Computational investigation of baffle configuration on impedance of channelized debris flow

C.E. Choi, C.W.W. Ng, R.P.H. Law, D. Song, J.S.H. Kwan, and K.K.S. Ho

Abstract: Channelized debris flows surge downslope in mountainous regions and have large impact forces. Arrays of debris flow baffles are frequently positioned in front of rigid barriers to engage torrents and attenuate flow energy. They are regularly designed on empirical and prescriptive basis because their interaction mechanism is not well understood. Numerical back-analysis of flume experiments using the discrete element method (DEM) is conducted to provide insight on flow interaction with an array of baffles. Varying configurations of baffle height, a second staggered row, and spacing between successive rows are examined. Upstream and downstream kinematics are monitored to capture and compare the Froude number, kinetic energy, and discharge resulting from each baffle configuration. Results from this study reveal that the height of baffles can be categorized relative to the initial approach flow depth ($h_0$), namely tall baffles ($1.5h$) and short baffles ($0.75h$). Tall baffles are characterized by the development of upstream subcritical flow conditions, whereas short baffles exhibit supercritical upstream conditions. Furthermore, tall baffles facilitate the suppression of overflow, and short baffles lead to excessive overflow that is supercritical in nature. Less flow attenuation occurs as the distance increases both upstream and downstream from each array of baffles. A second staggered row of short staggered baffles is ineffective in reducing debris kinetic energy, whereas tall baffles should be positioned as close as possible.

Key words: channelized debris flow, flume modeling, discrete element method, baffles, interaction mechanisms.

Introduction

Channelized debris flows can be classified as one of the most hazardous landslide processes (Jakob and Weatherly 2003) and commonly occur in mountainous regions around the world. Channelized debris flows travel at high velocity, have large impact forces, and can occur without warning. Countermeasures aimed to minimize risk to downstream facilities are essential to protect human lives, prevent damage to infrastructure, and avoid disruption to transportation lines. Structural countermeasures such as check dams (Mizuyama 2008), flexible barriers (Wendeler et al. 2008), slit dams (Watanabe et al. 1980), and an array baffles (Ng et al. 2012) can be strategically positioned along the flow path to reduce flow volume and mobility. Arrays of baffles are commonly positioned in front of rigid barriers to attenuate flow energy and reduce the impact induced on the rigid barrier. An array of baffles is positioned in front of a rigid barrier located in Lantau Island, Hong Kong (Fig. 1). The functionality of an array of baffles is to perturb the flow pattern such that flow slows down as it approaches each baffle and then accelerates towards the next row to promote energy dissipation (FHWA 2006). Furthermore, debris flow baffles should occupy a...
small footprint and be compact for constructability on steep natural terrain (Teufelsbauer et al. 2011).

During the early stages of impact, the debris is highly incoherent, and understanding the dynamics is imperative to facilitate the design of debris flow baffles positioned in front of a rigid barrier. Complex early-stage flow interaction mechanisms for individual obstacles such as dead zones, granular vacuums, and pile-up have been examined (Chu et al. 1995; Gray et al. 2003; Zanuttigh and Lamberti 2006; Faug et al. 2012). However, these interaction mechanisms have not been amalgamated to describe flow interaction with an array of debris flow baffles. Flume experiments on the influence of obstacles on dry granular materials flows have been conducted for flow regimes characterizing avalanche flows (Hákonardóttir et al. 2001, 2003; Faug et al. 2003), and it is reported that there is an obvious influence of obstacle configuration on flow impedance (Hauksson et al. 2007; Bugnion et al. 2012). However, Froude numbers characterizing snow avalanches are generally much higher (Froude numbers between 10 and 12), and findings may not be relevant for designing debris flow baffles.

Numerical investigations using the discrete element method (DEM) (Teufelsbauer et al. 2011) and finite volume simulations (Cosenza et al. 2006) have been adopted to model obstacle interaction with debris flow. Nonetheless, only brief quantitative results are presented, and further insight on the interaction mechanisms and influence of obstacle configuration on flow impedance are not revealed.

This paper serves to adopt flume tests from Ng et al. (2012) and conduct numerical back-analysis to examine key interaction mechanisms between an array of baffles and a channelized debris flow. Only the test program and model setup of flume experiments for simulating granular flow impacting an array of baffles are briefly introduced here. Detailed test results are reported and discussed by Ng et al. (2012) and are not repeated in this paper. Furthermore, the influence of upstream and downstream distance from an array, baffle height, a second staggered row, and spacing between successive rows are examined.

**Flume modeling of Ng et al. (2012)**

An early flume test program by the same research group (Ng et al. 2012) is adopted for calibration and subsequent numerical back-analyses using DEM to investigate flow interaction mechanisms. Details about flow characterization, the flume model, instrumentation, and testing procedures are discussed in the following sections.

