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Manuscript title: Effects of solid fraction of saturated granular flows on overflow and landing mechanisms of rigid barriers

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Abstract

Steep creek hazards are characterised according to their solid fraction $v_s$, which governs the flow dynamics. To arrest these hazards, rigid multiple barriers are installed along a channel. However, existing design guidelines are deficient because the fundamental overflow and landing mechanisms are not well understood. In this study, experiments were conducted using a 5-m-long flume to model the impact of flows with different $v_s$ on a rigid barrier. By varying the $v_s$ of sand-water mixtures, the dynamics of different steep creek hazards were modelled. The barrier height was varied to obtain Barrier Froude numbers $Fr_b$ (ratio of flow inertia to potential energy related to barrier height) from 0.7 to 3.4. Results show that barriers should be designed so that $Fr_b < 1$, which leads to downward overflow with reduces landing distances. Additionally, the landing distance for the watery flows ($v_s = 0$ to 0.1) is up to 87% longer than that of dry granular flows. This implies that the design spacing between barriers should cater for different types of steep creek hazards and $Fr_b$. An existing framework for multiple barriers is modified to provide guidance on the selection of the barrier height using the $Fr_b$.

**Keywords**: barriers; landing; landslides; overflow; steep creek hazards
Introduction

Channels with slopes greater than 3° (Church, 2010) transport floods, hyper-concentrated flows, and debris flows (Hungr et al., 2014), and often result in fatalities and damage to infrastructure (Froude & Petley, 2018). To mitigate these flows, rigid barriers are often installed along their predicted flow paths. An important consideration for designing a rigid barrier is its height $H$, which should be tall enough to suppress the runup and retain the debris (VanDine, 1996; Kwan, 2012). To ensure that rigid barriers are constructible and cost effective, several smaller rigid barriers in series (Takahashi, 2014) may be adopted instead of a single massive barrier at the end of a catchment. Barriers in series create a cascading effect to progressively retain and decelerate a mass flow (Wendeler, 2016; Ng et al., 2018). Current design approaches for multiple rigid barriers recommend design heights, $H$, based on the maximum volume of debris that can be retained (VanDine, 1996). Correspondingly, the recommended minimum barrier spacing, $L_{\text{min}}$, is the inclined distance between the upstream and downstream barrier (VanDine 1996; Osti & Egashira 2008):

$$L_{\text{min}} = \frac{H}{\tan\theta - \tan\psi} \quad (1)$$

where $\theta$ is the channel inclination and $\psi$ is the deposition angle, which is given as $\psi = n\theta$. $n$ has been recommended as 1/6 (NILIM, 2007) and 3/4 (CGS, 2004).

A four-step multiple barrier framework was proposed by Kwan et al. (2015) and Ng et al. (2018) based on the overflow and landing mechanisms for dry granular flows impacting dual rigid barriers. The first step in the multiple barrier framework includes velocity attenuation when the flow impacts the barrier. As the flow impacts the barrier, part of the flow forms a static wedge-like dead zone at the toe of the barrier. The incoming flow climbs on top of the dead zone and shearing between the flow and dead zone causes energy dissipation. The attenuated velocity $v_d$ and velocity reduction factor $R_d$ is as follows (Koo et al., 2017; Ng et al., 2019):

$$v_d = v (1 - R_d) \quad (2)$$

and,

$$R_d = 1 - \sqrt{1 - \frac{2g\tan\theta L_T h_d}{v^2}} \quad (3)$$

where $v$ is the pre-impact flow velocity, $L_T$ is the length of the free surface of the arrested granular material, $h_d$ is the height of the deposited granular material, and $g$ is the acceleration due to gravity.
The $\nu_d$ can then be used to calculate the impact force $F$. For the case with no overflow, the total impact force $F$ is a combination of the static force $F_s$ and the dynamic force $F_d$. The static force $F_s$ is caused by the dead zone arrested in front of the barrier. Whereas the dynamic force $F_d$ is from the debris riding on top of the dead zone (Fig. 1). The static force $F_s$ is estimated using the lateral earth pressure, which is earth pressure coefficient $k$ times the weight of the dead zone deposit. The $F_s$ is calculated as follows:

$$F_s = k\rho_b g h_d^2 w$$  \hspace{1cm} (4)

where $\rho_b$ is the flow bulk density and $w$ is the channel width. The earth coefficient $k$ ranges from 0.2 to 5.0 (Iverson et al., 2016). The dynamic force $F_d$ is:

$$F_d = \alpha \rho_b v_d^2 h_{max} w$$  \hspace{1cm} (5)

where $h_{max}$ is the maximum flow height and $\alpha$ is the hydrodynamic impact coefficient. The hydrodynamic coefficient $\alpha$ has been reported to range from 0.2 to 18 (Scheidl et al., 2013; Cui et al., 2015).

Once the barrier is filled, overflow occurs. The second step in the framework is to estimate the landing distance from the crest of the barrier. A horizontal overflow trajectory is assumed (Kwan et al., 2015). The landing distance is estimated as follows:

$$x_i = \frac{v_m}{g} \left[ \tan \theta + \sqrt{\tan^2 \theta + \frac{2\alpha H}{v_m^2}} \right]$$  \hspace{1cm} (6)

where $x_i$ is the maximum landing distance and $v_m$ is the horizontal overflow velocity. The $v_m$ is estimated using the horizontal component of the launch velocity $v_o$, launching at an angle $\xi$. Eqn. 6 can be used to check whether flow launches over the next barrier (Hákonardóttir et al., 2003; Faug, 2015b). The third step in the framework is to estimate the energy loss when flow lands on the channel. The flow velocity towards the next barrier $v_i$ depends on the slope-parallel component of the landing velocity $v_r$ and the angle of impact on the channel bed. Finally, a landing coefficient $C_r$ is introduced to account for the change in velocity after the overflow impacts the channel bed:

