Towards rational use of baffle arrays on sloped and horizontal terrain for filtering boulders

G.R. Goodwin, C.E. Choi, and C.-Y. Yune

Abstract: Baffle arrays are used to filter boulders from granular flows, such that the impact load exerted on barriers is reduced. However, current guidelines provide limited recommendations on baffle design. In this study, a calibrated discrete element method model was used to model boulders entrained in a bulk granular assembly interacting with baffles and a terminal rigid barrier. Different baffle spacings relative to the boulder diameter (1 < s/δ < 4) were considered. A ratio of s/δ = 1 is recommended for reducing the impact load by up to 80%, whilst s/δ = 4 renders an array of baffles inadequate for filtration. The optimum configuration is a staggered array with three rows of baffles on a horizontal plane in front of a barrier. This layout reduces the peak discharge by up to four times more than a similar array on sloping terrain, compared to channels without baffles. Furthermore, the transition from sloping terrain to a horizontal plane works together with the array of baffles to dissipate flow kinetic energy. On the horizontal plane, baffles attenuate the flow velocity more as the Froude number Fr increases, implying that baffles should be used if high Fr values are anticipated. Finally, guidance is provided on estimating load attenuation from baffle filtration.

Key words: landslides, baffles, discrete element method, boulders, impact load.

1. Introduction

Steep creek hazards in mountainous regions can entrain large boulders (diameter δ_{boulder} ≥ 1 m) (see Alexander and Cooker 2016; Koo et al. 2017; Kwan et al. 2018). Large barriers are often constructed to arrest geomaterial to prevent it from impacting facilities in mountainous areas, but are prone to damage from large boulders. Solutions to reduce the potential damage from large boulders include installing an array of baffles in front of the barrier.

Baffles are rigid columns that can form an array comprising multiple rows (e.g., VanDine 1996) (Fig. 1) and are installed on slopes (Fig. 1a) or horizontal planes in basins (Fig. 1b). Baffles are intended to (i) decelerate flows and (ii) filter out boulders (e.g., NILIM 2007, 2016; Piton and Recking 2016; Kwan et al. 2018). Baffle arrays have been widely implemented for landslide mitigation, but designs are prescriptive. Indeed, existing guidelines (e.g., VanDine 1996; Kwan et al. 2018) make no link between the placement of baffles and whether baffles are for trapping or controlling discharge. A better understanding is particularly important given potential space constraints at sites and the cost of installing these obstacles.

Loads on terminal barriers due to boulders are generally considered by (i) using Hertzian mechanics to explicitly calculate discrete impacts or (ii) increasing the empirical coefficient α that is applied to the continuum equation for dynamic pressure. International guidelines lack a consensus for when each approach is appropriate. Nonetheless, GEO (2016) suggests that boulder diameters of δ_{boulder} < 0.5 m should be dealt with using continuum mechanics.
For the continuum method, the load can be decomposed into static and dynamic components (e.g., 
Albaba et al. 2018), and written in the following form:

\[
F_{\text{flow}} = Bh(kgh + \alpha \rho U^2)
\]

where \(B\) is the channel width, \(h\) is the flow depth, \(k\) is an earth pressure coefficient, \(\rho\) is the bulk density of the flow material, \(g\) is gravitational acceleration, \(\alpha\) is a semi-empirical impact coefficient (e.g., Ng et al. 2018), and \(U\) is the flow velocity. (It is also worthwhile to note that a displacement-based approach, in which the barrier is considered to move upon impact (see Yong et al. 2019), is emerging in engineering design practice.)

A challenge for engineers is characterising the reduction in impact load on a terminal barrier for a given geometric configuration of baffles. Kwan et al. (2018) mentions \(1.5 < s/\delta < 4.0\), where \(s\) is the spacing between baffles and \(\delta\) is the particle (i.e., boulder) diameter, whilst Silva et al. (2016) proposes \(s/\delta\) of almost unity for a columnar array. However, for both cases, the link between \(\alpha\) (in eq. 1) and \(s/\delta\) (which does not appear in eq. 1) is unclear.