**Scaling**

Three types of similitude are required for modeling debris flow – baffle interaction: (i) geometric similarity, (ii) kinematic similarity, and (iii) dynamic similarity. Geometric similarity is achieved by normalizing model dimensions by the channel width and initial upstream flow characteristics such as the approach flow depth ($h$). Kinematic similarity describes the impedance resulting from baffle interaction, which is unknown, and constitutes the objective of this study. Two distinct approaches exist to scale the dynamics of debris flow between model and prototype. One approach emphasizes the soil–water interaction of natural debris flows; hence, Savage number, Bagnold number, and frictional number, etc., are adopted to describe the complex micro and macro interactions of debris flows (Iverson 1997; Zhou and Ng 2010). The second approach, commonly adopted by the engineering purposes, is the macro hydraulic scaling. In other words, the granular flow is treated as a continuum. To achieve dynamic similarity, only the most dominant forces are captured. Channelized debris flows are driven by gravitational forces, and interaction with flow-impeding structures is strongly influenced by the change in momentum (inertial forces). Hübl et al. (2009) identified the Froude number as a key dimensionless parameter to scale debris flow impacting on concrete structures. Armanini et al. (2011) recognized that the Froude number is the key dimensionless parameter that influences the impact mechanisms against a rigid obstacle. Dynamic similarity in this study is attained by adopting the Froude number, $Fr$, which governs the similitude of forces in gravity-driven flows, to dynamically characterize the physical tests with reported field cases. The value of $Fr$ is the ratio of inertial forces to the gravitational forces and is given as follows:

\[
Fr = \frac{v}{\sqrt{gh}}
\]
where \( v \) is frontal velocity (m/s), \( g \) is gravitational acceleration (m/s\(^2\)), and \( h \) is the approach flow depth (m).

Froude similitude was adopted to characterize the flow front impacting the array of baffles. Channelized debris flow can be characterized with approach Froude numbers ranging from 0 to 4.5 based on field observations (Arattano et al. 1997; Arattano and Franzini 2003; Hübl et al. 2009; Hung et al. 2014). A Froude number of about 3 was adopted for this study, and it is equivalent to prototype channelized debris flow events with an approach velocity of 10 m/s and a flow depth of 1 m. In other words, results from these experiments are applicable for flows with approach Froude numbers of about 3. Debris interaction with baffles is a complicated problem. With the Froude scaling group as the only dominated dimensionless group, flume model tests are only an approximate description of the real physical phenomenon. To gain fundamental understanding and eventually help engineers develop design guidelines, the strategy is first to model a simplified flow case (dry sand) in a uniform channel using the same Froude number with field cases. Although the model is idealized, there is no doubt that the physics from the flume model tests is real, and if the following DEM model can capture flow dynamics from a simplified case, then it may eventually be enhanced and used to model more complex cases to develop further insight.

**Flume model**

Figure 2 shows the 5 m long rectangular flume model developed to investigate debris flow interacting with an array of baffles. The flume has a 0.2 m base width and 0.5 m side walls. The channel inclination is set to 26° to attain the appropriate initial upstream conditions. The external frame encompassing the flume facilitates the mounting of instrumentation and lighting. Debris is contained in the storage container located at the most upstream end of the flume, and the container has a maximum volume of 0.08 m\(^3\). The debris is retained by a spring-loaded door that is secured and controlled by a magnetic lock.

**Instrumentation**

Ten photoconductive sensors are installed throughout the base of the flume at intervals of 0.5 m. Photoconductive sensors are used to estimate the frontal velocity. Laser sensors are mounted overtrop of the channel to measure centerline flow depth profiles. Furthermore, high-speed cameras are positioned overtrop and to the side of the flume to capture flow kinematics. The full resolution capacity of the cameras is 768 × 425, and the cameras can capture up to 227 frames per second.

**Testing program**

Four baffle configurations are examined in this study. Baffle heights of 0.75 and 1.5 times the approach flow depth (\( h \)) are examined. The measured approach flow depth using laser sensors is 80 mm and is discussed in Ng et al. (2012). Single-row and two-row baffle arrays are investigated for each baffle height. Each row of baffles characterize 30% transverse blockage; therefore, each row of baffles occupies 60 mm of the 200 mm channel width. A transverse blockage of 30% falls outside the range of slit dams based empirical relationships (Watanabe et al. 1980; Ikeya and Uehara 1980), which requires an equivalent of at least 40% transverse blockage. Figures 3a and 3b show the baffle arrangements in plan view and side view, respectively. Full- and half-shaped baffles are used to form staggered formations for the two-row arrays. The plan area of each full-shaped baffle and half-shaped baffle is 20 mm × 20 mm and 20 mm × 10 mm, respectively. The longitudinal spacing between successive rows (\( L \)) is examined and discussed later. In each test ID, \( H \) denotes the height of the baffle (H075 denotes 0.75 times the approach flow depth, and H15 denotes 1.5 times the approach flow depth), \( R \) denotes the number of rows (R1 denotes one row of baffles, and R2 denotes two rows of baffles), and \( L \) denotes the longitudinal spacing between successive rows (L5 denotes a spacing of 50 mm, and L25 denotes a spacing of 250 mm).
Fig. 3. Baffle arrangement: (a) plan view; (b) side view (all dimensions in millimetres).

Table 1. Input parameters for DEM simulations.

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of discrete elements</td>
<td>65,000</td>
</tr>
<tr>
<td>Particle diameter (m)</td>
<td>0.005</td>
</tr>
<tr>
<td>Particle density (kg/m^3)</td>
<td>2650</td>
</tr>
<tr>
<td>Particle–wall normal stiffness (N/m)</td>
<td>1 x 10^8</td>
</tr>
<tr>
<td>Particle–wall tangential stiffness (N/m)</td>
<td>1 x 10^8</td>
</tr>
<tr>
<td>Contact friction angle (°)</td>
<td>35</td>
</tr>
<tr>
<td>Coefficient of restitution</td>
<td>0.5</td>
</tr>
<tr>
<td>Rolling friction coefficient</td>
<td>0.7</td>
</tr>
</tbody>
</table>

and into a deposition container at the most downstream end of the flume.