$$C_r = R \cos \beta$$  \hspace{1cm} (7)
where $R$ is the landing velocity reduction factor due to friction between the flow and channel bed, and
\[ \beta \text{ is the landing angle and } v_1 = C v_r. \] The $v_1$ can then be used as an input in Eqns. 2 and 3 to predict the impact dynamics on the second barrier. Eqns. 2 to 7 can be used iteratively to design subsequent barriers in the channel. The framework assumes that material only overflows a barrier once it is completely filled. Moreover, the overflow trajectory from the crest of the barrier is assumed to be horizontal (Fig. 1). Such a trajectory implies that significant flow kinetic energy has been dissipated by the time the granular material has reached the barrier crest (Koo et al., 2017). However, Choi et al. (2016) conducted physical experiments and revealed that inertial flows may launch at an upward angle from the barrier crest before the barrier is filled to its capacity (Fig. 2). The overflow trajectory is important to estimate the overflow distance and retained volume. However, existing guidelines do not consider the overflow trajectory.

A strong foundation of work has been carried out to reveal the interaction between dry granular flows and barriers (Faug et al., 2008; Faug, 2015a). Dry granular flow constitutes an idealised frictional flow case where the macroscopic flow dynamics are regulated predominantly by grain contact forces (Iverson & Denlinger, 2001). Whereas, for two-phase flows, the pore fluid pressure regulates the Coulomb friction (Pudasaini et al., 2005). Furthermore, the volumetric solid fraction $\nu_s$, which is defined as the volume of the solid to the total volume of the flow, regulates the momentum transfer between the particles and fluid. Pierson (2005) reported that the flow shear resistance increases with the flow solid fraction, giving rise to a change in flow rheology. These grain-scale interactions ultimately give rise to the macroscopic flow dynamics (Pudasaini & Hutter, 2007). Song et al. (2017) demonstrated using centrifuge tests that the solid fraction in two-phase flows governs the impact dynamics. However, their study did not consider the overflow and landing mechanisms. Clearly, understanding the effects of flow composition on overflow and landing is an essential step to rationalise the design spacing between barriers.

In this study, physical experiments were carried out using a 5 m-long flume to investigate the effects of solid fraction and barrier height on the overflow and landing mechanisms resulting from flow-barrier interaction. Experimental results were then used to modify an existing analytical framework to provide guidance on selecting the design barrier height.
Flume modelling

Instrumentation and model setup

Figure 3 shows the elevation and plan views of the model setup and instrumentation layout. The model channel is made of acrylic boards with a total length of 5 m, a width of 0.2 m and a depth of 0.5 m. The upper part of the channel has a storage container (0.06 m³) to retain the debris material behind a pneumatic gate (Fig. 3a). The gate lifts upwards in about 1 s to simulate dam-break initiation, which allows the debris to collapse down the channel in a convenient and replicable manner (Iverson, 2015). The friction angle between the sand and the channel is measured by following the method used in Savage and Hutter (1989), i.e., by raising the channel inclination gradually till the sand starts to flow. By using this method, the friction angle between sand and the channel is measured to be 21°. A square basal load plate with a nominal length of 100 mm was installed at an inclined distance of 100 mm upstream of the barrier location. The plate is guided by four linear bearings to transfer load one-dimensionally to a load cell (Kyowa Lux-B-500N) underneath the plate (Fig. 3b). A laser displacement sensor (Wenglor YT44MTGV) was installed above the plate to measure the flow thickness. Based on the normal stress and flow thickness, the bulk density of the flow can be calculated. Additionally, another load cell was sandwiched between an acrylic plate and a reaction frame to form a rigid barrier that can measure the impact force. The barrier is 0.19 m in width, and its height was varied as 100, 180 and 260 mm. In each test, a rigid barrier was installed at an inclined distance of 0.8 m downstream from the gate. Two high-speed cameras, namely C1 and C2 (Mikrotron EoSens mini2), with a sampling frequency of 200 frames per second (fps) and an image resolution of 1696 x 1440, were mounted at the side of the channel to capture the kinematics through the transparent side walls. An additional camera, namely C3 (model no.: Prosilica GE640), with a sampling rate of 200 fps and an image resolution of 480 x 320, was also mounted at the side of the channel to capture the overflow kinematics for flows with longer landing distances.

Flow characterisation

Dynamic similarity can be achieved at the mesoscopic or macroscopic scale. In mesoscopic scaling, the particle-particle and fluid-particle shear stresses are characterised (Iverson, 1997; Iverson, 2015). Mesoscopic stresses ultimately give rise to macroscopic behaviour (Iverson, 2015). However, some mesoscopic parameters such as the dynamic viscosity and the number of grains above the slip plane...
are difficult to measure meaningfully. In contrast, macroscopic scaling only requires parameters, such as the velocity and flow height, that are measurable. Froude scaling is generally used to achieve macroscopic similarity for channelised flows (Scheidl et al., 2013; Faug, 2015a; Armanini et al., 2020). The Froude number characterises the ratio of inertial to gravitational forces:

\[ Fr = \frac{v}{\sqrt{gR_{\text{max}}}} \]  

Prototype debris flows have been reported to be characterised by Froude numbers from 0.5 to 7.6 (Hübl et al., 2009). In this study, trial experiments were conducted to identify the flume inclination and locations along the channel that would enable Froude similarity with prototype flows. The Froude number, \( Fr \), of unsteady open-channel flows is influenced by the initial mass, the channel inclination, and flow material. Choi et al. (2015) reported that large initial volumes generate large flow heights, which results in lower \( Fr \). The change in flow height also depends on the distance from the storage container after dam-break initiation and the flow material involved. Generally, the flow height for a fixed initial volume of material decreases as the debris spreads downslope (Ng et al., 2013). Water, which has negligible shear strength, spreads longitudinally at shorter timescales compared to dry sand. Therefore, water flows develop smaller flow heights compared to dry sand flows under the same initial experimental conditions. Based on the aforementioned considerations, trial tests were conducted in this study to identify the position along the flume, the initial mass, and the channel inclination that would generate \( Fr \) in the range observed in the field, which is from 0.5 to 7.6 (Hübl et al., 2009). Consequently, an initial mass of 100 kg of dry sand at a channel inclination of 26° was adequate to achieve prototype \( Fr \) at an inclined distance of 0.8 m from the gate. Whereas for water and water-sand mixtures, a mass of 30 kg at a channel inclination of 26° was appropriate to develop field \( Fr \) at an inclined distance of 0.8 m from the gate.

