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ORIGINAL ARTICLE

Laboratory experiments on debris flow processes in sharp channel bends

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Abstract

The restriction of sharp channel bends on debris flow movement will lead to strong erosion action on concave bank, which was an important reason for the expansion of the channels and the instability of the slopes. Most studies only focus on bed erosion but ignored the concave bank also suffer strong erosion action. In order to analyze the erosion mechanism, a series of erodible and rigid bank experiments with different curvature radii of bends were carried out. After obtaining the calculation equations for the shear force and the shear resistance of the concave bank in impact zone, we revised the commonly entrainment rate. Finally, we obtained a formula for calculating the entrainment rate of concave banks by debris flow, it can provide reference for the study of slope stability.

Keywords Debris flow · Bend channel · Entrainment rate · Shear force

List of symbols

B	Width of channel (m)
R_c	Curvature radius of bend (m)
λ	Curvature parameter of bend (–)
E	Entrainment rate (m/s)
τ_d	Debris flow's shear force (kpa)
τ_{res}	Shear resistance (kpa)
σ	Positive stress (kpa)
ϕ_{bank}	Internal friction angle
c	Internal cohesion (kpa)
u_0	Factors that considering the pore water pressure (–)
$\tau_{res}\prime$	Shear resistance of concave bank (kpa)
ΔF	Difference of shear resistance (N)
S	Additional area of concave bank (m^2)

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$f(\lambda)$	Shear force enhancement coefficient (–)
P	Dynamic pressure of the debris flow (kpa)
Fr	Froude number (–)
β	Shear angle (°)
v	Flow velocity (m/s)
ρ	Debris flow mixture density (g/cm^3)

1 Introduction

Entrainment was a distinctive feature of debris flows during its movement process, which could increase its scale by constantly entraining solid matter in the channel, and expanding dozens of times of the volume before accumulation than the beginning stage. And debris flow's destructive power was also increasing, there are large numbers of casualties and economic losses caused by debris flows [1–3].

Although many scholars have systematically studied the erosion mechanism of debris flows and achieved significant results, the main controlling factors of erosion mechanism are still debated [4–6]. Lyu et al. [7], studied the effect of bank erosion on the debris flow's initiation and movement, but he didn't consider the effect of bend conditions. The entrainment mechanism of debris flow on the channel is very complex, and contrary to the water, the collision of particles inside the debris flow will also enhance the erosion capacity, and the amount of erosion is also related to the physical properties of the channel bed material, such as moisture content and particle characteristics [8]. At present, it is generally believed that the damage of the slope toe is the main reason for the occurrence of landslide [9], and the erosion of the bank by debris flow will greatly affect the stability of the slope, so that massive landslides material accumulate in the channel and even block the channel to form a landslides dam [10–12]. The failure of landslides dams can cause the peak flow of debris flows to increase instantaneously [13].

Due to the relatively slightly of bank erosion to beds erosion, the current research mainly focuses on channel bed [8, 14–17], but this comparison only applies to relatively straight channels, which are mostly bend channel in the debris flow watersheds. Due to the limitation of the curved terrain, when the debris flow movement within the bend, centrifugal acceleration motion will occur, debris flow strongly erodes the concave bank. Current research focuses on the relationship between the superelevation and debris flow's velocity [18–20], while ignoring the co-existing phenomenon of bank erosion. Therefore, it is necessary to conduct a serial of research on the concave bank erosion.

The objective of this study is to gain a fully understanding of the erosion mechanism in concave banks. Therefore, the rigid and erodible bank experiments were conducted, the purposes were to explore the erosion mechanism on the concave bank under the limitations of bend channels conditions, as well as the calculation method of shear force and entrainment rate of during the debris flow process. Finally, I hope that my research can provide a reference for analyzing the effect of debris flow process on the stability of slopes.

Figure 1 shows some landslide disasters induced by debris flow entrainment at concave bank zone. The erosion phenomenon of debris flow was mainly reflected in bed erosion, but it is slightly in channels bank. However, when the channel was winding, the erosion effect will increase significantly. When the foot of the channel bank was eroded by a debris flow, it will