Discrete element method

The DEM is adopted to simulate the dynamics of granular flow in this study. The software package large-scale atomic–molecular massively parallel simulator improved for general granular and granular heat transfer simulations (LIGGGHTS, Kloss and Goniva 2010) is used. In the DEM, contact forces and displacements of a stressed assembly of particles are found by tracing the movement of individual particles. Discrete elements displace independently of each other and interact at contacts between particles and boundaries. The particle motion of each discrete element is calculated from forces acting on it by Newton’s law of motion and finite displacements of discrete elements are computed progressively during the simulation.

Numerical model setup

The numerical model adopts the same channel and baffle configuration as the flume experiments. Planar rigid walls are used to model the baffles and channel bed while periodic boundary conditions (PBCs) are used for the side walls. The PBC is applied along the transverse direction of the computation domain, and it is reported by Rapaport (2004) that the PBC is required to eliminate the unrealistic particle arrangement at the wall boundary caused by the constraint of particle sizes in discrete element simulations. The velocity of the discrete elements incipient to impinging an array of baffles is 2.7 m/s, which is the measured frontal velocity from photoconductive sensors as discussed in Ng et al. (2012).

Input parameters

The parameters used for each simulation is given in Table 1. The granular flow is modeled as a total of 65,000 spherical discrete elements with material density of 2650 kg/m^3. It is important to ensure flow similarity of discrete elements across the baffles during the calibration. The transverse spacing of baffles adopted is 10 times the diameter of each element, and the typical flow depth is about 16 times the diameter of each element. The experimental observations and numerical simulation showed reasonable agreement (see figure in section “Model calibration”). Therefore, the element size of 0.005 m is selected for further analysis and to enhance numerical efficiency. The discrete element and wall normal stiffness and tangential stiffness are both set to 1 x 10^8 (N/m). According to Crosta et al. (2001), the contact stiffness of each discrete element has negligible influence on the computed mobility of granular material. Frictional granular flow is the focus of this study; thus, the relative translational and rotational motions between the discrete elements are mainly resisted by the contact friction. The contact friction angle of dry sand is set as 35° (Chiou 2005; Pudasaini et al. 2005; Pudasaini and Hutter 2007; Mancarella and Hungr 2010; Teufelsbauer et al. 2011). Based on field and laboratory tests (Azzoni and Freitas 1995; Robotham et al. 1995; Chau et al. 2002), the coefficient of restitution is set as 0.5. Calvetti and Nova (2004) observed that, as a consequence of the nonangular shape of the particles, the macroscopic friction angle of the granular mass is generally very low, typically much less than 30°, irrespective
of the value of the interparticle friction angle adopted. Therefore, Calvetti et al. (2003) and Tamagnini et al. (2005) emphasized the need to inhibit particle rotations and calibrate the interparticle friction angle based on the desired value of the macroscopic friction angle of the granular mass.

In this study, a rolling resistance term is applied to the rolling motion of discrete elements in the numerical simulations. The rolling resistance is calculated using a directional constant torque model as elaborated by Ai et al. (2011). The model applies a constant torque on a particle to represent the rolling friction. The direction of the torque is always against the relative rotation between the two contact entities. The torque between two in-contact spheres $i$ and $j$ can be expressed as

$$M_r = - (\omega_{rel} \mu_r) R_r F_n$$

where $\omega_i$ and $\omega_j$ are the angular velocities of sphere $i$ and $j$ respectively, $\omega_{rel}$ is the relative angular velocity between them, $\mu_r$ is the rolling friction coefficient, $F_n$ is the normal contact force, and $R_r$ is the radius of the discrete element.

A calibration exercise is conducted to identify the proper range of rolling friction coefficient. The numerical setup for the calibration work is shown in Fig. 4. All boundaries are periodic, except the channel bed, to allow the granular material to transport on the incline indefinitely. The inclination contact friction angle of the granular material is set to 35°. It is expected that the granular material will reach a terminal velocity given that the contact friction angle is the same as the channel inclination. Based on the calibration exercise, it is noted that a terminal velocity is attained when the rolling friction coefficient suitable for this study is 0.7.

**Model calibration**

Three major limitations exist in using the DEM analyses: (i) particle size is approximated; (ii) only spherical particles are used; and (iii) input parameters are difficult to determine correctly. Although the DEM allows the fundamental particle motions of bouncing, falling, sliding, and rolling to be modeled, some input parameters pertaining to these motions are difficult to determine and quantify accurately and reliably to ensure that input parameters and modeling techniques are appropriate for simulating the interaction of flow against debris flow baffles. Flow kinematics from flume experiments and computed flow kinematics are compared before subsequent numerical back-analysis is conducted.

**Numerical testing procedures**

Each numerical simulation requires the formation of randomly packed discrete elements onto the slope to the same flow depth profile as that captured in the physical model test before impact. The assembly of discrete elements stabilizes itself under gravity. Currently, there is no convenient way to obtain the internal velocity gradient of the flow mass. A measured frontal velocity of 2.7 m/s is then uniformly applied to the wedge of discrete elements. The flow is initiated and the flow kinematics is monitored. Monitoring sections are used to capture the velocity, flow depth, Froude number, and kinetic energy of each discrete element.