Barrier heights were selected based on prototype barrier Froude numbers. The Barrier Froude number is defined as the ratio of flow kinetic energy to the potential energy related to barrier height, i.e. \( \sim gH \) (Faug, 2015b). The \( Fr_b \) is the measure of kinetic energy required for the flow to climb over the barrier:

\[ Fr_b = \frac{v}{\sqrt{g \cos \theta H}} \]
Typical barrier Froude numbers in the field range from 0.1 to 5, which is equivalent to barrier heights from 2 to 10 m (Lo, 2000), flow depths from 0.5 to 2.0 m (Kwan 2012), slopes from 0 to 30° (Ng et al., 2012) and velocities from 1.5 to 15 m/s. In this study, three different model barrier heights, 100, 180 and 260 mm were selected (Table 1).

**Test programme**

Toyoura sand was used in the experiments. Toyoura sand is a monogranular sand with uniformity coefficient of 1.21 and characteristic particle size of 0.2 mm (Wu et al., 2013). Coussot & Menuier (1996) reported that, generally, stream floods have solid fractions from 0 to 0.04, hyper-concentrated flows have solid fractions from 0.04 to 0.6, and debris flows have solid fractions greater than 0.6. Flows with different solid fractions \( \nu_s \), specifically 0, 0.09, 0.20, 0.36 and 0.60 were prepared in a storage container. Two types of tests were carried out, control tests and impact tests. In control tests, no barrier was installed in the channel. The purpose of a control test is to measure the maximum unimpeded flow height \( h_{\text{max}} \), the maximum unimpeded frontal flow velocity \( \nu \), and the maximum unimpeded bulk density \( \rho_b \). The unimpeded values are used to conservatively estimate the design Froude number and the design impact force for barriers (i.e. Eqns. 4 and 5). The use of unimpeded flows to obtain pre-impact parameters for the design of barriers is referred to as the ‘free field’ approach in engineering design practice (Kwan, 2012; Kwan & Koo, 2015; Koo et al., 2018). The maximum unimpeded flow height was measured using a laser sensor. The average frontal velocity was obtained by using the approach proposed by Ashwood & Hungr (2016). Following their approach, the frontal velocities are calculated based on the time recorded for the flow front to travel distances of 50 mm and 100 mm along the channel. The difference from the average values is less than 10% for all the tests. The average of the frontal velocities calculated for these two distances is given in Table 1.

A comparison between the average frontal velocity deduced using the approach proposed by Ashwood & Hungr (2016), and the velocity deduced using PIV shows percentage differences of less than 10% for the dry sand tests and up to 180% for the water and water-sand mixture tests. The large percentage differences in velocity for the water and water-sand mixture tests is caused by the splatter of turbid water on the sidewall, the presence of turbulence and air bubbles; and the reflection of light off the two-phase flows, which can obscure the image texture for reliable PIV analysis (Nobach &
Bodenschatz, 2009; Take, 2015; Chen et al., 2017). Figure A1 shows snapshots of the splatter on the sidewall of the channel. Obtaining reliable velocity fields from PIV for unsteady turbid flows such as soil-water mixtures remains a technical challenge (Pagliardi, 2007; Poelma, 2017; Poelma, 2020). We concluded from our comparison between the approach proposed by Ashwood & Hungr (2016) and PIV for deducing the frontal velocity that the former approach is more reliable.

The bulk density of the flows, \( \rho_b \), with different solid fraction was estimated using the unimpeded maximum flow height measured by the laser sensor and the peak basal load measured from the basal load plate (Fig. 4). The corresponding bulk density is calculated using \( \rho_b = F_b/A_b g h_{max} \) where \( F_b \) is the peak force measured by the basal load plate, and \( A_b \) is the area of the basal load plate. The maximum bulk density is used to calculate the solid fraction using the following equation (Iverson, 1997):

\[
\nu_s = (\rho_b - \rho_l)/(\rho_s - \rho_l) \quad (10)
\]

where \( \rho_s \) is the solid density and \( \rho_l \) is the interstitial fluid density. Here, \( \rho_s \) is 2650 kg/m\(^3\) and \( \rho_l \) is 1000 kg/m\(^3\) for water-sand mixtures and 1.2 kg/m\(^3\) for dry sand flows.