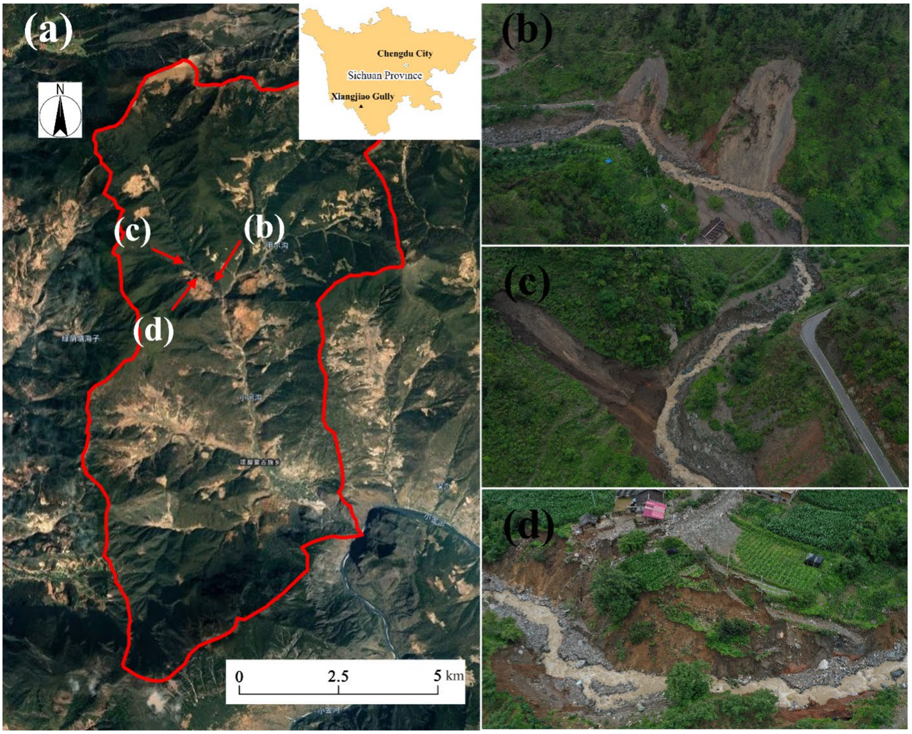


Fig. 1 Overview of Xiangjiaogou Basin gully. **a** The entire Xiangjiaogou watershed and its geographical location; **b** and **c** The landslides induced by debris flow's entrainment at concave bank; **d** Collapse of farmland caused by banks erosion

cause the instability of the slopes, and providing abundant material for debris flow. The collapse soils will even block the channel, induce blockage and collapse phenomenon.

2 Methods

2.1 Model experiment with bend channel

In order to explore the bank material entrainment under bend channels condition, we conduct a serial of rigid and erodible bank experiments. The objective of rigid bank experiments is to monitor evolution characteristics of shear forces on concave banks. Based on the rigid bank experiment, the erodible bank experiment further determined the spatial characteristics of the erosion failure and the entrainment rate. The curvature radius of bend was an important parameter to measure its limiting effect on debris flow movement, and also significantly affects the entrainment rate on a concave bank. In this study, λ was used as a dimensionless parameter to describe the curvature degree of bend:

$$\lambda = \frac{B}{R_c} \tag{1}$$

where: λ is a dimensionless parameter to measure the curvature degree of bend; B is the channel width;R_c is the curvature radius of the bend.

2.2 Rigid bank experiment

This experiment was conducted in the Institute of Mountain Hazards and Environment, Chinese Academy of Sciences. As show in Fig. 2, the flume was 4 m long, 30 cm wide and 40 cm high. The flume is welded into a skeleton with iron plates, and the two sides of the flume were made of tempered glass, which is convenient to observe the motion of the debris flow. There was a fixed hopper (1.2×1.0×1.5) in the upper part of the flume, and a gate that can be opened vertically at the connection between the tank and the flume to control the debris flow into the flume. The maximum opening height of the gate is 60 cm, and the height of opening gate is 20 cm during the test in order to keep consistent flux of debris flow into the flume continuously.

As shown in Fig. 3, five triaxial sensors are installed at points A to E on the entire concave bank to monitor the shear force during the debris flow movement process. The point B ~ C zone was most severely affected by debris flow erosion, which was defined as impact zone in the text. We can get different flow velocity of debris flow by changing the slope of flume, which are 9°, 11°, 13°, and 15°, respectively. There are three bend models that $\lambda =$ 0.150, 0.182, and 0.231, respectively. The debris flow samples are excavated from undisturbed debris flow accumulation in the field. In rigid bank experiments, the debris flow's density was 1.6, 1.7, 1.8, 1.9, 2.0, 2.1 g/cm^3, and cross experiments were conducted with the variables of the slope and the curvature radius of the bend.

2.3 Erodible bank experiment

The site of erodible bed experiment was selected in a mountain area of southwest Sichuan Province. Debris flow sample is mainly used in situ to screen gravel with a particle size greater than 20 mm from the accumulation fan. Due to the debris flow sample is seriously deposited inside the hopper during the experiment, which couldn't flow into the bend totally, so silty clay had mixed into the sifted debris flow sample according to the ratio of

