flows, respectively, which was consistent with the results of our field survey. The two remote sensing images reflected two aspects: (1) the channel in the moraine terrace was narrow because branches and leaves from both sides could cover the channel, and (2) the debris flows induced serious bank failure and subsequent tree and shrub loss on the bank, thus leading to a wider channel as seen in the clear remote sensing image.

During our field survey, we were fortunate to interview one herdsman, Nima, who had grazed sheep for years in the Zongzhai Valley. Nima told us that the middle and downstream of stream 2 was quite narrow, and he could cross the channel in three to four steps at its narrowest section, suggesting it was approximately 3 m wide there and approximately 4 m wide at the other sections. Stream 5 was wide and shallow and presented a width of 3–5 m and depth of 1–2 m. At the middle of stream 5, Nima noted the previous section morphology at the scene (Figure 6). According to Nima’s identification of the location change of the bamboo on the western bank, the channel bed was approximately 3 m deeper and the entrainment of the channel bed had induced serious bank collapse and subsequent vegetation loss, suggesting that the erosion rate of this section was over 20 m$^3$/m.

### Table 2. Debris flow density calculations based on the soil particle size distribution.

| Stream | $P_{0.5}$ | $P_2$ | $\gamma_c$ (g/m$^3$) | $\gamma_x$ (g/m$^3$) | $\gamma_y$ (g/m$^3$) |
|--------|---------|-------|---------------------|---------------------|---------------------|
| 2      | 0.087   | 0.39  | 2.0                 | 1.4                 | 1.73                |
| 4      | 0.045   | 0.5   | 2.0                 | 1.4                 | 1.74                |
| 5      | 0.1     | 0.29  | 2.0                 | 1.4                 | 1.66                |
Figure 4. Channel profile changes along the stream.

Table 3. Calculation of discharge in the three streams.

| Stream | Section | n   | $l_c$ (m) | $\gamma_c$ (g/m$^3$) | $R_c$ (m) | $A_c$ (m$^2$) | $V_c$ (m/s) | $Q_c$ (m$^3$/s) |
|--------|---------|-----|-----------|-----------------------|-----------|---------------|------------|-----------------|
| Stream 2 | S21     | 0.13 | 0.11      | 1.73                  | 2.10      | 24.95         | 2.37       | 59.60           |
|         | S22     | 0.09 | 0.12      | 1.73                  | 1.76      | 21.66         | 3.19       | 68.98           |
|         | S23     | 0.12 | 0.15      | 1.73                  | 2.21      | 36.01         | 3.11       | 111.83          |
|         | S24     | 0.13 | 0.08      | 1.73                  | 2.78      | 54.88         | 2.44       | 133.94          |
| Stream 4 | S31     | 0.13 | 0.25      | 1.74                  | 1.03      | 8.73          | 2.20       | 19.24           |
|         | S32     | 0.13 | 0.23      | 1.74                  | 1.34      | 12.60         | 2.53       | 31.86           |
|         | S33     | 0.12 | 0.13      | 1.74                  | 1.54      | 16.95         | 2.26       | 38.28           |
| Stream 5 | S41     | 0.15 | 0.21      | 1.66                  | 1.22      | 11.62         | 2.10       | 24.39           |
|         | S42     | 0.15 | 0.20      | 1.66                  | 1.61      | 13.51         | 2.47       | 33.32           |
|         | S43     | 0.15 | 0.16      | 1.66                  | 1.95      | 19.55         | 2.50       | 48.84           |
|         | S44     | 0.13 | 0.10      | 1.66                  | 1.96      | 27.31         | 2.29       | 62.53           |

Figure 5. Changes in debris flow discharge along the channels.
Debris flows are a type of gravity-driven, supply-dependent erosion process (Iverson 1997; Mangeney et al. 2010; Iverson and Ouyang 2015), and direct entrainment is restricted beneath the surface of the debris flow (Schürch et al. 2011; Theule et al. 2015). For non-dam-breaching debris flows, discharge is the lowest at the beginning and reaches a maximum during the period of flow. In a steep channel, vertical entrainment dominates beneath the flow surface and horizontal entrainment is much smaller, thus leading to a much steeper channel bank (Lyu et al., 2017). Typically, erosion beneath the surface can extend to the inside of the bank, thereby increasing the area of free face and the stability of the bank (Frank et al. 2015; Vázquez et al. 2016; Lyu et al. 2017; Zhang and Zhang 2017), which explains why we discovered a large number of bank collapses on both sides of the channel along the moraine terrace during our field investigation, with a few far above the highest surface of the debris flows (Figures 6 and 7).