Based on the free-field approach to obtain pre-impact flow parameters, the unimpeded maximum flow height \( h_{max} \) obtained from the control tests for each flow type is assumed to be the same for the impact test. For simplicity, the maximum unimpeded bulk density and corresponding solid fraction measured from the control tests were assumed to be the same as those for the impact tests. This is because the presence of a barrier in the channel causes the rapid accumulation of material behind the barrier, thus obscuring the pre-impact bulk density required for Eqns. 4 and 5 from being measured. The back-calculated solid fractions along the channel are lower than the initial solid fractions of the two-phase mixtures prepared in the storage container likely because of flow consolidated in the channel before reaching the loading plate. The initial solid fractions were 0.09, 0.20, and 0.36, while the measured solid fractions from the load plate were 0.05, 0.18 and 0.30, respectively. In this study, a solid fraction of zero corresponds to water. According to Denlinger & Iverson (2001), the solid fraction for dry sand in a loose static state is about 0.60. The measured \( \nu_s \) for the dry granular flows in this study was about 0.61. A summary of measured and deduced flow parameters is given in Table 1.
Modelling procedures

For each impact test, first the gate was closed, and the mixture with a pre-determined solid fraction was prepared in the storage container. Next, an electric mixer was used to mix the soil and water. Afterwards, the channel was inclined to 26°. The gate was then opened by using the pneumatic actuator. The debris material flowed down the channel and impacted the barrier. The high-speed cameras and data logger captured the images and measurements, respectively.

Interpretation of results

Observed flow-barrier interaction

Figure 5 shows the observed kinematics of dry sand impacting a rigid barrier and the corresponding particle image velocimetry PIV (White et al., 2003) analysis for a short barrier with a Fr of 1.2 (Fig. 5a) and a tall barrier with a Fr of 0.7 (Fig. 5b). As stated earlier, it was not possible to obtain meaningful velocity measurements using PIV analysis. Therefore, the PIV generated velocity fields are qualitative. The time just before the flow impacts the barrier is taken as zero.

A notable difference in the impact mechanism is observed when Fr is less than unity. For a short barrier, the flow impacts the barrier (t = 0 s) and jumps up along the barrier face. A wedge-like dead zone (Choi et al., 2014) forms behind the barrier before sand launches over the barrier as a jet (Fig. 5a). The launch angle of the jet is nearly parallel to the channel bed. In contrast, when sand impacts a tall barrier, the flow direction changes from a slope parallel one to a slope orthogonal one as the material climbs along the face of the barrier. As the incoming flow rides on top of the deposited material, energy loss due to shear occurs (Koo et al., 2017; Song et al., 2019). Additionally, the conversion of kinetic to potential energy attenuates the flow. When Fr < 1, a granular bore develops and travels in the upstream direction before coming to rest (t = 1.00 and 1.50 s). The granular bore is caused by a shock wave due to flow obstruction (Gray et al., 2003). Across the shock, the flow height abruptly increases (Faug, 2020). The granular bore is an effective energy dissipation mechanism and has been reported to be a possible consideration when spacing barriers (Wendeler, 2016). In summary, the observed kinematics show that a granular bore develops when Fr < 1 and a granular jet develops when Fr > 1.
Figure 6 shows a comparison of the kinematics of a two-phase flow with a solid fraction of 0.3 impacting a short barrier with a $Fr_b$ of 2.9 (Fig. 6a) and a tall barrier with a $Fr_b$ of 1.7 (Fig. 6b). The impact process can be characterised in three stages. In the first stage, the flow impacts the barrier and forms a vertical jet ($t = 0.15$ s). In the second stage, a dead zone forms. Depending on the barrier height, momentum redirection takes place. For the short barrier, when the vertical jet reaches its highest point of ascent, the incoming flow climbs on the ramp-like dead zone at the base of the barrier and launches over the barrier (Ng et al., 2018). For the tall barrier, once the jet reaches its highest point of ascent, part of the flow rolls back upstream and part of the flow overspills the barrier. The size of the dead zone observed behind the tall barrier is smaller than the height of the barrier (Fig. 6b, $t = 0.5$ s). In the third stage, the dead zone accumulates to the crest of the barrier and overflow is observed until the supply from the storage container is depleted. The surface of the arrested material behind the barrier at the end of the test is nearly horizontal (Fig. 6b, $t = 1.5$ s).

Figures 7a and 7b show a comparison between the observed impact kinematics of water for a short barrier with a $Fr_b$ of 3.3 and a tall barrier with a $Fr_b$ of 2.4, respectively. Similar to the two-phase flows, the impact process for water occurs in three stages. In the first stage, the flow impacts the barrier and forms a vertical jet ($t = 0.15$ s). In the second stage, a ramp-like dead zone forms at the barrier toe ($t = 0.5$ and 1.0 s). In the final stage, the jet either rolls back towards the channel or over-spills the barrier (Fig. 7a). A comparison of impact kinematics for the different barrier heights reveals differences during the second stage of impact. For the short barrier, water climbs over the ramp-like dead zone and launches as a jet from the barrier crest at an upward angle of about 50°. In contrast, for the tall barrier, the flow is reflected by the barrier.

Generally, the impact mechanisms for dry sand and water flows result in pileup and runup mechanisms, respectively. For two-phase flows, the rheology changes with solid fraction, whereby the shear resistance of the flow decreases with solid fraction and the impact mechanism transitions from a pileup to a runup one (Song et al., 2017). In contrast to dry sand, water flows do not dissipate energy via frictional contacts but by viscous forces. Consequently, water flows experience less energy dissipation upon impact, and longer overflow distances are observed. Generally, steep creek hazards evolve as they flow downslope (Cui et al., 2019) because of the change in solid fraction. The design of
mitigation measures should be robust enough to consider the impact dynamics for flows with a wide range of solid fraction.

To suppress overflow, the barrier height should be designed so that $F_r < 1$, which implies that the flow kinetic energy is less than the potential energy of the height of the barrier ($\sim gH$). For the flow to overspill the barrier, the kinetic energy of the flow must be greater than the potential related to the barrier, which can be expressed as follows:

$$\frac{1}{2} m v^2 > mgH \quad (11)$$

Rearranging the above expression for the barrier height $H$ gives us:

$$H < \frac{v^2}{2g} \quad (12)$$

Eqn. 12 does not consider energy dissipation. So depending on the flow type, the energy loss during the impact process may differ significantly (Song et al., 2017). Also, Eqn. 12 idealises the flow as a point mass, which is generally inaccurate because the centroid of the runup mass needs to be considered instead of just the snout of the runup (Iverson et al., 2016). Thus, a threshold of unity for $F_r$ is indicative only.