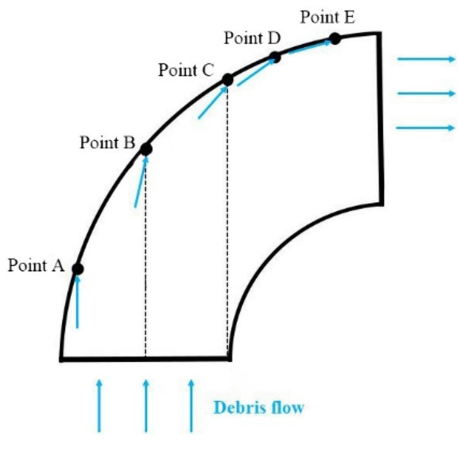


Fig. 2 diagram of Sensor installation position

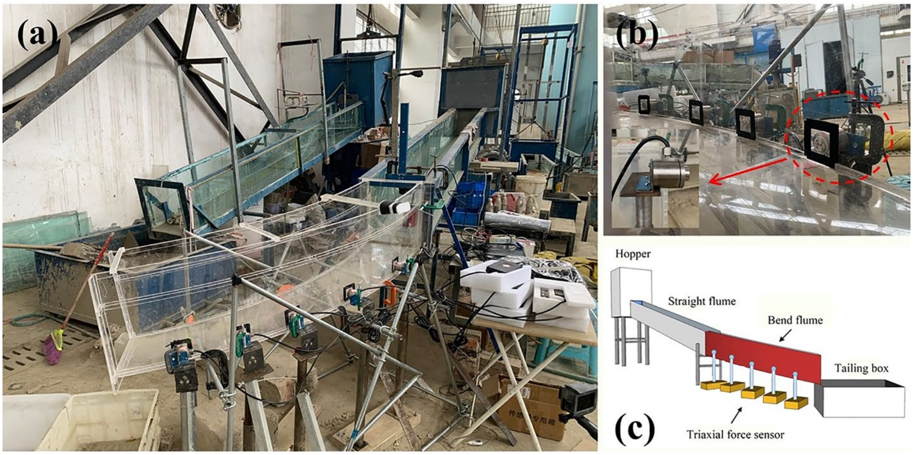


Fig. 3 Model experiments device diagram **a** Overall arrangement drawing of the device; **b** Sensor installed on the concave bank, and the schematic diagram of sensor installation (bottom-left); **c** Three-dimensional schematic diagram of experimental equipment

6:4. In the experiment, the density of debris flow is between 1.60 and 2.0 g/cm^3, which belongs to dilute debris flow. The erodible bank is compacted using debris flow samples. We changed the shear resistance of erodible bank by changing its the water content. As show in Fig. 4, the curvature radius of the bend is 2.7 m, 2.4 m, 2 m, 1.6 m and 1.3 m respectively. During the experiment, the slope of the straight flume is fixed at 11°, and the

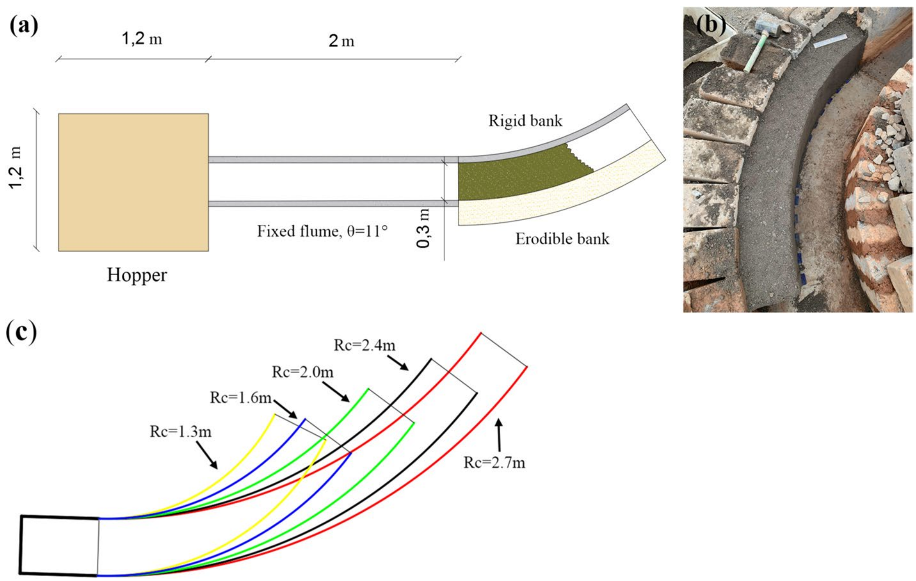


Fig. 4 Experimental set-up of erodible bank experiments. **a** Schematic of the experimental facility; **b** Erodible concave bank composed of sandy soil; **c** Merged sketch of bank channels cross sections with different RC for different groups of experiments

flow depth meter is set up above the end of the straight flume to monitor the flow depth when the debris flow enters the bend. The arrangement of the erodible bank experiment is shown in the Fig. 3:

In order to ensure the accuracy of erodible concave bank, the curved shoreline is marked with paint on the ground before laying soils, and then the mold is set up and filled with sample according to the line. After the debris flow washed out, a ruler was used to measure the erosion depth at different positions according to the previous curved shoreline with a spacing of 5 cm. Figure 5 is the concave bank after debris flow's entrainment.

2.4 Theoretical analysis of entrainment rate for bend channels by debris flow

Regarding the entrainment effect of debris flow on concave banks, we refer to the entrainment rate formula proposed by Medina et al. [21]. They think that the necessary condition for soil erosion is that the shear force applied by the debris flow on erodible layer was greater than the shear strength of bank itself. Medina et al. [21] applied a dynamic equilibrium approach in their entrainment process simulation, where the erosion mass quantity of erodible layers were closely related to the availability of momentum. The calculation formula is as follows:

$$E = \frac{\tau_d - \tau_{res}}{\rho v} \tag{2}$$

where, ρ is the density of the debris flow and v is the speed of the debris flow; E is the entrainment rate of the debris flow; τ_d is the shear force applied by debris flow on the surface of the channel bed; τ_{res} is the shear resistance of the bed. Based on the infinite slope theory, it is calculated through the Mohr–Coulomb failure criterion. The calculation form is as follows:

$$\tau_{res} = \sigma tan\phi_{bank} + c \tag{3}$$

where: σ is the positive stress applied to the surface of the erosionable layer, ϕ_{bank} is the internal friction angle of the erosionable layer; c is the internal cohesion of the erosionable layer.

The pore water pressure inside the channel bed will significantly affect the momentum conversion between the fluid and the erodesible layer and thus the erosion rate [17, 22], but how to quantitatively evaluate the impact of pore water pressure is very complicated, however, [15, 16] proposed we can asume a constant value to quantify this effect as follows:

Fig. 5 Concave bank after erosion action, $R_C = 2.7$ m and 1.6 m respectively

$$\tau_{res} = (1 - u_0)\sigma tan\phi_{bank} + c \tag{4}$$

where: u_0 is the factors that considering the pore water pressure.