A plan view and side view inclined at 26° of the computational domain are shown in Figs. 5a and 5b, respectively. The computational domain is divided into monitoring sections to capture the flow kinematics through, over, upstream, and downstream of each array of baffles. The flow direction is from right to left. The first monitoring sections upstream (U) and downstream (D) of the baffles are positioned immediately adjacent to the baffles and labeled U1 and D1, respectively. Subsequent sections are spaced 30 mm apart. Upstream and downstream monitoring sections are 30 mm in thickness parallel to the flow direction, and span both the width of the channel (200 mm) and the height of the side walls (500 mm) to ensure airborne particles are captured. Monitoring sections capturing the overflow span the width of the channel, have the same length (parallel to the flow direction) as the array of baffles, and span the height of the side walls (500 mm). Lastly, monitoring sections through the baffles span the width of the channel, and adopt the same height and length as the baffle array to capture the kinematics of the discrete elements traversing through the baffles.

**Figure 6** shows a comparison of flow kinematics from flume experiments and computed flow kinematics for test configuration.
Fig. 5. Typical computational domain (one row of baffles): (a) plan view; (b) side view.

Fig. 6. Comparison of flume experiments and computed flow kinematics (test H075_R1): (a) t = 0 s; (b) t = 0.03 s; (c) t = 0.06 s; (d) t = 0.09 s.
with a single row of 0.75h baffles (test H075_R1). The flow interaction from flume experiments captured with a high-speed camera mounted overtop is shown on the left, and a similar view of the computed discrete element simulation is shown on the right. The flow front arrives in front of the baffles at time $t = 0$ s (Fig. 6a), the velocity measured by the photoconductive sensors at the location before impact is 2.7 m/s and applied uniformly to the assembly of discrete elements for simplicity. At $t = 0.03$ s, the flow front impacts the row of baffles and three narrow jets of granular material discharge through the slits (Fig. 6b). The discrete elements are larger in diameter; thus, the thickening region around the baffles from the flume experiments cannot be fully captured. Three streams of jets thicken at $t = 0.06$ s and further propagate downstream while simultaneous run-up is observed (Fig. 6c). At $t = 0.09$ s, run-up begins to launch sand upwards and dispersed airborne particles are observed (Fig. 6d). During the run-up process, three streams of granular jets continue to propagate downstream and thicken. Turbulent splashing of sand material subsequently occurs, and the overflow cascades above the baffles. The measured and computed flow depth profiles for test H075_R1 at upstream monitoring section U4 are compared to ensure that the upstream conditions are appropriately captured (Fig. 7). The laser sensor of test H075_R1 captures flow depth measurements as the flow front propagates through the array of baffles. Before the flow front enters the array of baffles, the wedge of sand is about 20 mm thick, after which the flow depth gradually increases over a time span of 0.2 s. Both measured and computed upstream flow depth profiles exhibit agreement with each other for the captured flow duration.

It is observed from the comparison of flume experiment and computed flow kinematics that the set of input parameters, the simplified initial velocity, and the numerical model used for this study are appropriate for modeling debris flow baffle interaction. Furthermore, a comparison of measured and computed flow depths shows the selected input parameters can facilitate upstream conditions for further analysis. The flow kinematics is reasonably similar.

Flow processes from flume experiments

Chronological plan and side views of flow interaction with a single row of 0.75h baffles (test H075_R1) are shown in Fig. 8. The single-row array aims to reveal typical flow processes involved during flow interaction. A flow front with an approach velocity of 2.7 m/s remains laterally uniform prior to impacting the array of baffles at $t = 0$ s (Fig. 8a). The flow front impacts the row of baffles, and debris in the regions surrounding each baffle thickens. The flow front divides into three streams of granular jets discharging through the slits, and run-up occurs along the upstream face of the baffles at $t = 0.014$ s (Fig. 8b). Granular jets further discharge through the baffles, and deposition along the upstream face of the baffles (dead zones) occurs simultaneously with run-up at $t = 0.028$ s (Fig. 8c). Run-up along the upstream face of the baffles eventually exceeds the baffle height, and the upward thrust results in airborne particles. Furthermore, granular jets discharging through the slits thicken and continue propagating downstream at $t = 0.042$ s (Fig. 8d). Run-up eventually begins cascading over the row of baffles, and further airborne debris is observed. The downstream discharge through the baffles continues to thicken, and distinct granular vacuums (voids where no debris exists) form immediately downstream behind each baffle at $t = 0.056$ s (Fig. 8e). The formation of a ramplike dead zone stabilizes and overflow commences. As overflow cascades over the array to conceal the granular vacuums, the upstream flow depth beings to level with the baffle height at $t = 0.070$ s (Fig. 8f). Overflow continues to cascade over the baffles and begins engulfing the granular vacuums at $t = 0.084$ s (Fig. 8g). A granular vacuum is observed from the side view underneath the overflow at $t = 0.100$ s (Fig. 8h). Details of the influence of the aforementioned flow processes and key interaction mechanism on flow impendence are examined and discussed in the following sections.

Interpretation of DEM results

The DEM simulations are interpreted and analyzed to study the influence of varying the baffle configuration on flow impedance. The influence of baffle height, adding a second staggered row, and
Fig. 8. Typical interaction mechanisms from flume experiments: (a) $t = 0\, \text{s}$; (b) $t = 0.014\, \text{s}$; (c) $t = 0.028\, \text{s}$; (d) $t = 0.042\, \text{s}$; (e) $t = 0.056\, \text{s}$; (f) $t = 0.070\, \text{s}$; (g) $t = 0.084\, \text{s}$; (h) $t = 0.100\, \text{s}$. 

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varying the spacing between successive rows of baffles are presented. Furthermore, flow impedance at varying upstream and downstream distances away from the array of baffles is investigated.