Overflow mechanism

Figure 8 shows the influence of the volumetric solid fraction on the landing distance. Barrier heights of 100, 180 and 260 mm are compared. The landing distance is defined as the inclined distance between the point at which the overflow detaches from the barrier crest to the point when the overflow front impacts the channel bed (Fig. 3). Due to air resistance, as overflow detaches from the barrier crest, the flow front disperses (Hákonardóttir et al., 2003). The dispersed front may slightly increase $x_i$. Nonetheless, selecting the farthest landing point to obtain $x_i$ is conservative. Flows with a higher solid fraction result in shorter landing distances because more energy dissipation occurs from grain shearing as sand is deposited in layers to the barrier crest. A comparison between water ($v_s = 0$) and dry sand ($v_s = 0.60$) flows shows that the landing distance for sand is 87, 80 and 82 % shorter than water for barrier heights of 100, 180 and 260 mm, respectively. Taller barriers result in shorter landing distances because of greater velocity attenuation (Koo et al., 2017). Landing distances for a 180 mm barrier height are in between the tallest (260 mm) and shortest (100 mm) barriers for each solid fraction. The difference in landing distances for the dry sand flows and water impacting against barrier
heights of 100 mm (shortest) and 260 mm (tallest) is 56% and 67%, respectively. The measured results for the landing distance for flows with different solid fractions and barrier heights indicate that both the barrier height and flow solid fraction govern the landing distance and consequently the barrier spacing.

The measured landing distances for different flow types in this study are compared with the calculated landing distances using Eqn. 6 (Kwan et al., 2015). The calculated distances are up to 71% higher than that measured. This is because the flow velocity before impacting the barrier is assumed to be the same as the overflow velocity in the analytical framework proposed by Kwan et al. (2015). In reality, significant velocity attenuation occurs due to the conversion of kinetic to potential energy and via shearing among grains during the impact process (Koo et al., 2017). Nonetheless, the landing model from Kwan et al. (2015) is an appropriate upper bound for estimating the landing distance.

Figure 9 shows the effects of the $Fr_b$ on the normalised landing distance. The $Fr_b$ governs the overflow dynamics (Figs. 5 to 7), and the overflow distance depends on the barrier height (Fig. 8). To provide a generalised expression for design, the relationship between $x/H$ and $Fr_b$ is obtained by normalising Eqn. 6 (Kwan et al., 2015) by the barrier height $H$ and assuming that the launch velocity is the same as the initial barrier impact velocity. The generalised equation is as follows:

$$\frac{x}{H} = Fr_b^2 \left[ \frac{\tan \theta}{\sqrt{\frac{\tan^2 \theta + \frac{2}{Fr_b^2}}}} \right]$$

(13)

The predicted landing distance using Eqn. 13, data from Koo (2017), relevant design guidelines (CGS, 2004; NILIM, 2007) are compared with measured data in this study. Experiments conducted by Koo (2017) adopted the same barrier heights and the same flume setup as this study. However, they used dry Leighton Buzzard sand, which has a mean particle diameter that is three times larger than the mean particle diameter used in this study. Furthermore, Koo (2017) conducted flume tests inclined at 26° and 32°. While in this study, the flume is inclined at 26° only. Both the particle size (Ng et al., 2017) and channel inclination resulted in higher $Fr_b$ obtained by Koo (2017) compared to this study.

The normalised landing distance increases with flow inertia, which is reflected by an increase in $Fr_b$.

The measured landing distances for flows with $v_s$ from 0 to 0.30 in this study exhibit longer landing distances compared to that of dry sand with a similar $Fr_b$. The dry sand experiments from Koo (2017) resulted in a landing distance that is 40% lower than that of water measured in this study with a similar $Fr_b$. The shorter landing distance observed for the dry sand tests is because of enhanced
energy dissipation due to grain contacts. By contrast, energy dissipation from viscous resistance in water flows is less. Therefore, longer landing distances are observed for water. Comparison of the measured results to theoretical predictions shows that Eqn. 13 is an appropriate upper bound. Furthermore, the assumption of using the initial velocity before impact as the launch velocity provides a robust and conservative estimate of the landing distance invariant of the flow type.

The measured landing distances suggest that design approaches based on retained volume alone are insufficient for designing multiple barriers (Osti & Egashira, 2008) because they do not consider the interaction mechanism between the flow and barrier and may underestimate the spacing required. For instance, volume-based spacing $L_{\text{min}}$ using approaches CGS (2004) and NILIM (2007) is smaller than the landing distance $x_i$ for $Fr_0$ greater than ~2.5 and ~1.2, respectively. $L_{\text{min}} < x_i$ implies that the overflow from the first barrier can launch past the second barrier. Similarly, the landing distance $x_i$ is lower than the $L_{\text{min}}$ recommended by CGS (2004) and NILIM (2007) for $Fr_0$ of less than ~2.5 and ~1.2, respectively. This implies that when $L_{\text{min}} > x_i$, a spacing based on $x_i$, may compromise the volume retention capacity of the second barrier due to its close proximity with the first barrier. Therefore, for a robust and conservative design, the barrier spacing should be the maximum of the overflow distance $x_i$ (Eqn. 13) and the volume-based spacing $L_{\text{min}}$ (Eqn. 1).