A separate issue is that guidelines do not state whether baffles should ideally be placed on a slope or on the horizontal plane (Table 1), although it is acknowledged that this is sometimes dictated by the constraints of individual sites. Although baffle arrays are often installed on a horizontal plane (Fig. 1b), only Fei et al. (2020) has considered a baffle array on a horizontal runout zone. The abrupt transition from a slope to a horizontal plane enhances the dissipation of energy. This energy dissipation is potentially an important factor contributing to the apparent effectiveness of baffles.

Modelling interactions between a flow, boulders, and baffles is challenging because multiple mechanisms are involved, many of which are inherently discrete. For instance, jamming can occur if \(s/\delta\) is sufficiently small, particle size segregation affects the trajectory of boulders (e.g., Zhou and Ng 2010; Song et al. 2018), and the formation and destruction of arches at the meso-scale are responsible for localized force fluctuations during impact with obstacles (Faug 2015). Frictional behaviour can occur concurrently with fluid-like behaviour. For example, material can accumulate behind baffles, forming a ramp (e.g., Hákonardóttir et al. 2003a, 2003b), whilst other material continues to flow downstream. As baffles have a finite height, this can enable boulders and other flow material to overtop baffle arrays (Kwan et al. 2018). Furthermore, if granular material discharges between baffles at high velocities, fluid-like jets of discharging material undergo mutual interference (Hákonardóttir et al. 2003b; Choi et al. 2014, 2015a).

These discrete, coupled mechanisms make it difficult to develop analytic equations to describe flow–boulder–baffle interaction. To understand the impact load on a terminal barrier, it is necessary to model the problem using a discrete approach, as per the majority of studies collected in Table 2. Both physical

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**Fig. 1.** Arrays of baffles installed in Hong Kong SAR: (a) near New Territories Circular Road on a slope; (b) installed in front of a rigid barrier on a near-horizontal plane. [Colour online.]
Table 1. Summary of recommendations for baffle design from various international guidelines.