**Influence of baffle height**

Two classes of baffle heights are examined in this study, namely short (0.75h) and tall (1.5h) baffles. The effect of baffle height on upstream flow kinematics is investigated by monitoring the Froude number of the flow. Subsequently, the influence of baffle height on overflow and discharge through an array is analyzed. Finally, the downstream energy dissipation resulting from different baffle heights is compared.

**Upstream Froude conditions**

The upstream flow kinematics is captured for 0.2 s, and t = 0 s is taken when the flow front is about to impact the array of baffles. A reference line is shown to characterize transition from supercritical to subcritical flow conditions (Fr = 1). The evolution of the Froude number upstream of the array of baffles during interaction is compared for a single row of short (test H075_R1) and tall baffles (H15_R1) in Figs. 9a and 9b, respectively.

Monitoring section U1 for a single row of short baffles initially exhibits a high Froude number (Fr = 6.0) before impact due to an initial upstream wedge-shaped flow front (Fig. 9a). Upon impacting the array of baffles, flow conditions exhibit a sharp drop in Froude number to about 2.5 after t = 0.01 s in supercritical flow conditions as flow velocity decreases and flow depth thickens. Froude number continues to gradually decrease as the interaction continues and flow reaches Froude conditions of about two. At monitoring section U2 (30 mm upstream from U1), a sharp drop in supercritical conditions is also exhibited (Fr = 2.8) upon impacting the baffles, similar to U1. After a rapid reduction in supercritical flow conditions, the Froude profile plateaus as upstream deposition of sand begins to form a stagnant ramp-like dead zone up (Fig. 8) until t = 0.04 s. Subsequent debris then rides on top of the ramp-like dead zone and overflows the array of baffles. The flow can be characterized by a further reduction in supercritical flow conditions until t = 0.06 s where the Froude number gradually decreases for the rest of the captured flow process. Monitoring section U3 exhibits similar behavior as U2; however, the reduction in supercritical flow is less obvious as the distance increases upstream from the array of baffles. Furthermore, monitoring sections U4–U6 reveal similar behavior as U3, except the spatial distribution of the Froude number generally decreasing towards t is observed as the distance increases upstream from the baffles. Flow remains supercritical within monitoring sections U1–U6 for a single row of short baffles during the captured flow process.

Monitoring section U1 immediately upstream from the tall baffles (test H15_R1) exhibits a sharp reduction in supercritical flow conditions to about 2.8 at t = 0.01 s, after which flow conditions gradually decrease towards subcritical flow conditions at about t = 0.08 s (Fig. 9b). A similar rapid reduction in supercritical flow conditions upon impact due to the initial upstream wedge-shaped flow front is exhibited and as observed previously for the single row of short baffles (test H075_R1). Monitoring section U2 also reveals a rapid reduction of supercritical flow conditions upon impact to a Froude number of about 3.2 at t = 0.01 s, after which the Froude number temporarily plateaus until t = 0.04 s. The Froude number then gradually decreases towards subcritical flow conditions after t = 0.16 s. Moreover, the temporary plateau and subsequent decline is a result of upstream deposition and ramp-like dead zone formation that promotes overflow as mentioned previously. Monitoring section U3 exhibits similar behavior as monitoring section U2; however, flow conditions in U3 remain supercritical, and subcritical flow conditions do not develop for the entire captured flow process. Furthermore, Froude number evolution with time captured within U4–U6 exhibits similar behavior as monitoring U3, except increasing the distance upstream from the baffles leads to a decrease in supercritical flow suppression. The presence of subcritical conditions at U1 and U2 and supercritical conditions from U3 onwards implies the potential development of a hydraulic jump, which is believed to result in more effective energy dissipation.

From a comparison between short (0.75h) and tall (1.5h) baffles, results reveal taller baffles have the capacity to develop upstream subcritical flow conditions, which may potentially lead to further energy dissipation compared to supercritical flow conditions exhibited by short baffles. Results imply that critical flow conditions (Fr = 1) should be considered when designing baffles to minimize the specific energy of the flow. Furthermore, as the distance increases upstream from each array of baffles, an attenuated response in supercritical flow reduction is observed for both short and tall baffles.

**Discharge and supercritical overflow**

Discharge is separated into overflow and flow through an array of baffles. A comparison of discharge characteristics between single rows of short (test H075_R1) and tall (test H15_R1) baffles is conducted (Fig. 10). An array of short baffles (0.75h) exhibit a gradual increase in discharge as the flow front enters the array of baffles until a threshold of about 60 cm³ is reached. Overflow occurs almost simultaneously as the discharge through the array of baffles. Overflow eventually exceeds the discharge through the array of baffles at t = 0.05 s, and the overflow component comprises the majority of the overall discharge (flow through and overflow) for the single row of short baffles. For tall baffles (1.5h), an increase in discharge is observed as the flow front enters the baffles, after which flow through the baffles eventually increases to a threshold value of ~112 cm³. Overflow does not commence until t = 0.05 s, after which it gradually increases and eventually exceeds the discharge through the baffles. Although overflow exceeds the component of flow through the baffles at t = 0.11 s, overflow does not continue exhibit a distinct increase for remainder of the captured flow process compared to short baffles (0.75h).

Overflow is significantly suppressed by taller baffles (1.5h) compared to short baffles (0.75h). The suppression of overflow is important as overflow travels over an array of baffles unimpeded and can discharge at high energies downstream (Jóhannesson et al. 2009). Supercritical overflow is particularly hazardous in situations where its trajectory cannot be easily predicted. Jóhannesson (2001) surveyed a torrent that had been deflected by a dam at Flateyri in northwestern Iceland and observed that the deflected stream came to rest 100 m further downslope than the undeflected part. Supercritical overflow requires careful consideration in the design of flow-impeding structures.