Influence of solid fraction on measured impact force

Figure 10 shows the influence of the barrier height on the measured force-time histories for flows with different solid fractions. The time is shown on the abscissa and the normalised impact force $F_i / \rho_s \nu^2 h_{\text{max}}w$ is shown on the ordinate. The impact history of the water, water-sand mixture with 0.3 solid fraction, and dry sand flows are compared. In each case, the impact force for barrier heights of 100 and 260 mm are compared to reveal the contribution of drag on the peak impact force. There are two types of drag, form and surface. Form drag is proportional to $\rho_s \nu^2 h_{\text{max}}w$ and is also termed as hydrodynamic drag. This type of drag is caused by the normal pressure of the fluid against an obstruction (Faug, 2015a; Jiang et al., 2015). In contrast, surface drag is the traction between the flow and the retained material behind the obstacle for a channelised flow. The surface drag force $F_{\text{drag}}$ for a frictional material can be calculated as follows (Kwan, 2012; Vagnon & Segalini, 2016):

$$ F_{\text{drag}} = \frac{\rho_s \theta \phi \tan \theta}{\tan \theta} h_{\text{sw}} $$  (14)
where $h_o$ is the height of overflowing debris. The surface drag force calculated using Eqn. 14 assumes that the surface of the deposited material is horizontal and the mobilised frictional resistance is constant and governed by the angle of repose for dry sand (i.e., 31°).

The measured results in Figs. 10a and 10b show that the peak impact force for both barrier heights is similar. This is because, for viscous flows, the impact process is predominantly governed by viscous forces, which generally results in a vertical jet-like runup (Choi et al., 2015), as observed in Figs. 6 and 7. Furthermore, the fluctuations in the measured force are due to fluctuations in the wave height of the material retained behind the barrier (Peregrine, 2003). The fluctuations in the measured force are more prominent for the tall barrier because more volume is retained at the end of the experiment. In contrast to water flows, no surface waves were observed for water-sand mixtures and dry sand because the contact forces between grains dissipate energy and enable flows to come to rest at shorter timescales.

The normalised impact force is lower than unity for the water and the water-sand mixtures. This indicates that the impact force is dominated by the hydrodynamic drag (Faug, 2015a). Whereas, for dry sand in Fig. 10c, the normalised force is higher than unity for both barrier heights. This is because for dry sand, energy dissipation due to frictional contact is higher, causing the flow to deposit and form a dead zone as it impacts the barrier. Therefore, the static load due to the dead zone dominates the loading process. The larger dead zone for the 260 mm barrier height compared to that of the 100 mm barrier height (Fig. 5), results in an impact force that is 36% higher compared to the 100 mm tall barrier (Fig. 10c). Moreover, for dry sand flow, the short barrier exhibits a gradual increase in force until it reaches a peak load, afterwards the force reaches a static load. In contrast, the loading response for a tall barrier shows a gradual increase in load towards the static load without a distinct peak load. The differences observed in the overall loading response between the short and tall barrier is partly due to the different dead zones (Fig. 5). For the tall barrier, minimal overflow is observed, and the dead zone height increases up to the barrier crest only after a second of impact (Fig. 5), which is when the peak impact force is observed. However, for the short barrier, in addition to the force due to the dead zone, the surface drag also contributes to the impact force (Fig. 5a), resulting in a peak load in the force-time history. When the $F_{drag}$ deduced using Eqn. 14 is subtracted from the total impact force exerted on the short barrier, a similar loading response between the short and tall barrier is
observed. The increase in the total force exerted on the barrier resulting from the surface drag force is about 40%. Evidently, the surface drag force should be considered in the overall design load of the barrier when overflow is expected. For water (Fig. 10a) and water-sand mixtures (Fig. 10b), similar peak loads in the force-time history were observed, invariant to the barrier height. This is because, for water and the water-sand mixture, the peak force occurs at initial impact when redirection of the flow takes place. In natural debris flows, the flow front may be unsaturated (Iverson, 1997), while only the body and tail may be fluidised. Thus natural debris flows that are frictional may induce significant surface drag forces on barriers.

Landing mechanism

Figure 11 shows the effect of the landing angle $\beta$ on the landing factor $C_r$. The $C_r$ is calculated using Eqn. 7, with $R$ is equal to unity. Physically, it is assumed that the landing momentum is completely destroyed when overflow impacts the channel perpendicularly, i.e. $\beta = 90^\circ$, $C_r = 0$. In contrast to perpendicular impact, no energy loss occurs when flow lands parallel to channel, i.e. $\beta = 0^\circ$, $C_r = 1$. Predictions based on Eqn. 7 are compared with the measured results from this study and results reported by Koo (2017). Results for only granular flows are compared due to difficulties in obtaining reliable velocity measurements for water and water-sand mixtures (see Appendix A).

Measured results show that $C_r$ decreases with $\beta$ because less energy is dissipated from directly impacting the channel bed. For a short barrier ($F_{r_5} > 1$), an upward overflow angle develops, leading to longer overflow distances (Fig. 9). The longer trajectory impacts the channel at smaller landing angles (i.e. $\beta = 25^\circ$ for $F_{r_5} = 1.2$). For a tall barrier ($F_{r_5} < 1$), the overflow angle is downwards, leading to larger landing angles ($\beta = 45^\circ$ for $F_{r_5} = 0.7$) and smaller $C_r$. Findings suggest that for dry granular flows, barrier heights characterised using $F_{r_5}$ influence the energy dissipation at landing. As $F_{r_5}$ decreases, the energy dissipation at landing increases. Interestingly, Kwan et al. (2015) reported that shorter barriers are more efficient at dissipating flow energy because the flow cannot gain momentum when it overflows the barrier. However, findings from this study show that increasing the barrier height results in less inertial flows, which increases energy dissipation when the overflow lands on the channel.
Volume retained