The bank collapse will fully or partly block the channel, and debris flow will stay behind these blockages. As deposition reaches a certain amount, the debris flow will rush out from the lower groove. Outburst debris flows will forward entrain the collapsed loose material and amplify the discharge (Kean et al. 2013). As the channels widen in the moraine terrace, a channel bank is formed of coarse-grained gravel soil, and bank collapse resulting from debris flow erosion could be successive along the channel. The amplification of debris flows derived from the outburst of bank collapse, channel blocking and dam breaching has been verified in debris flow cases and experiments (Theule et al., 2012; Cui et al. 2013; Kean et al. 2013). Indeed, channel scouring is highly notable in the channel with abundant gravels (Berger et al. 2011; Theule et al. 2012), and a much wider and deeper section along the moraine terrace can form (Theule et al. 2012, 2015; Frank et al. 2015; Vázquez et al. 2016; Zhang and Zhang 2017). In general, the processes by which debris flows scour the channel bed, induce bank collapse, block the stream and trigger an outburst flood result in a change in the section morphology, as shown in Figure 8.

Figure 6. Change in section morphology in the middle of stream 5.
4.5. Debris flow mitigation measurement

(1) Theoretical background

Sediments on the bed and bank constitute the debris flow source, and bank collapse is more controlled by channel bed entrainment (Frank et al. 2015; Vázquez et al. 2016; Lyu et al. 2017; Zhang and Zhang 2017). The mechanism of bed entrainment of debris flows can be classified into three categories: (1) the surface layer of the channel bed initiates when the basal stress generated by moving debris flows is larger than the resistance of the bed material (Papa et al. 2004; Hungr et al. 2005; Haas and Woerkom 2016); (2) the collision of moving debris flows induces the segregation of bed material, and the dispersive particles are progressively scoured by debris flows (Stock and Dietrich 2006; Berger et al. 2011); and (3) rapid undrained loading is exerted on the saturated bed material by the debris flows, resulting in increasing pore-water pressure and decreasing contact stress and shearing strength (Hungr et al. 2005; Iverson et al. 2011).

Figure 7. Bank collapse of the branches of the Zongzhai Valley: (a) bank collapse in stream 2 and (b) bank collapse in stream 4.
Indeed, the tremendous growth of pore-water pressure can trigger the liquefaction of bed sediments (Sassa and Wang 2005).

The entrainment of debris flows is controlled by debris flow characteristics, such as flow depth (Berger et al. 2011; Schührch et al. 2011; Vázquez et al. 2016), velocity (Fagents and Baloga 2006; Frank et al. 2015; Haas and Woerkom 2016), particle size distribution (Egashira et al. 2001; Haas and Woerkom 2016), channel gradient (Mangeney et al. 2010; Zheng et al. 2016; Theule et al. 2015; Vázquez et al. 2016; Haas and Woerkom 2016) and bed sediment resistance (Moore and Masch 1962; Ansari et al. 2003). Measures taken to alleviate the entrainment of debris flows should follow the aforementioned three aspects. Generally, high check dams are often set at a proper location of the middle part of the stream to intercept large boulders in the debris flows and subsequently decrease flow discharge; in addition, low check dam groups are used to decrease the channel gradient. However, the implementation of these engineering measures requires significant excavation and concrete, and the changes in channel morphology could have adverse ecological impacts.

According to field observations by McCoy et al. (2012), only the surface bed material experiences the full pore-water pressure changing process when overridden by debris flows and thus can be more easily entrained, whereas the pore-water pressure of the layers below is quite limited because loading and sediment structure deformation is restricted to the surface layer and the stress dispersion beneath is sharp. In addition, the collision stress occurs as particle collision at the bed surface. In general, surface layer control should be considered if the channel is formed along a terrace and the bed and bank are formed with gravel sediment. Here, we propose a new type of shallow dam that is a smaller check dam. The difference is that only a small portion of the dam is above the bed surface, while most of it is beneath the bed. The shallow dam can alleviate the channel gradient as deposits accumulate behind the dams, and the subsurface dam can greatly increase the resistance of the bed sediments and enhance the stability of the channel bed. This type of measure can avoid a

![Figure 8](image-url)
considerable excavation and could lead to the formation of a lower water gradient, thus allowing more rapid recovery of the ecological environment.