The Froude behavior of overflow for single rows of short and tall baffles is compared (Fig. 11). The time is taken as t = 0 s when overflow commences for each array. Overflow for one row of short baffles (test H075_R1) exhibits supercritical behavior for the entire captured flow process. In contrast, overflow from one row of tall baffles (test H15_R1) exhibits subcritical flow behavior. Results reveal that short baffles lead to large volumes of supercritical overflow, whereas tall baffles can effectively suppress overflow volume and develop subcritical overflow conditions.

**Downstream energy dissipation**

A comparison of computed downstream energy dissipation profiles for short (test H075_R1) and tall (test H15_R1) baffles is shown in Figs. 12a and 12b, respectively. The kinetic energy of the flow, $E_k$, is normalized with the approach kinetic energy, $E_{k,a}$, which is the same for all tests before impact with an approach velocity of 2.7 m/s.

At the downstream monitoring station closest to the array of short baffles (D1), granular jets are discharged from the slits at about 1.4 times the initial upstream kinetic energy conditions, after which rapid reduction in kinetic energy is observed (Fig. 12a). The increase in kinetic energy as the debris discharges from the
array is attributed to reduced area between the slits. If continuity is assumed and Bernoulli’s equation is taken for reference, an increase in flow velocity results from reducing the flow area. From $t = 0.04$ s onwards, overflow commences and the kinetic energy within the monitoring section increases slightly before becoming relatively steady at about 0.6 times initial upstream conditions. Further downstream, monitoring section D2 exhibits similar kinetic energy reduction behavior as monitoring section D1. The kinetic energy of the flow exhibits a rapid deceleration of discharge, followed by a slight increase in kinetic energy due to overflow before stabilizing above 0.6 times the initial upstream condition. Likewise, for monitoring sections D3–D6, similar kinetic energy dissipative trend is exhibited as that observed for both monitoring sections D1 and D2. However, as the distance increases downstream from the baffles, the kinetic energy dissipation response is attenuated. At monitoring section D6, the kinetic energy is
~0.8 times the approach kinetic energy near the end of the captured flow process.

Monitoring section D1 (directly downstream from the array of tall baffles) initially exhibits kinetic energy of about 1.6 times the initial upstream condition (Fig. 12b). As mentioned previously, the increase in kinetic energy compared to the initial upstream condition results from the discharge of high-velocity granular jets that develop from decreasing the flow area. Subsequently, the kinetic energy profile decreases to about 0.5 times the initial upstream condition before a slight increase from overflow is observed. After the slight increase in kinetic energy, the profile continues to decrease to 0.3 times initial upstream conditions near the end of the captured flow process. At monitoring section D2, the same kinetic energy response is captured as monitoring section D1 except the kinetic energy of the flow is higher than monitoring section D1. As the distance increases downstream from the array of baffles, the
The same dissipative behavior is exhibited from monitoring sections D3 to D6. However, it is apparent that the influence of the array of baffles on energy dissipation diminishes as the distance increases downstream.

The reduction of kinetic energy from $t = 0.1\ s$ onwards for tall baffles ($1.5h$) compared to short baffles ($0.75h$) where the kinetic energy remains relatively unchanged may be attributed to the development of upstream subcritical flow conditions (Fig. 9b). The development of subcritical conditions for tall baffles helps to further dissipate flow energy, thus resulting in progressive downstream energy dissipation compared to short baffles. Moreover, tall baffles provide $\sim 25\%$ more energy dissipation at monitoring section D5 at the end of the captured flow process compared to short baffles.
Salm (1987) reported that energy dissipation from obstacles is proportional to half the fraction of blockage. The peak flow depth is adopted as the channel depth to approximate the energy dissipation based on the empirical relationship. Reference lines based on the empirical relationship are shown in Fig. 12. The relationship estimates 6% energy dissipation for one row of short baffles (0.75h) and 10% energy dissipation for one row of tall baffles (1.5h). However, the empirical recommendation only considers the upstream surface area of obstruction relative to the channel cross-sectional area to contribute to the impedance. This criterion appears to be conservative, as it cannot capture key interaction mechanisms previously described in Fig. 8 and the initial approach flow conditions are not considered. Furthermore, the position where the estimated energy dissipation occurs is not clearly defined, making it difficult to gauge the relevancy of the estimated energy dissipation.

From experimental studies, Jóhannesson et al. (2009) reported 20% energy dissipation for a single row of snow avalanche breaking mounds. Reference lines are shown in Fig. 12 for comparison. The recommendation is based on supercritical flows characterizing that of avalanche flows (Fr = 10); hence, it may not be suitable for comparison of debris flow baffles (Fr = 3). Moreover, the location downstream where 20% energy dissipation occurs is not clearly defined, making a comparison rather ambiguous. The downstream energy dissipation for debris flow baffles in this study appears to exhibit greater energy dissipation compared to the snow avalanche recommendations. Snow avalanches and debris flow–obstacle interaction mechanisms are different. This study aims to model debris flow baffle interaction and may not be entirely applicable to snow avalanche obstacles.