In the actual situation, the curved channel can restrict the movement of debris flow and significantly increases the erosion degree in concave bank, if we analyze the terrain structure of the bend, the concave bank has stronger shear failure resistance than that of the straight channel bank. As shown in Fig. 6, the straight and the curved channel situations have compared during the process of debris flow entrainment, and a microelement with length dl and depth and thickness is 1 have selected respectively. Assuming that microelement will be destroyed by debris flow, the shear resistance was totally different. Therefore, the following results can be obtained:

$$\tau_{res}\prime dl - \tau_{res}dl = \Delta F \tag{5}$$

By comparing the two situations in Fig. 6, the difference in shear strength was mainly due to the shaded part S in Fig. 6b. Therefore:

$$\Delta F \propto S \tag{6}$$

Under the straight channels condition, the concave bank's shear resistance of the microelement is $\tau_{res}dl$. The shear strength generated mainly comes from the resistance of the surrounding soil and the friction force between the underlying soil layers. Therefore, by comparing the volume relationship between S and the microelement soil, the following relationship was obtained:

$$\Delta F = f(\lambda)\tau_{res}dl \tag{7}$$

By combining Eqs. 5 and 7, the calculation method for shear strength of curved concave bank can be obtained:

$$\tau_{res}\prime = \left[1 + f(\lambda)\right]\tau_{res} \tag{8}$$

where: $\tau_{res}\prime$ is the shear strength of concave bank; S is the additional soil area compared to the straight bank; ΔF is the difference of shear resistance caused by the terrain of the bend compared to the straight bank; $f(\lambda)$ is the coefficient of shear strength considering the influence of concave banks, and its functional relationship is determined through the following erodible bank experimental data.

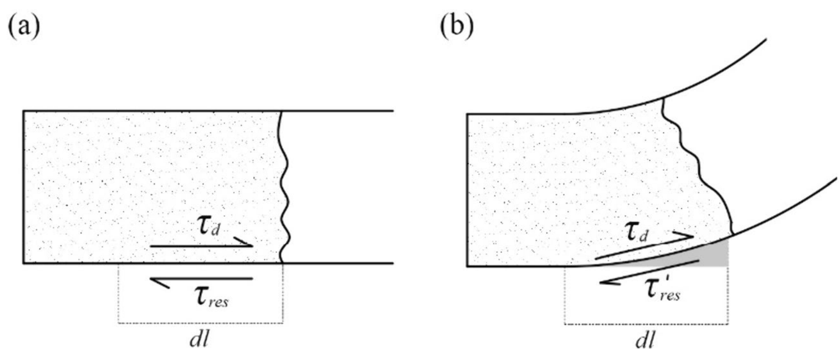


Fig. 6 Schematic diagram of debris flow entrainment mechanism. **a** straight channels; **b** bend channels

The shear strength of concave bank at different positions remains constant, however, the entrainment mechanism of debris flow on concave banks at different locations is significantly different. As shown in Fig. 7, the debris flow does not rapidly convert to centrifugal movement after entering the bend, but gradually transitions to centrifugal deflection motion with the restrictions effect increase gradually.

When the debris flow movement to the B ~ C zone of the concave bank, its motion state changes most obviously. At this time, the debris flow has not completely transformed into centrifugal movement, and the erosion process is accompanied by severe impact effect; On the C-E zone, the debris flow basically moves in a centrifugal state by adhering to the concave bank. Therefore, there is a significant difference in the stress mechanism of the two regions, and the erosion mechanism of debris flows should be discussed separately.

When debris flow passes through the transition area of the bend and enters the downstream, due to the continuous constraints of the concave bank, the direction of the debris flow movement basically changes to the tangent direction along the bank of the bend.