(2) Engineering measurement settings

The shallow dam has a lower groove in the centre where debris flows are confined, and two higher wings are set on both sides to prevent debris flows from crossing and eroding the bank. In the design, Equations (1) and (2) are combined to calculate the corresponding depth of the debris flows for a designed discharge, and an additional safety height should be added to determine the height of the two wings (Figure 9). As the channel gradient decreases after the construction of the shallow dams, the channel gradient of the newly formed channel bed should be used in Equation (2) to calculate the velocity. The wings of the dams should be inserted into the banks, the depth should be 2–3 m for the check dams with loose banks, and only 0.5 m (Figure 9) is required for shallow dams because the stability of the dams is less controlled by the banks. The wings of the dams should be exposed outside of the bank for at least 0.5 m so that debris can deposit beside the bank to alleviate bank scouring from debris flows and increase the stability of the banks.

Exposure of the shallow dams above the channel bed should be minimal so that only a low water drop is able to form before the dams, thereby avoiding the strong erosion caused by a high-water drop. Normally, a height of 0.5–1.0 m (Figure 9) is required, and large boulders should be set before the dams to alleviate the score of the base. The shallow dams should penetrate the bed for at least 1.0 m (Figure 9) to maintain the stability of the dams and the surface layer of the bed material; however, the excavation of sediments could be increased at deeper depths. The width of the shallow dams could increase the resistance of the bed sediments. Because the distance of the two shallow dams is less than 10 m, a width of 1.0 m is needed for the shallow dams (Figure 9).

After the completion of shallow dams, the reservoir behind of the dams could be filled by sediment accumulation, and the channel gradient will be much lower. According to previously reported statistics (Institute of Mountain Hazards and Environment, Chinese Academic of Sciences, IMHE 2000), the
gradient of the channel newly filled by debris flows behind the check dams is 0.5–0.9 times that of the former channel, and typically, a mid-range value of 0.7 times is applied. The depth of the deposits would reach the top at the back of the dams and decline gradually upstream. The last shallow dam is set where the depth of the deposits decreases to 0 m (Figure 9) to ensure that the channel bed is fully covered by the debris flow deposits.

5. Conclusions
A debris flow of a large magnitude occurred in the Zongzhai Valley on 19 August 2015, and it represented the sole occurrence over the last 100 years. Based on a field survey, section measurements and discharge calculations, the discharge of the debris flows above the moraine terrace was relatively small, while it was greatly enhanced by the successive channel bed scoring and bank collapse along the moraine terrace, which increased the potential danger downstream. We analyzed the mechanism of debris flow entrainment and determined that channel bed scouring is a precondition for bank collapses for a gravel-dominated channel bed. Finally, shallow dams were designed for bed strength reinforcement. After completion, the channel will be divided into dozens of intervals by the shallow dams and present a gentler channel gradient and higher resistance of the bed material.

The application of shallow dams should be combined with other engineering measures. Debris flow entrainment and erosion depth are more controlled by the magnitude of the flow. Shallow dams can be mobilized by debris flows when the debris flows reach a certain magnitude; therefore, decreasing the magnitude of the debris flows should be addressed first. Normally, high check dams with large drainage holes or concrete pile groups can be set above the shallow dams to intercept large boulders and decrease the discharge of debris flows. In addition, the removal of large boulders for the debris flows can decrease the collision of particles and the possibility of blocking and outburst floods.

Drainage canals are similar to shallow dams in channelized debris flow mitigation. If a rib designed to prevent scour were to be added to the drainage canal, the bed stability and bank stability could also be strengthened. Debris flows in the Zongzhai Valley are of low frequency, and the channel along the moraine terrace is too long. Building the drainage canal along the channel would be prohibitively expensive, which is why a drainage canal has not been adopted in the Zongzhai Valley. In addition, the construction of shallow dams can avoid significant evacuation, and the material of the channel bed and banks are still naturally deposited; thus, vegetation along the channel can recover much more easily, and the ecological environment is greatly enhanced.

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