

# Effects of flow-bed interactions on barrier impact

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**Abstract.** Debris flow mobility is governed by complex interactions at the flow-bed interface. These interactions may cause flow bulking and increase in momentum. Both factors need to be considered for the design of barriers installed along the flow path. In this study, channelized debris flow over a wet erodible bed impacting a terminal flexible barrier is modelled in a 28-m-long and 2-m-wide flume facility with 20° slope inclination in Hong Kong. Tests with flow volumes of 6 m<sup>3</sup> and 9 m<sup>3</sup> overriding both erodible and non-erodible beds are conducted. The change in normalised flow energy over the erodible bed section, the change in flow momentum and the impact dynamics on the terminal barrier is assessed.

## 1 Introduction

Debris flows occur in mountainous regions when masses of saturated sediment and water surge downslope and cause fatalities and damage to infrastructure [1]. The most distinct feature of debris flows compared to other landslide types is its ability to erode bed material [2,3]. The spatial-temporal patterns of erosion and deposition strongly influences the final debris flow volume and mobility of debris flow [4,5]. Evidently, a robust barrier design must cater for any change in volume and momentum of a debris flow before impacting it.

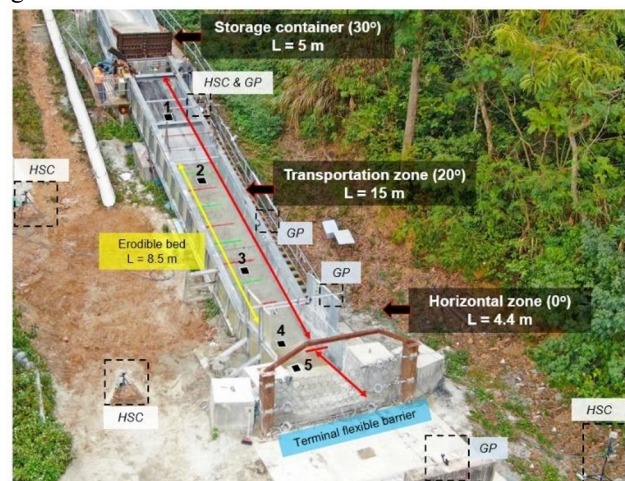
In this study, debris flows with volume 6 m<sup>3</sup> and 9 m<sup>3</sup> are tested in a 28-m-long flume model, with and without an erodible bed to investigate the effects of erosion on the flow kinematics and impact mechanisms on a flexible barrier.

## 2 Physical flume modelling

The 28-m-long flume facility at the Kadoorie Centre in Hong Kong is used in this study to conduct a series of physical experiments. A terminal flexible barrier with a height of 1.5 m and a width of 4 m is installed at a distance of 4.4 m from the outlet of the inclined section of the flume in the horizontal runout zone. The barrier has three load bearing cables holding up a ring net panel. Load cells are attached to each cable to measure the cable impact forces. Figure 1 shows the flume model with an erodible bed and the instrumentation setup. Details of the instrumentation can be found in [7].

Four tests were conducted. The volumes were varied as 6 m<sup>3</sup> (V6) and 9 m<sup>3</sup> (V9). For each flow volume a control test was conducted where the entire flume length is non-erodible (denoted as S). For the erodible bed tests, the flume base was modified to include wet soil bed material. V6E test consists of an erodible section with a

length ( $L_e$ ) of 6 m and thickness ( $t_e$ ) of 120 mm. The V9E test consists of an erodible section with  $L_e$  of 8.5 m and  $t_e$  of 200 mm (Figure 1). The debris flow material consists of gravel 36%, sand 61%, clay 3% by mass with a 30% volumetric water content. The erodible bed material consists of fine coarse sand 33%, sand 63% and fines 4% by mass. The details of preparation of erodible bed are presented in [7] and a summary of the test program is given in Table 1.



**Fig. 1.** 28-m-long flume modified to include the erodible bed in the V9E test (HSC denotes high-speed camera, GP denotes GoPro camera and black boxes marked on the flume base shows the locations of the instrumentation boxes and flow height sensors).

**Table 1.** Test Program

Test ID	Flow Volume (m <sup>3</sup> )	Bed Setup
V6S	6	Non-erodible bed
V6E	6	Erodible bed ( $L_e = 6$ m)
V9S	9	Non-erodible bed
V9E	9	Erodible bed ( $L_e = 8.5$ m)

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### 3 Interpretation of test results