<table>
<thead>
<tr>
<th>Guideline</th>
<th>Objectives given</th>
<th>Number of rows of baffles</th>
<th>Baffle spacing: downstream</th>
<th>Other aspects of baffle design</th>
<th>Baffle placement</th>
</tr>
</thead>
<tbody>
<tr>
<td>VanDine (1996) (Canada)</td>
<td>Decelerate granular flow and cause deposition; deflect trajectory of flow.</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Suggests that baffles are more commonly placed in (nearly-horizontal) deposition areas.</td>
</tr>
<tr>
<td>FHWA (2006) (USA)</td>
<td>Decelerate fluvial flow; prevent acceleration of flow during vertical drop; have greater control over the hydraulic jump; enable stilling basins to be made smaller.</td>
<td>Baffle width and horizontal baffle spacing should be 1.5H.</td>
<td>States that four rows of baffles can “control the flow”, but that fewer rows can also be “successful”.</td>
<td>Downstream spacing of baffles on a 27° slope should be 2H, whilst on lower gradients the spacing can be larger.</td>
<td>(i) Baffle height should be 0.8 times the critical depth; (ii) baffles should be staggered. Schematics show that baffles can be placed on slope or on the horizontal.</td>
</tr>
<tr>
<td>Jóhannesson et al. (2009) (EU)</td>
<td>Decelerate and break up avalanches.</td>
<td>Mounds should be “close together”.</td>
<td>Authors suggest one row of mounds should reduce velocity by 20%, whilst a second row reduces velocity by a further 10%.</td>
<td>Mounds should be “close together”.</td>
<td>(i) Height should be 2–3 times that of the dense avalanche core; (ii) upstream face of baffle should be “steep” (&gt;60°); (iii) aspect ratio of upstream face should be around unity.</td>
</tr>
<tr>
<td>Kwan et al. (2018) (Hong Kong)</td>
<td>Filtering out boulders; reducing the load on a terminal barrier.</td>
<td>Document implies range $1.5 &lt; s/d &lt; 4.0$, based on other recommendations from other countries.</td>
<td>No guidance given. The example case given contains two rows of baffles.</td>
<td>Based on the trajectory of an idealized point mass overflowing the array if a plug forms between the baffles.</td>
<td>(i) Baffle height should be “sufficiently high to intercept boulders”; (ii) gives an equation for calculating energy dissipation of the baffle due to formation of a plastic hinge, as well as bending moment; (iii) suggests that sliding and overturning failure should be considered in design; (iv) baffle arrays proposed for reducing force on terminal barriers, but not quantitative.</td>
</tr>
<tr>
<td>Studies</td>
<td>Objective(s)</td>
<td>Study type</td>
<td>Material</td>
<td>Baffle placement: lateral (m)</td>
<td>Baffle spacing: downstream (m)</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-------------------------------</td>
<td>------------</td>
<td>---------------------------</td>
<td>-------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>Hákonardóttir et al. (2003a)</td>
<td>Overfl ow trajectory</td>
<td>Physical</td>
<td>Snow</td>
<td>Orthogonal to slope</td>
<td>0.400</td>
</tr>
<tr>
<td>Hákonardóttir et al. (2003b)</td>
<td>Trajectory, velocity and energy reduction</td>
<td>Physical</td>
<td>Glass beads</td>
<td>Orthogonal to slope</td>
<td>0.030</td>
</tr>
<tr>
<td>Cosenza et al. (2006)</td>
<td>Model evaluation and baffle deformation</td>
<td>—</td>
<td>Finite volume: shallow water</td>
<td>Orthogonal to runout zone</td>
<td>—</td>
</tr>
<tr>
<td>Teufelsbauer et al. (2011)</td>
<td>Deposition and impact force on a final obstacle</td>
<td>DEM</td>
<td>Orthogonal to slope</td>
<td>—</td>
<td>0.090</td>
</tr>
<tr>
<td>Ng et al. (2014)</td>
<td>Velocity and energy reduction</td>
<td>Physical</td>
<td>LB sand</td>
<td>Orthogonal to slope</td>
<td>0.046-0.080</td>
</tr>
<tr>
<td>Choi et al. (2014)</td>
<td>Velocity and energy reduction</td>
<td>Physical</td>
<td>LB sand</td>
<td>Orthogonal to slope</td>
<td>0.047</td>
</tr>
<tr>
<td>Ng et al. (2015a)</td>
<td>Velocity and energy reduction</td>
<td>Physical</td>
<td>LB sand</td>
<td>Orthogonal to slope</td>
<td>0.080</td>
</tr>
<tr>
<td>Choi et al. (2015a)</td>
<td>Velocity and energy reduction</td>
<td>DEM</td>
<td>Orthogonal to slope</td>
<td>—</td>
<td>0.047</td>
</tr>
<tr>
<td>Law et al. (2015)</td>
<td>Force reduction</td>
<td>DEM</td>
<td>Orthogonal to slope</td>
<td>—</td>
<td>0.080</td>
</tr>
<tr>
<td>Silva et al. (2016)</td>
<td>Trapping</td>
<td>Physical</td>
<td>Mixture of rocks and water</td>
<td>Orthogonal to slope</td>
<td>0.04-0.07</td>
</tr>
<tr>
<td>Wang et al. (2017a)</td>
<td>Velocity and energy reduction, deposition</td>
<td>Physical</td>
<td>Mixture of water, sand and clay</td>
<td>Orthogonal to slope</td>
<td>0.050</td>
</tr>
<tr>
<td>Wang et al. (2017b)</td>
<td>Velocity and energy reduction, baffle shape</td>
<td>Physical</td>
<td>Mixture of water, sand and clay</td>
<td>Orthogonal to slope</td>
<td>0.050</td>
</tr>
</tbody>
</table>
modelling and numerical tools such as the discrete element method (DEM) can be used.