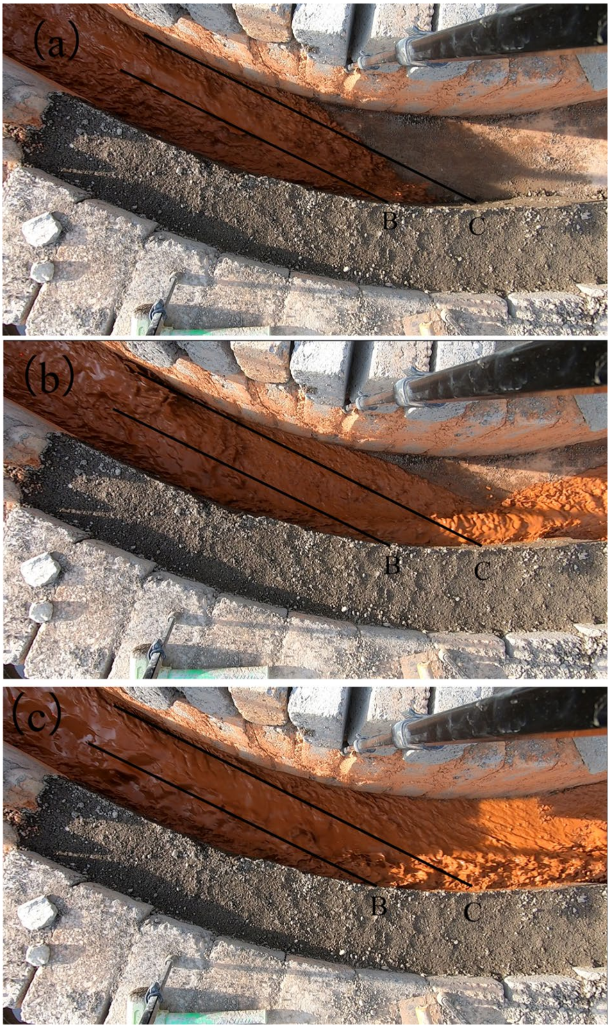


Fig. 7 debris flow erode concave bank at different time

Therefore, the erosion of debris flows on the side walls of bends in this area is mainly caused by the centrifugal acceleration of the debris flow, and the erosion of debris flow jet impact has basically disappeared. When debris flow erodes the bed, the gravitational acceleration g is the main erosion driving force. In this process the centrifugal acceleration a_n as the main driving force.

Froude number is often used to correct the theoretical calculation of the dynamic pressure of debris flows [23, 24]. The dimensionless method has been used to calculate the impact of debris flow on structures [25]:

$$\frac{P}{\rho v^2} = aFr^b \tag{9}$$

where: P is the dynamic pressure of the debris flow; a and b are the undetermined coefficients.

It should be pointed out that P represents the debris flow pressure on the concave bank, and the shear force of the debris flow plays a decisive role in the entrainment process, therefore:

$$\tau_d = Pcos\beta \tag{10}$$

where, τ_d is the shear force of the debris flow in the B–C point zone; β is the angle between the impact force and the tangent line of the concave bank.

3 Result and analysis

3.1 Evolution of debris flow's shear force

The data analysis in this chapter is mainly based on laboratory experiment. Due to the limitation of bend terrain, there is a certain angle between the impact force and tangent line of the concave bank, and the angle is various at different position. Therefore, the uniaxial sensor cannot accurately determine the physical characteristics of the impact force, and the triaxial sensor can accurately measure the value of the shear force and its spatial orientation. As show in Fig. 8, the force was mainly reflected in the Z axis, and the X axis also has obvious fluctuation, but the force value change on the Y axis was very weak, which was mainly related to the debris flow motion characteristics, the value of the Z-axis and X-axis can reflect the angle relationship between the impact force and the tangent line of the concave bank.

Figure 9 shows the spatial distribution of the peak impact forces at concave bank. Firstly, the point B suffers the greatest impact force, in the initial stage, debris flow's motion state was less affected by bend channels, however, it stands in transition stage between the centrifugal movement and straight movement, and the debris flow head impact at point B directly. After passing through point B, the debris flow basically changes to the centrifugal movement and tightly fitting on the concave bank, therefore, the shear force at C ~ E zone mainly depends on the degree of centrifugal acceleration.

As shown in Fig. 10, with the increase of curvature and slope, the impact force will have a significant increase on the concave bank. The curved terrain will generate a significant restriction effect on the movement of debris flow, which was also related to the straightness of debris flow and will cause strong erosion to the B ~ C zone of the concave bank. While impacting the concave bank, the shear angle of the impact force was also closely related to the flow velocity.

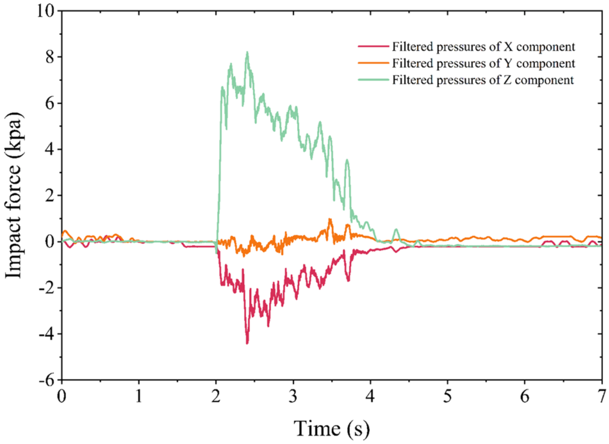


Fig. 8 The components of the impact force in the X, Y, and Z directions, λ=0.231, ρ=1.9 g/cm3, θ=15°

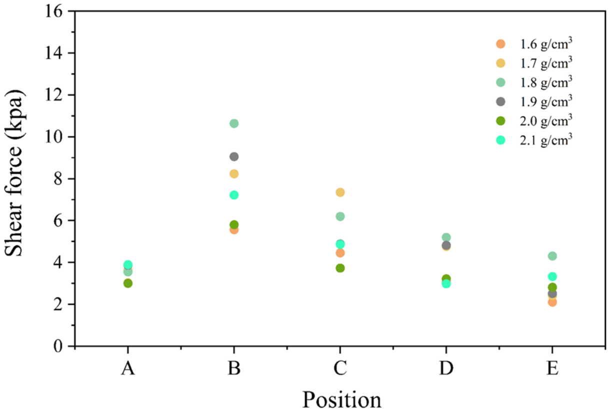


Fig. 9 Spatial-depend evolution of impact force, λ=0.182, θ=15°

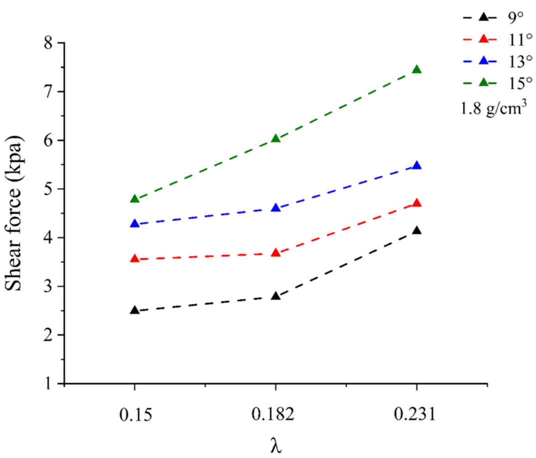


Fig. 10 Distribution of peak shear force with different λ and v

Therefore, when considering the erosion process on the concave bank, the velocity and curvature of the channels are important parameters.