Figure 12 shows a comparison between the measured volume retained $V_i$ and calculated volume retained $V_c$ for different $Fr_b$. The calculated volume retained is:

$$V_c = \frac{0.5H^2W}{\tan(\theta - \psi)} \quad (15)$$

The normalised measured volume $V_i/V_i$ and the normalised calculated volume $V_c/V_i$ are compared. $V_i$ is the initial source volume. $V_i/V_i$ is the ratio of the initial volume that should be retained compared to the design volume (CGS, 2004; NILIM, 2007). In contrast, $V_i/V_i$ is the actual volume retained. Both the measured $V_i/V_i$ and calculated $V_i/V_i$ are shown for different $Fr_b$. Results for water, water-sand mixture and dry sand tests are compared. Tests with water-sand mixtures have solid fractions of 0.05, 0.12 and 0.30. In general, barriers that resist more inertial flows ($Fr_b > 1$) retain less material because the barrier potential head is lower than the flow kinetic energy, thereby enabling overspill. A comparison between the measured and calculated volumes for dry sand flow (Fig. 12e) shows that the volume retained in the experiments is higher than that predicted using Eqn. 15. The higher than expected retained volume is because the friction angle of sand is higher than the recommended deposition angle in design guidelines (CGS, 2004). In contrast, the retained volume for flows with water and water-sand (Fig. 12a-d) are over-estimated by using Eqn. 15 because the free surface of the observed retained volume is nearly horizontal. The water and water-sand mix flow in this study were more inertial before impact, so most of the flow overtopped the barrier. The difference between the calculated (CGS, 2004) and the measured retained volume for water flows (Fig. 12a) is 84% and 92% for $Fr_b$ of 2.4 and 3.3, respectively. Whereas for flows with a solid fraction of 0.30 (Fig. 12d) the difference between the calculated and the measured retained volumes is 79% and 72% for $Fr_b$ of 1.9 and 2.7, respectively. With higher solid fraction, more material is retained because of enhanced grain contacts, which facilitate energy dissipation and deposition dissipating energy and facilitating deposition. The lower volume retention for water and water-sand mix flows is due to their high flow inertia relative to the barrier potential. Therefore, less energy is dissipated during the flow and impact processes. Findings suggest that the $Fr_b$ and the internal friction angle relative to the channel inclination govern the volume of material retained. Existing guidelines generally underestimate the retained volume for dry flows and overestimate the retained volume for water and water-sand mix flows. A deposition angle of zero is recommended to ensure a conservative retention volume.
Modified multiple barrier framework

The assumption that the overflow only occurs when the barrier is filled may not always be valid because highly inertial flows can still overtop a barrier (see Fig. 6). For a multiple barrier design, the barrier height, characterised using the \( Fr_b \), is perhaps the most important parameter. The height governs both the overflow trajectory and landing distance, which consequently governs the spacing between barriers. Kwan et al. (2015) implicitly assumed overflow follows a horizontal or downward angle initially in their framework. This is valid when significant velocity attenuation occurs during impact when \( Fr_b \) is less than unity. In contrast, when the \( Fr_b \) is greater than unity, an upward overflow angle occurs. Therefore, the existing multiple barrier framework (Fig. 1) should include an additional step to design the barrier height. A precondition for selecting the initial barrier height is that the \( Fr_b \leq 1 \) so that the overflow follows a horizontal or downward trajectory, which also results in a higher landing angle to more effectively dissipation flow kinetic energy (see Fig. 11). Lastly, \( Fr_b \leq 1 \) enables greater volume retention because the highly inertial material does not overspill the barrier upon initial impact.

Conclusions

Physical flume experiments were carried out to study the overflow and landing mechanisms of two-phase flows impacting multiple rigid barriers. The effects of solid fraction and barrier height were investigated. Key findings may be drawn as follows:

1) The Barrier Froude number \( Fr_b \) governs both the overflow and landing mechanisms for the two-phase flows, with a wide range of solid fraction, impacting rigid barriers. Experimental results reveal that energy dissipation at landing can be enhanced when the \( Fr_b \) is less than unity.

2) For dry granular flows \((\nu_s \sim 0.6)\), the total load acting on a barrier increases by up to 40% when overflow occurs. The higher load is caused by surface drag between the overflow and arrested material behind the barrier. The additional surface drag force should be included in the total load. The horizontal deposition length and maximum flow thickness can be used to estimate the surface drag force. In contrast to dry sand, no surface drag force was observed for viscous flows.

3) Existing guidelines (CGS, 2004; NILIM, 2007) that recommend a barrier spacing based on the retained volume alone are insufficient and only valid when \( Fr_b \sim 1 \). For a conservative design, the barrier spacing should use the maximum of overflow distance \( x \) and retained volume-based
spacing $L_{\min}$. Furthermore, for inertial flows ($Fr_b >> 1$), the volume retained is 90% less than that estimated based on retained material.

4) Flows with high solid fraction result in shorter landing distances due to enhanced grain contact friction. The landing distance for dry granular flows ($\nu_s \sim 0.6$) is 87% shorter compared to watery flows ($\nu_s \sim 0$ to 0.1). This implies that robust multiple barrier designs need to cater for watery flows as well as frictional ones.

5) The existing multiple barrier framework was modified to provide guidance on selecting an appropriate barrier height based on $Fr_b$. The implicit precondition of the horizontal overflow angle from the crest is satisfied when $Fr_b$ less than unity.

It is acknowledged that laboratory-scale experiments are an idealised representation of natural mass flows. In reality, natural mass flows are highly heterogeneous and travel on complex flow paths. Furthermore, the lab-scale experiments may entail scaling disproportionalities (Iverson, 2015). Nonetheless, the experimental results in this study provide a basis to understand a complex natural phenomenon to advance the current state of barrier design.