Some studies have investigated the trapping of boulders impacting columnar arrays for values of $\sigma/d$ conducive to trapping (e.g., Choi et al. 2016 and Goodwin and Choi 2020), whereas others have looked at the load on terminal obstacles shielded by baffles (Law et al. 2015 and Bi et al. 2018a). However, these studies used approximately monodisperse flow material. Monodisperse flows are a helpful simplification for characterising the grain diameter, which is relevant for $\sigma/d$. However, monodisperse flows may increase the grain-trapping efficiency relative to non-monodisperse flows for a given value of $\sigma/d_{\text{max}}$. For non-monodisperse flows interacting with an aperture with a given width $s$, the presence of grains much smaller than the boulders is likely to inhibit stable arch formation. This is because the average ratio of $\sigma/d$ would be increased to be outside of the range required for trapping (see also Pardo and Sáez 2014).

In this study, a series of physical tests of granular flows impacting a baffle-like structure was performed to calibrate a DEM model. The calibrated DEM model was then used to investigate the effects of the geometric configuration of baffles on the reduction of impact load on a terminal barrier due to boulders entrained by a granular flow. The parameters considered included (i) baffle spacing relative to the boulder diameter ($\sigma/d$) and (ii) the placement of the baffle array relative to a terminal barrier.

### 2. Methodology

#### 2.1. Physical modelling

Physical tests were required to calibrate the numerical model. A modular channel with a rectangular cross section was used for the physical tests. The channel had a maximum length of 6.0 m, a width of 0.2 m, and a height of 0.5 m. Two modules with a combined length of 3.0 m are shown in Fig. 2a. A baffle-like slit-structure comprising two rigidly fixed planes was placed 0.984 m downstream from the storage area. The planes each had widths of 0.075 m, creating a slit with a width of 0.05 m (Figs. 2b and 2c). The grain diameter adopted in the experiments was 0.01 m, giving a ratio of $\sigma/d = 5$. The slit-structure is similar to the opening between a pair of baffles.

A three-dimensional (3D) printer was used to print three identical roughened basal plates. Each plate had a width of 200 mm, a length of 208 mm, and a depth ranging from 3 to 6 mm, giving a height difference of 3 mm between the highest and lowest points. The topography was generated procedurally based on a triangular lattice. The triangles were equilateral and had a side length of 20 mm. Procedural generation (see, e.g., Flaischlen and Wehinger 2019) was selected because it reduces crystallization effects of spherical discrete elements at the base that can otherwise affect flows that are nearly monodisperse (e.g., Marchelli et al. 2020). The ratio of the side length of the triangles to the channel width was 1:10. The height difference between the highest and lowest points (of 3 mm) was chosen following Iverson et al. (2010), where tests were performed using a bed roughened with protruding cylinders 16 mm in length. The maximum bulk grain diameter in Iverson et al. (2010) was 32 mm, giving a ratio of bed to flow grain sizes, $\delta_{\text{bed}}/\delta_{\text{bulk}}$, of less than 0.5. The bulk flow grain diameter adopted in the present study was 10 mm, giving a ratio $\delta_{\text{bed}}/\delta_{\text{bulk}}$ of 0.3. It should be noted that according to Iverson et al. (2010), the distinctive behaviour of granular flows (including debris flows) cannot be attributed to a fixed, non-Newtonian rheology, and that this type of morphological boundary friction is critical.

All of the 3D-printed basal plates were covered with adhesive transparent film to ensure that the material interface friction angle was the same as the rest of the flume. The 3D-printed plates are shown in Figs. 2b and 2c. The three roughened plates were placed upstream of the baffle-like slit-structure.

### Table 2

<table>
<thead>
<tr>
<th>Study type</th>
<th>Baffle gridding</th>
<th>Material</th>
<th>Geometry</th>
<th>Height</th>
<th>Width</th>
<th>Depth</th>
<th>Velocity reduction</th>
<th>Material interface friction angle</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orthogonal</td>
<td>1:100</td>
<td>Sand</td>
<td>Triangular</td>
<td>20 mm</td>
<td>208 mm</td>
<td>3 mm</td>
<td>0.3</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>Orthogonal</td>
<td>1:200</td>
<td>Sand</td>
<td>Triangular</td>
<td>10 mm</td>
<td>100 mm</td>
<td>1 mm</td>
<td>0.3</td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>Orthogonal</td>
<td>1:500</td>
<td>Sand</td>
<td>Triangular</td>
<td>5 mm</td>
<td>50 mm</td>
<td>0.5 mm</td>
<td>0.3</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

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plates was flush with the initial part of the flume channel (Fig. 2d).
Schematics are shown in Figs. 2d and 2e.