As analyzed above, point B in the entire concave bank had suffering the greatest impact force. Therefore, this paper mainly analyzes the debris erosion process at point B. Point B was at the intersection of the midline of the bend entrance and the concave bank, and it suffered direct impact by the debris flow head. The impact force mainly depends on the density and velocity of the debris flow, and the bend restriction also has a significant effect on it. Dimensionless analysis is introduced and makes the factors influencing the evolution of impact force into two parts: λ (curvature degree of the bend), and Fr (the kinetic energy component ratio between horizontal and vertical directions). The following equation is obtained by fitting analysis (Fig. 11):

$$P_{imp} = 0.130 * F_r^{-0.35} \lambda^{0.83} \rho v^2 \tag{11}$$

where: P is the debris flow's impact force at point B.

The calculation method for calculating the impact force of debris flow in the B–C zone has obtained, but the decisive factor during the erosion process is the component of the impact force along the tangent line of the concave bank. We have measured the 3 components of the impact force in space through a triaxial sensor (as show in Fig. 8), therefore, we can calculate the angle between the impact force and the tangent line of the concave bank, which is the shear angle.

As shown in Fig. 12a, with the slope increases, the shear angle β present a decreasing trend,And which means the proportion of the impact force on the tangent line of the concave bank gradually increases. Due to the channels slope is the most important factor affecting the flow velocity of debris flows, therefore, we extracted the relationship between the cosine of the shear angle and the flow velocity, as show in Fig. 11b, We have:

$$\cos\beta = 0.307\ln(v - 0.848) \tag{12}$$

Therefore, we can obtain the formula for calculating the shear force of debris flow in the B–C zone of theconcave bank:

$$\tau_d = cos\beta * 0.130 * F_r^{-0.35} \lambda^{0.83} \rho v^2 \tag{13}$$

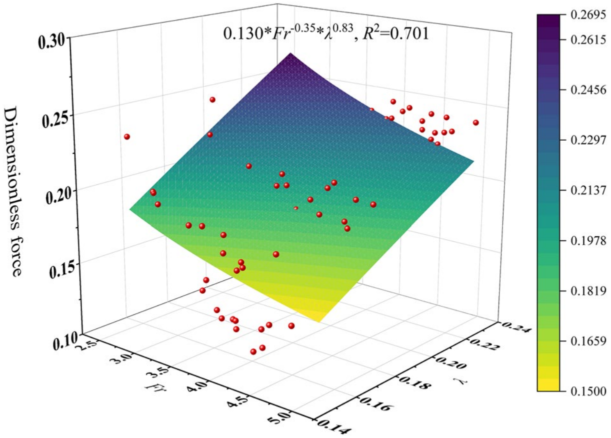


Fig. 11 Schematic diagram of fitting relationship for the impact force of the debris flow acteding on point B of the bend

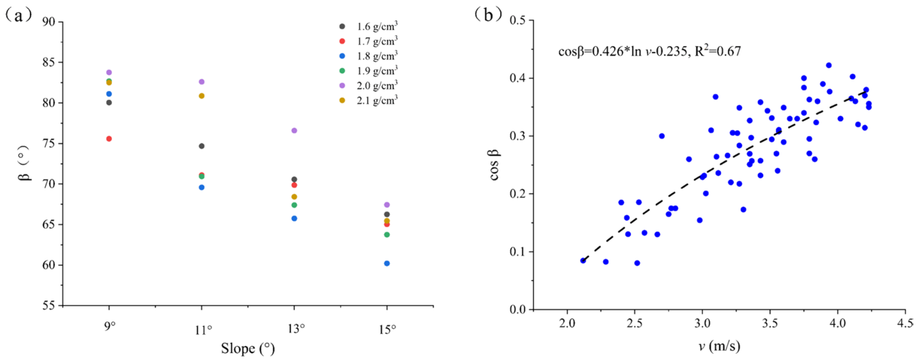


Fig. 12 Shear angle generated by debris flow on concave bank **a** The relationship between the flume slope and the β, λ=0.182. **b** The relationship between the cos β and flow velocity in point B

where, β is the angle between the impact force and the tangent line of the concave bank; v is the velocity of debris flow.

3.2 Entrainment characteristics of debris flow within bend channels

The data analysis in this chapter is mainly based on field experiment. In order to obtain more data on the entrainment rate of concave banks, we get different shear resistance of erosible bank by changing its moisture content. And the moisture content of 6.5% was measured through indoor direct shear experiments: φ_{bank}=30°, c = 0.22 kpa; the moisture content of 11%: φ_{bank}=20°, c = 0.60 kpa.