Acknowledgements
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Appendix A
Fig. A1 Turbulent flow at landing for different flow types. Flow direction is from right to left
Notations

$H$ is the barrier height

$L_{\text{min}}$ is the minimum barrier spacing recommended by guidelines

$\theta$ is the channel inclination

$\psi$ is the deposition angle recommended by guidelines

$n$ is the ratio of deposition angle to the channel inclination

$x_i$ is the maximum landing distance

$v_{\text{in}}$ is the horizontal launch velocity

$g$ is the acceleration due to Earth’s gravity

$Fr$ is the Froude number

$h$ is the maximum flow thickness

$\nu$ is the velocity of the flow before impact

$\nu_c$ is the debris launch velocity

$\nu_d$ is the attenuated runup velocity

$\nu_i$ is the velocity before landing

$\nu_i$ is the velocity after landing

$h_d$ is the deposit height

$R_d$ is the velocity reduction factor

$L_T$ is the free surface length of the deposit in front of barrier

$Fr_b$ is the Barrier Froude number

$d_{50}$ is the mean grain diameter

$\nu_s$ is the volumetric solid fraction

$F_I$ is the measured instantaneous impact force

$F_S$ is the static force

$F_d$ is the dynamic force

$F_{\text{drag}}$ is the drag force

$h_{\text{ad}}$ is the thickness of overflowing debris

$\phi$ is the internal friction angle or angle of repose

$\rho_b$ is the bulk density of the flow
\begin{align*}
\rho_f & \quad \text{is the density of the fluid} \\
\rho_s & \quad \text{is the density of solids} \\
w & \quad \text{is the channel width} \\
C_v & \quad \text{is the landing factor} \\
\beta & \quad \text{is the landing angle} \\
V_c & \quad \text{is the calculated volume retained} \\
V_i & \quad \text{is the initial source volume} \\
V_r & \quad \text{is the measured volume retained} \\
\alpha & \quad \text{is the hydrodynamic coefficient} \\
\xi & \quad \text{is the launch angle}
\end{align*}

References


capacity from momentum and energy perspectives. Engineering Geology 251, 81–92.
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Table 1. Test program and corresponding dimensionless numbers

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<th>Average frontal velocity $v$ (m/s)</th>
<th>Unimpeded maximum flow height $h_{max}$ (mm)</th>
<th>Measured bulk density $\rho_b$ (kg/m$^3$)</th>
<th>Back-calculated volumetric solid fraction $\nu_s$ (-)</th>
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* Test ID type C-Sxx, the acronym ‘C’ represents the control test without a barrier installed in the channel. Whereas ‘Sxx’ stands for solid fraction with ‘xx’ representing the corresponding volume fraction of solids in the flow. For tests with a barrier installed in the channel, the test ID is of type Sxx_Hyy, the acronym ‘Sxx’ has similar meanings as stated above, while ‘Hyy’ represents the tests with a barrier installed with ‘yy’ representing the barrier height in centimetres. Furthermore, the acronym ‘SD60’ represents the dry sand with ~ 60% solid fraction with air as the interstitial fluid.
Figure captions

Fig. 1. Four-step multiple barrier framework (modified from Kwan et al., 2015); 1) velocity attenuation impact model to estimate force $F$ on the first barrier; 2) estimation of overflow trajectory once the barrier is filled and flow detaches from the barrier crest; 3) overflow then lands on the channel and landing factor is used to estimate the velocity after landing and; 4) the impact force on the second barrier can be estimated using $v_i$.

Fig. 2. Two types of overflow; (a) downward; and (b) upward.

Fig. 3. Schematic of laboratory flume test setup with instrumentation; a) elevation view and b) plan view. Dimensions $L$ and $x$ are equal to 0.8 and 0.1 m, respectively. (figure drawn not to scale)

Fig. 4 Time histories of measured basal load and flow height for test C-S12

Fig. 5. Interaction between dry sand and rigid barriers with $Fr_b$ of (a) 1.2; (b) 0.7.

Fig. 6. Observed interaction between water-sand mixture ($v_s=0.30$) and rigid barriers with $Fr_b$ of (a) 2.9; (b) 1.7.

Fig. 7. Observed interaction between water and rigid barriers with $Fr_b$ of (a) 3.3; (b) 2.4.

Fig. 8. Normalised landing distance $x_i/H$ for the flows with different solid fraction $v_s$ and barrier heights $H$ of 100, 180 and 260 mm.

Fig. 9. Influence of Barrier Froude Number $Fr_b$ on landing distance $x_i/H$.

Fig. 10. Normalised measured impact force with time for test (a) S00 (water); (b) S30 (hyper-concentrated flow) and; (c) SD60 (dry sand).

Fig. 11. Effect of landing angle $\beta$ (°) on the landing factor $C_r$.

Fig. 12. Effects of Barrier Froude Number $Fr_b$ on normalised volume retained $V_r/V_i$ for water and dry sand.
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Ng Fig 6
Barrier Froude Number $Fr_b$

$\text{Ng\_Fig9\_1}$
Accepted manuscript doi: 10.1680/jgeot.21.00170

![Graph showing landing angle (β) vs. landing factor (Cr). The graph includes data points for SD60_H26, SD60_H18, and SD60_H10, as well as measured data from Koo (2017). The graph also shows calculated values using Eqn. A6, R=1.](Ng_Fig11)
(a) S10 Measured (this study)
S10 Calculated (CSS, 2004)
S10 Calculated (NLM, 2007)

(b) S10 Measured (this study)
S10 Calculated (CSS, 2004)
S10 Calculated (NLM, 2007)

(c) S10 Measured (this study)
S10 Calculated (CSS, 2004)
S10 Calculated (NLM, 2007)

(d) S10 Measured (this study)
S10 Calculated (CSS, 2004)
S10 Calculated (NLM, 2007)

(e) S10 Measured (this study)
EDR Calculated (CSS, 2004)
EDR Calculated (NLM, 2007)

Fig. 12

Vol. related V/C (%) vs. Barrier Froude number F_R

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## Annexure A

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