**Influence of second staggered row**

A comparison of the influence of placing a second staggered row of short (0.75h) and tall (1.5h) baffles with varying row spacing (l) is shown in Figs. 13a and 13b, respectively. The kinetic energy of the flow, $E_k$, normalized with the approach kinetic energy, $E_{ka}$, is the same for all tests before impact with an approach velocity of 2.7 m/s. All kinetic energy profiles are captured at monitoring station D1, which is located immediately downstream of the second row of baffles.

Comparisons for short baffles (0.75h) are conducted for spacing of (i) 50 mm (test H075_R2_L5), (ii) 150 mm (test H075_R2_L15), and (iii) 250 mm (test H075_R2_L25). A single row of short baffles (test H075_R1) is shown to compare the effectiveness of the second row in reducing the kinetic energy of the flow and has been previously shown in Fig. 12a. Test H075_R2_L5 introduces a second row with a spacing (l) of 50 mm, and no significant difference in kinetic energy reduction is exhibited compared to a single row of baffles (Fig. 13a). The kinetic energy of the flow exiting the baffles (at $t = 0$ s) is about 1.4 times the initial upstream condition, after which the kinetic energy rapidly decreases to a minimum for the captured flow process at $t = 0.03$ s. The kinetic energy of the flow subsequently remains relatively steady as the kinetic energy of the flow reduces to about 0.6 times the initial upstream condition. A row spacing (l) of 150 mm (test H075_R2_L15) exhibits an initial kinetic energy of approximately two times the initial upstream condition before rapid reduction of kinetic energy to about 0.7 times the initial upstream condition at $t = 0.05$ s. As the downstream discharge progresses, the kinetic energy remains relatively stable around 0.7 times the initial upstream condition for the duration of the captured flow process. A row spacing (l) of 250 mm (test H075_R2_L25) exhibits an initial downstream kinetic energy of about three times the initial upstream condition, after which the debris rapidly reduces in kinetic energy to about 0.5 times the initial upstream condition at $t = 0.13$ s.

**Two rows of staggered short baffles (0.75h)**

A row spacing of 50 mm for short baffles (test H075_R2_L5) exhibits negligible kinetic energy reduction at monitoring section D1 compared to a single row of short baffles (test H075_R1). The ineffectiveness of the second row in providing impedance may be attributed to an excessive volume of supercritical overflow as previously discussed and shown in Fig. 10, which launches off a ramplike dead zone over the second row of baffles. The overflow mechanism (Fig. 8) may reduce the effectiveness of the second row if it is placed too close to the first row. By increasing the row spacing from 50 to 150 mm (test H075_R2_L15), less kinetic energy reduction is exhibited compared to a single row. The initial kinetic energy of debris ($t = 0$ s) exiting the second row of baffles with 150 mm spacing is about 30% greater than the initial kinetic energy of debris discharging through the two-row array with 50 mm spacing. The increased spacing between successive rows from 50 to 150 mm allows unimpeded acceleration of debris; thus, the initial exit kinetic energy ($t = 0$ s) for 150 mm spacing is higher than the initial kinetic energy for the two-row array with 50 mm spacing. Furthermore, the array with 150 mm spacing exhibits a higher kinetic energy profile compared to 50 mm spacing for the remainder of the captured flow process.

The overflow trajectory travels a maximum launch distance that is dependent on the geometry of the first row of baffles (Hákonardóttir et al. 2003; Fig. 13a). The launch distance measured in the flume experiment for one row of short baffles (0.75h) is about 240 mm; therefore, it is intuitive to place the second row of baffles at a distance greater than the maximum launch length to promote optimum energy dissipation. Thus, a longitudinal spacing of 250 mm (test H075_R2_L25) is selected and the downstream behavior is monitored. Initially, the flow exiting the baffles ($t = 0$ s) is about three times the initial upstream condition. As overflow commences, the kinetic energy profile does not effectively reduce the kinetic energy of the flow compared to a single row. The strategic placement of the second row to a distance slightly greater than the launch length may intercept the overflow trajectory, but the reduction in kinetic energy does not appear to be effective compared to a single row. Increasing the longitudinal spacing to 250 mm allows for a longer stretch for debris to accelerate. Results reveal that a second row of short baffles is ineffective in further reducing the kinetic energy of the debris, and increasing the spacing between successive rows allows the debris to accelerate.

**Two rows of staggered tall baffles (1.5h)**

Comparisons for tall baffles (1.5h) are conducted for spacing of (i) 50 mm (test H15_R2_L5), (ii) 100 mm (test H15_R2_L10), (iii) 150 mm (test H15_R2_L15), and (iv) 200 mm (test H15_R2_L2). The kinetic energy profile for debris exiting a single row of tall baffles (test H15_R1) has previously been shown in Fig. 12b. A row spacing of 50 mm between two rows (test H15_R2_L5) exhibits an initial kinetic energy from the second row at $t = 0$ s of about 1.3 times initial upstream conditions (Fig. 13b), after which the kinetic energy profile decreases to about 0.2 times initial upstream conditions at $t = 0.05$ s and remains relatively unchanged for the remainder of the captured flow process. The array with 100 mm row spacing (test H15_R2_L10) exhibits an initial kinetic energy of about 1.9 times the initial upstream condition. The energy profile subsequently reduces to about 0.5 times the initial upstream condition at $t = 0.05$ s and continues to gradually decrease to 0.3 times the initial upstream conditions for the remainder of the captured flow process. A row spacing of 150 mm (test H15_R2_L15) exhibits an initial kinetic energy of 2.3 times initial upstream conditions, after which the kinetic energy profile decreases to about 0.6 times initial upstream conditions at $t = 0.05$ s before gradually decreasing for the remainder of the captured flow process. Lastly, a row spacing of 200 mm (test H15_R2_L20) exhibits an initial kinetic energy of 2.3 times initial upstream conditions, after which the kinetic energy profile decreases to about 0.7 times the initial up-
stream condition at $t = 0.05$ s before subsequent kinetic energy reduction for the remainder of the captured flow process.