As shown in the Fig. 13, the erosion characteristics of the concave bank by debris flow in the erodible bank experiment. Overall, the erosion characteristics generated by the debris flow on the concave bank show an arched shape, which is also matched with the phenomenon of superelevation. Compared with Fig. 13b and c, in terms of the entire erosion depth, the increase rate change fast before point B (80 cm), and the B–C zone has the highest erosion depth. Therefore, in order to improve the accuracy of the results when analyzing the entrainment rate in the following, we will extract the average erosion depth among the B–C zone within each bend as a representative of the maximum erosion depth.

We generally recognize that as the curvature radius of the bend decreases, the entrainment degree becomes stronger. However, the quantitative relationship between the curvature radius of the bend and the entrainment rate is still unclear and which is the focus of this study. As shown in Fig. 14, the degree of erosion action increases significantly with the decrease of curvature radius, but its growth rate also gradually slows down. The entrainment rate and curvature radius show a relatively consistent logarithmic function relationship.

As shown in Fig. 15, the as increasing of debris flow's density, its erosion ability decrease gradually. Iverson [26] found that during the erosion process it will be accompanied by large positive pressure development, and the rapid change of pore water pressure will promote momentum conversion between fluid and erodible layers, thus causing erodible layers be eroded and damage. In this experiment, high-density debris flow, its internal viscosity of the slurry also increases. The viscous slurry forms a "barrier layer" between the flow and the

Fig. 13 Entrainment experiments on erodible bank, R_c=2.0 and ρ =1.7; **a**Time-depend of flow depth (mm) recorded; **b** erosion depth records along the concave bank; **c** concave bank eroded by debris flow

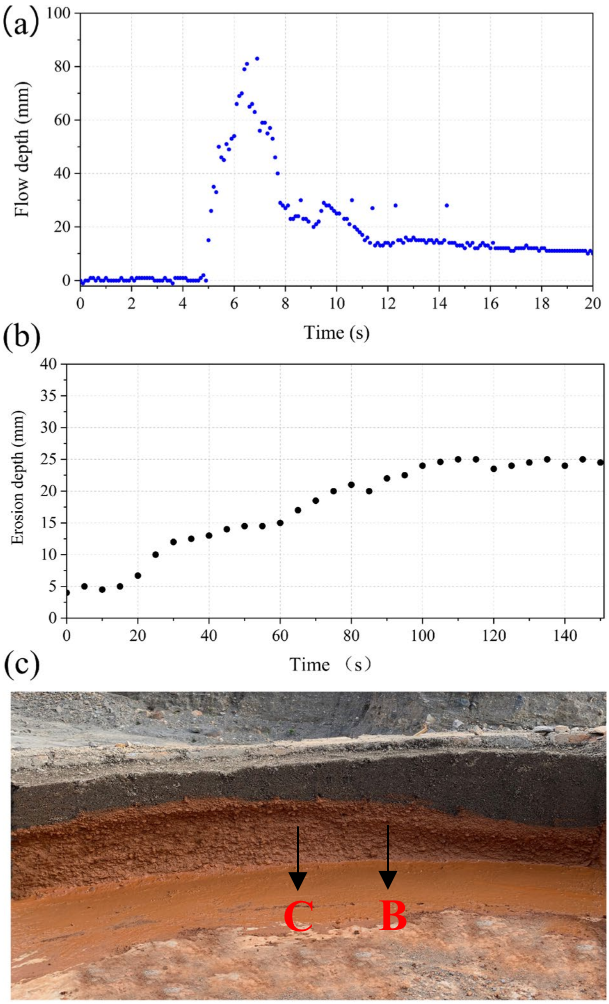
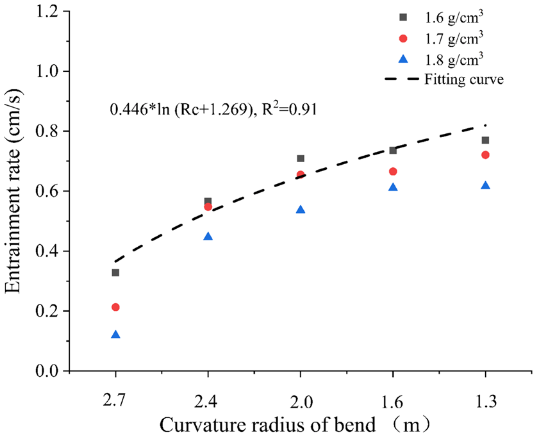


Fig. 14 Entrainment rate of debris flow at different curvature radius of bend



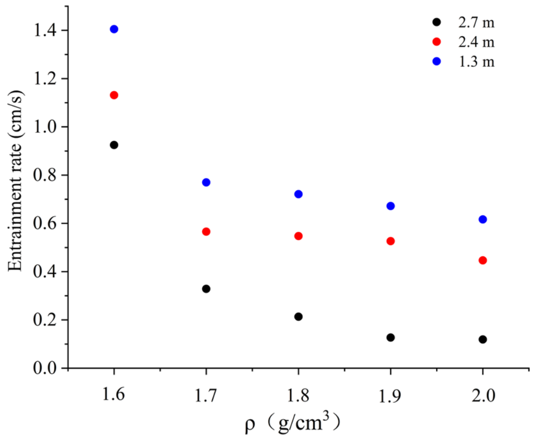


Fig. 15 Entrainment rate evolution by different debris flow densities

bank, which reduces the changes in pore water pressure inside the bank soil and hinders the momentum conversion. Finally it has a weak erosion ability of high-density debris flows.