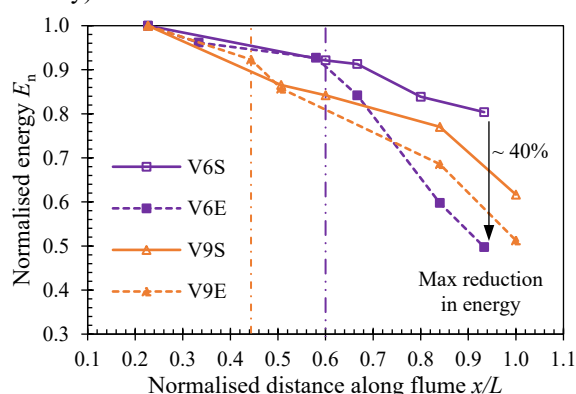
The flow kinematics can be characterised by the flow frontal velocity and peak flow depths measured at specific locations along the flume transportation zone ( $x = 0$  m to  $x = 15$  m). By using these two flow parameters, the evolution of the flow energy along the flume length can be calculated as:

$$E = z + h_{fe} \cos \theta + v_f^2 / 2g \quad (1)$$

where  $z$  is the elevation from datum,  $v_f$  is the measured flow frontal velocity,  $h_{fe}$  is the measured peak flow depth adjusted to consider the erosion depths,  $\theta$  is the flume inclination of  $20^\circ$  and  $g$  is the gravitational acceleration. The  $v_f$  is indicative of the changes in flow front kinematics during the interaction with the erodible bed [2] and governs the peak impact load on the terminal flexible barrier [8]. The datum is taken at the end of the flume transportation zone (i.e.,  $x/L = 1.00$ , where  $x$  is the length along the flume from gate and  $L$  is the total length of 15 m). The calculated  $E$  is normalised by the flow energy at  $x/L = 0.23$  (at Box-1) such that the normalised flow energy ( $E_n$ ) is unity at that specific location.

Figure 2 shows the  $E_n$  for the four tests along the normalised flume length.  $E_n$  decreases along the flume length for all tests. Interestingly, both the erodible bed tests show a higher energy dissipation after the flow reaches the erodible bed ( $x/L = 0.44$  for V9E and  $x/L = 0.60$  for V6E) compared to the corresponding control tests.

Test V6E with the highest erosion volume shows a higher dissipation of flow energy, where a maximum of  $\sim 40\%$  energy is lost compared to the test V6S by the time the flow reaches the end of the inclined section of the flume. This implies with an increase of eroded bed material the dissipation of flow energy also increases. In essence, the increase in potential energy (i.e., flow depth) from the addition of eroded material is relatively lower compared to the decrease in flow kinetic energy (i.e., flow velocity).



**Fig. 2.** Normalised flow energy along the flume inclined distance (start of the erodible section shown by vertical lines at  $x/L = 0.44$  for V9E and  $x/L = 0.60$  for V6E)

The observed changes in flow kinematics and flow energy over the erodible bed section and its effects on the impact dynamics are assessed. Due to the abrupt transition in flume angle from  $20^\circ$  to  $0^\circ$  at the end of erodible bed

( $x/L = 1$ ), the energy of the flow is further dissipated in all tests, before reaching the barrier.

The normalised flow momentum change ( $\Gamma_n = V_n \times S_n$ ) prior to the impact on barrier can be calculated relative to the control tests. The normalised flow frontal velocity prior to the barrier location (at Box-5) ( $S_n$ ) and the normalised frontal flow volume at impact ( $V_n$ ) are used for the calculation (Table 2) [2]. Furthermore, the peak impact force of the terminal flexible barrier can also be normalised with corresponding control tests. It is observed that at the impact location, the flow frontal velocity is reduced, and the flow volume is slightly increased due to the presence of the erodible bed. A value of  $\Gamma_n < 1$  indicates that flow momentum is lost in the erodible bed tests compared to the control tests. A maximum momentum loss of  $\sim 22\%$  is observed for the V6E test where higher erosion led to a higher reduction in the normalised flow energy compared to V9E test (Figure 2). Moreover, the normalised peak impact force ( $F_n$ ) against the flexible barrier conforms with the observed  $\Gamma_n$ , which shows a higher momentum loss and thus a lower measured peak impact force at terminal barrier.

**Table 2.** Normalised flow momentum and peak impact force at the terminal flexible barrier

Test ID	Normalise -d flow frontal velocity ( $S_n$ )	Normalise -d flow volume ( $V_n$ )	Normalised flow momentum ( $\Gamma_n$ )	Normalised peak impact force ( $F_n$ )
V6E/S	0.68	1.15	0.78	0.91
V9E/S	0.94	1.02	0.96	0.98

### 4 Conclusions

A series of physical experiments were conducted in a state-of-the-art 28-m-long flume to model the effects of flow-bed interactions on flow kinematics and terminal barrier impact.

Normalised flow energy reduction of up to  $\sim 40\%$  is observed at the end of flume transportation zone for the erodible bed tests compared to the control tests with non-erodible bed. Results show that erosion induced reduction in flow kinetic energy is higher than the increase in potential energy from the eroded mass, leading to lower peak impact forces on the terminal barrier. The findings indicate the need for future research to further verify and evaluate erosion induced changes in flow kinematics and barrier impact.

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