Results reveal that optimum kinetic energy reduction for tall baffles ($1.5h$) is facilitated by placing a second staggered row of baffles with a spacing of 50 mm (test H15_R2_L5) in front of the first row. The initial kinetic energy ($t = 0$ s) is reduced by about 33% compared to a single row (test H15_R1). A row spacing of 100 mm (test H15_R2_L10) reveals less energy dissipation than a single row of baffles for the first 0.04 s of the flow process, after which the kinetic energy reduction becomes greater than a single-row array. A spacing between rows of 150 mm (test H15_R2_L15) leads to less kinetic energy reduction compared to that of a single-row array.
for the first 0.09 s of the flow process, after which the kinetic energy reduction exceeds a single-row array. Lastly, a row spacing of 200 mm (test H15_R2_L20) results in less kinetic energy reduction compared to a single-row array for the first 0.14 s of the flow process before exhibiting greater kinetic energy reduction than the single-row array. The kinetic energy profiles for different row spacing for tall baffles (1.5h) eventually merge to a similar level of kinetic energy at the end of the captured flow process. This implies that influence of the second row is greatest during the initial impact of the flow front (first 0.12 s of flow interaction), and the row spacing for tall baffles may not have a significant contribution to energy dissipation after initial interaction.

For the case of short baffles (0.75h), the spacing criterion for optimum reduction of flow energy does not exhibit dependency on the launch length of the overflow. Increasing the spacing between rows leads to acceleration of debris, and a second row of short baffles does not exhibit significant influence on kinetic energy reduction. For the case of tall baffles (1.5h), the spacing between successive rows should be placed as close as possible; 50 mm or 0.25 times the channel width (w) in this study. Positioning rows of tall baffles as close as possible promotes lateral deflection and further energy dissipation as described by FHWA (2006).

Jóhannesson et al. (2009) reported energy dissipation of 20% with a single row of snow avalanche breaking mounds and 10% additional energy dissipation with a second staggered row. The energy dissipation attained from experiments is based on higher supercritical flows characterizing snow avalanches (Fr = 10) and estimates less energy reduction compared to the debris flow baffles modeled in this study (Fr = 3). Moreover, the location of measured energy dissipation is unclear and a comprehensive comparison cannot be facilitated. Furthermore, the empirical relationship reported by Salm (1987) provides an estimated 12% energy reduction for two rows of short baffles (0.75h) and 20% for two rows of tall baffles (1.5h). The empirical formulation appears to be conservative compared to the results of this study. Moreover, the empirical relationship cannot capture the flow kinematics observed in this study during interaction (Fig. 8), does not consider initial upstream conditions, and is independent of baffle array parameters such as spacing between successive rows (L).

**Effectiveness of second staggered row with time**

A comparison of normalized kinetic energy ($E_k/E_a$) with varying row spacing normalized by the channel width ($L/w$) for short (0.75h) and tall (1.5h) baffles at $t = 0$, 0.01, 0.025, and 0.2 s is conducted (Fig. 14). All measurements are taken at monitoring section D1, which is immediately downstream from the array of baffles. As debris exits the array of baffles ($t = 0$ s), an increase in kinetic energy is exhibited as the longitudinal spacing between rows increases from 0.25 to 1.25 times the channel width (w). The kinetic energy remains well above initial upstream conditions ($E_{ka}/E_0 = 1$). The increase in kinetic energy is because of acceleration in the longitudinal stretch between the two rows. At $t = 0.01$ s of the flow process, an increase of kinetic energy with spacing between rows is still observed; however, the kinetic energy of the debris has attenuated compared to $t = 0$. At $t = 0.025$ s, the kinetic energy of the flow as further attenuated, but the trend of increased kinetic energy with spacing between rows is still observed. After 0.2 s of the flow process, the influence of row spacing on kinetic energy does not appear to be significant.

**Conclusions**

Numerical back-analysis of flume experiments was conducted using DEM simulations to gain further insight on the interaction mechanisms between channelized debris flow and an array of baffles. The influence of baffle height, a second staggered row, and spacing between successive rows on flow impedance at varying upstream and downstream distances from the array were examined. Conclusions and insight from the results of this study may be drawn as follows:

1. Two classes of baffle heights can be categorized relative to the approach flow depth (h), namely tall (1.5h) and short baffles (0.75h). Tall baffles facilitate subcritical upstream conditions that promote more efficient energy dissipation, whereas upstream flow conditions for short baffles remain supercritical.
2. Tall baffles can more effectively suppress downstream discharge, reduce overflow, and the overflow is subcritical in nature. Short baffles promote large volumes of supercritical overflow and are not effective in suppressing downstream discharge.
3. The formation of a ramp-like dead zone leads to subsequent overflow, which requires consideration when designing debris...
flow baffles. Furthermore, discharge of granular jets through baffles exhibits high kinetic energy and requires stabilization with a second row of staggered baffles.

4. Optimum spacing between successive rows of short baffles is dependent on the maximum launch length of overflow. The addition of second row of staggered short baffles leads to insignificant kinetic energy reduction compared to a single row.

5. Spacing criteria for tall baffles recommends baffles to be positioned as close as possible (0.25 times the width of the channel for this study).

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References

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