The concave bank not only restricts the movement of debris flows, but also enhances its shear resistance to a certain extent. In this article, we express this relation by $f(\lambda)$. According to formulas 2 and 13, in the case of obtaining the debris flow's shear force, the shear resistance of concave bank, and the entrainment rate, we can use the data to calculate the values of $f(\lambda)$. In order to accurately estimate the suitable form of $f(\lambda)$, we extracted relevant data for fitting analysis, as shown in Fig. 16. After obtaining the functional form of $f(\lambda)$, we can obtain the calculation formula for entrainment rate on concave bank, as follows:

$$f(\lambda) = 0.546 + 0.221 ln\lambda \tag{14}$$

$$E = \left[0.130 cos\beta * F_r^{-0.35} \lambda^{0.83} \rho v^2 - (1.546 + 0.221 ln\lambda)\tau_{res}\right] / \rho v \tag{15}$$

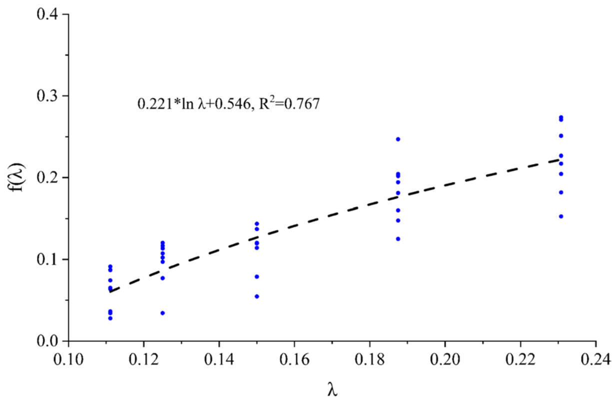


Fig. 16 Fit curve of $f(\lambda)$ vs. dimensionless bend parameters λ

4 Discussion and conclusions

Entrainment is an important incentive for the volume amplification of debris flows, and many scholars have focused on the erosion of channels bed. Most debris flow channels present a winding shape, and the limiting effect of the bends on debris flow movement significantly increases the erosion degree on the concave banks. In the bend channels zone, debris flow couldn't rapidly convert into centrifugal motion, so there are two erosion mechanisms for the concave bank: impact erosion dominated by debris flow impact force and friction erosion dominated by centrifugal acceleration. Regardless of the erosion mode, it poses a great threat to the stability of the slopes near the concave bank.

In order to accurately understand the erosion characteristics on concave banks, it is necessary to obtain a calculation formula for the shear force. We classify the areas with the most severe erosion on the concave bank into B ~ C zone and C ~ E zone based on different debris flow erosion mechanisms. The impact force of debris flow in the B ~ C zone is co-determination by the characteristics of debris flow and the restriction effect of bend. Therefore, the relevant force values are measured by triaxial sensors in the rigid bank experiment. Through analysis, we have obtained the calculation formula of the impact force. The decisive factor during the process of erosion and damage is the shear force τ_d, which is the component of the impact force on the tangent line of the concave bank. Through the analysis of triaxial data, it was found that the shear angle $cos\beta$ is closely related to the velocity of debris flow. Therefore, we ultimately obtained the formula for calculating the shear force on the concave bank:

$$\tau_d = 0.130cos\beta * F_r^{-0.35}\lambda^{0.83}\rho v^2$$

$$cos\beta = 0.307ln(v - 0.848)$$

Although the concave bank may limit the movement of debris flow and increase the degree of erosion, bend structure will enhance its shear resistance. Therefore, we carried out a erodible bank experiment in the field to obtain the distribution data of erosion depth along the concave bank, which is complementary to the rigid bank experiment. In summary, by analyzing the shear force and erosion depth data, the value of the shear resistance increase coefficient $f(\lambda)$ was obtained, and a suitable form between $f(\lambda)$ and the bend parameter λ was obtained. Finally, we obtain the formula of entrainment rate on concave bank by debris flow movement. The formula of entrainment rate for concave bank is:

$$E = \left[0.130cos\beta * F_r^{-0.35}\lambda^{0.83}\rho v^2 - (1.546 + 0.221ln\lambda)\tau_{res}\right]/\rho v$$

The model has been used to calculate the entrainment rate on the concave bank during the impact erosion process. Firstly, when the curvature radius is too large or the channel width is too wide, which situation weren't applicable for this model. Secondly, estimating the velocity of debris flow is an important step, and the influence of channels roughness should be carefully considered. Roughness not only affects the velocity of debris flow, but needs to be considered when estimating the impact shear angle. Although this study provides a detailed analysis of debris flows' erosion and damage act on concave banks within bend channel, it is worth pointing out that there are still limitations in this study, as the bend section in the erodible bank experiment is a rectangular cross section, however, natural river sections often exhibits irregular cross-sections. In the following work, I will take natural river sections as the research object to analyze the debris flow entrainment characteristics within bend channels. Although the formula that I proposed has some limitations in applicability, we hope that our research can provide reference for the study of debris flow erosion in bend channels.

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Author contributions ML carried out the experiments and analyzed the data; JL initiated and sponsored this work; HS assisted data analysis; HD assisted with experimental guidance and provided comments on the pictures modifying.

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Declarations

Conflict of interest The authors declare that there are no conflict of interests, we do not have any possible conflicts of interest.

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