2.2. Discrete element method

The DEM has been widely adopted for modelling the interaction between flows and obstacles (e.g., Teufelsbauer et al. 2009, 2011; Zhao and Shan 2013; Ng et al. 2013; Shan and Zhao 2014; Albaba et al. 2015; Choi and Law 2015; Law et al. 2015; Leonardi et al. 2015, 2016, 2019; Shen et al. 2018; Marchelli et al. 2020; Choi and Goodwin 2020; Zhou et al. 2020). The open-source DEM package LIGGGHTS was used (Kloss and Goniva 2011). The forces acting on each grain at each time step were calculated as follows:

\[ m_i \frac{dU_i}{dt} = F + m_i g \]

where \( m_i \) is the mass of grain \( i \), \( U_i \) is the flow velocity of grain \( i \), \( t \) is time, \( F \) includes all non-gravitational external forces acting on the grain (i.e., contact forces), and \( g \) is gravitational acceleration. The acceleration, velocity, and position of each grain are calculated sequentially using Newtonian mechanics. For calculating the forces on grains during collisions, a Hertzian (non-linear) contact model was used. (Readers may refer to DCS Computing (2020) for details.) This contact model was chosen because grain interactions are inherently non-linear (Maranzano and Hancock 2016).

The material density was 2650 kg/m\(^3\), which is characteristic of rock, sand, and glass. For monodisperse spheres, which have a maximum packing fraction of around 0.6, this gives rise to a bulk density of around 1600 kg/m\(^3\). The elastic modulus (\( E \)) was set at 0.1 GPa (Law et al. 2015). Although this value is less than the characteristic value of rock, sand or glass (10 GPa < \( E < 100 \) GPa), a more computationally efficient time step can be used. The time step adopted was 5 μs (Law et al. 2015). The internal friction angle was 20°, which was back-calculated from the comparison of physical and numerical flow dynamics in Ng et al. (2019) and can be considered conservative. The interface friction angle was physically measured for glass beads in Choi et al. (2016) using tilt-tests. Poisson’s ratio was set at 0.3 as per previous studies (e.g., Law et al. 2015). Rolling resistance was set at zero because spheres were being modelled.

The coefficient of restitution (\( e \)) determines the energy lost during each collision between objects. In reality, the coefficient is a function of the impact velocity (e.g., Lam et al. 2018). A value of \( e \) of unity implies that the impact is fully elastic, whereas zero implies that the impact is entirely non-elastic. A consequence of higher values of \( e \) is that collisions tend to be shorter, which implies that the transient load imparted on a barrier tends to increase, according to

\[ F = \frac{m(U_2 - U_1)}{\Delta t} \]

where \( m \) is the mass of the impacting object; \( U_1 \) and \( U_2 \) are the velocities before and after impact, respectively; and \( \Delta t \) is the impact time. As the value of \( e \) for glass is higher than for rock, this implies that the impact load will tend to be higher for the same mass, thus erring on the conservative side.

Indeed, Ng et al. (2019) used physical drop tests to characterise the coefficient of restitution of glass beads 10 mm in diameter. These beads impacted a fixed metal slab and had a measured coefficient of restitution of 0.74. Chau et al. (1998) tested rock fragments falling onto slopes and found the coefficient of restitution to be between 0.39 and 0.49. Pfeiffer and Bowen (1989) back-analysed the coefficient of restitution for rockfalls considering various bed materials, reporting a range of 0.28 to 0.42, whilst Hungr and Evans (1988) back-analysed a value of 0.5. Choi et al. (2015a) and Law et al. (2015) also used a value of 0.5 for DEM back-analyses of sand flows. Of these studies, values for the coefficient of restitution nearer the lower end may be more plausible for full-scale modelling. This is because large rocks can dissipate energy through fracturing (Bowman et al. 2012). Nonetheless, the coefficient of restitution was set at 0.5 as a maximum plausible.
value. It should be noted that a value of \(e\) that is higher than that for natural geological materials suggests that results from this study should tend to be on the conservative side, in terms of impact load. Numerical parameters are summarised in Table 3.

### Table 3. Parameters adopted in numerical simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Numerical simulations</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle density (kg/m(^3))</td>
<td>2650</td>
<td></td>
</tr>
<tr>
<td>Internal friction angle (')</td>
<td>20</td>
<td>Ng et al. (2019)</td>
</tr>
<tr>
<td>Interface friction angle (')</td>
<td>17</td>
<td>Choi et al. (2016)</td>
</tr>
<tr>
<td>Elastic modulus (Pa)</td>
<td>10(^8)</td>
<td>Ng et al. (2019)</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
<td>Ng et al. (2019)</td>
</tr>
<tr>
<td>Rolling resistance</td>
<td>0</td>
<td>Ng et al. (2019)</td>
</tr>
<tr>
<td>Contact model</td>
<td>Hertz</td>
<td>Ng et al. (2019)</td>
</tr>
<tr>
<td>Coefficient of restitution</td>
<td>0.5</td>
<td>See text</td>
</tr>
</tbody>
</table>

2.3. Evaluation of numerical parameters

Computed and physical flow kinematics were compared to evaluate the numerical parameters discussed in the previous section. Figure 3 compares physical and numerical flow kinematics for a flow impacting a slit-structure with a single slit. The DEM channel geometry and grain diameter were identical to the experimental experiments. Indeed, the stereolithography (STL) files for the rough basal plates created using the 3D printer were the same ones used in the DEM. A detailed numerical procedure for back-analyses of small-scale model flume experiments of monodisperse flows is given in both Ng et al. (2019) and Goodwin and Choi (2020). This procedure is similar to the procedure detailed in Section 2.6 of this study.

Figure 3 shows that the DEM model captures the essential kinematics of the interaction between the flow and the slit-structure. Particle image velocimetry (PIV) was also performed using the open-source PIV package OpenPIV (Thielicke and Stamhuis 2014) to show the local velocities quantitatively. The granular flow approaches the slit-structure (Figs. 3(a) and 3(b)) and then piles up, forming a ramp (e.g., Håkonardóttir et al. 2003b). At the same time, the granular material flows out of the slit as a granular jet (e.g., Håkonardóttir et al. 2003b; Choi et al. 2015a) (Figs. 3(a–i)–v) and 3(b(i–v)). The velocity profiles at each time step are qualitatively similar.

A direct comparison of the physically measured and numerically extracted maximum pile-up heights and average outflow rates is given in Figs. 4a and 4b. The values for the pile-up heights are normalised by the maximum flow depth of flows in channels without obstacles (see Choi et al. 2016). The depths agree between 89% and 99%. The physical and numerical values for the outflow rates follow the same trend closely, and differ by 6% for the channel inclination adopted in the main part of this study (i.e., 30°). Taken together, Figs. 3 and 4 show that interactions between the flow and the structure are captured well by the numerical DEM model. This lends further confidence to the input parameters.

2.4. Scaling and characterisation of key dimensionless groups

Key scaling groups for granular flows include the Froude number, \(Fr\); the number of grains per unit depth: and the solid volume fraction (Armanini et al. 2011, 2014; Armanini 2015; Choi et al. 2015b; Ng et al. 2018, 2019):

\[
Fr = \frac{U}{\sqrt{gh \cos \theta}}
\]

where \(U\) is the flow velocity; \(g\) is gravitational acceleration; \(h\) is the flow depth; and \(\theta\) is the channel inclination. Flows in channels without obstacles were used to characterise the frontal Froude number (Ng et al. 2019) to give a clear benchmark for future studies. The placement of baffles on the slope was decided based on the tests without obstacles. This was to ensure that \(Fr\) before impact was the same as for baffles on the horizontal channel. The methodology and results for this exercise are detailed in Appendix A.

2.5. Numerical domain for main study: baffles, baffles, and barriers

The numerical domain is shown in Fig. 5 and consists of several components: a storage area for retaining granular material before dam break; an initial channel section 3 m in length; a horizontal perch 1 m in length for baffles; a second channel section with a variable length to control \(Fr\) (details given in Appendix A); and, finally, a horizontal channel. The channel was inclined at 30°, which is typical of real hillsides (see Kwan 2012 and CEDD 2020).

The base was given a slight morphological roughness using the same method described in the methodology for the calibration exercise. The purposes of this roughness included (i) promoting a limited-slip condition near the base so that the velocity profile of the bulk granular material was closer to that of prototype flows and (ii) promoting bouncing of the baffles, because the motion of baffles on slopes is governed primarily by bouncing (Wyllie 2014). Increasing the degree of roughness further would tend to retard the flow (see Kumaran and Bharathraj 2013), thus reducing the Froude number and reducing the amount of granular material travelling through the baffle array. Decreasing the basal roughness from the amount set in this study creates minimal difference to the Froude number, but causes rolling to become more important for the motion of the baffles, at the expense of bouncing (see Wyllie 2014). It is worth noting that other authors (e.g., Bryant et al. 2015) have also used roughened beds for promoting a limited-slip condition, although the method of roughening varies. Specifically, Bryant et al. (2015) used a circular steel mesh on the channel base, but the effect is the same as in the present study.

For the tests with obstacles, an array of baffles was added, either on the horizontal channel (Fig. 5a) or on the slope (Fig. 5b). A barrier was placed 9.5 m away from the start of the horizontal channel. The obstacle layout for both cases is shown in Figs. 5c and 5d.

The length for the upper channel section before the perch was determined based on the minimum Froude number required to dislodge the baffles. This was calculated using an expression from Alexander and Cooker (2016) considering drag force, impulsive force, and frictional force:
was around 85 m$^3$. The volume of material is characteristic of small landslides in Hong Kong and was conducive to the general range of Froude numbers of debris flows; specifically, $0 < Fr < 7.5$ (Hübli et al. 2009). The characterisation of the Froude number for the flow front is given in Appendix A. The bulk grain size was chosen such that the ratio $s/d$ for the bulk assembly was large enough that jamming was unlikely to occur if boulders were not present (see also findings from Law et al. 2015, Choi et al. 2016, and Goodwin and Choi 2020). If the ratio $s/d$ is high enough for trapping not to occur, the main influence of the grain size in the bulk granular assembly relates to energy dissipation during transport (Ng et al. 2017), and hence the flow Froude number.

### 2.6. Numerical procedures

Dam break, which is a well-established technique for initiating model flow-type landslides, including granular flows, was adopted in this study (see Iverson 2015 as well as Iverson et al. 2010 and Ashwood and Hungr 2016). Granular material was generated...
Fig. 4. Comparison of physical and computed flow characteristics: (a) maximum pile-up height at the slit-structure normalised by the maximum depth of flows in channels without obstacles; (b) average outflow rate of the flow from the slit-structure. \( F_{r_{\text{min}}} \) was taken from a series of flows in channels without obstacles (see Choi et al. 2016).

within the inclined storage area and allowed to settle (see Fig. 5). The gate was then deleted, allowing granular material to flow downstream into the boulders, entraining them. The flow and boulders then moved towards the baffle array. The simulation was terminated after impact, once the system energy fell below a certain threshold (around 0.1% of the maximum kinetic energy of the entire system of grains that was recorded during outflow). It was found that the boulders had always stopped moving by the time this threshold was reached. Furthermore, it is acknowledged that it would also be possible to terminate the simulations on conditions relating to unbalanced forces (e.g., Wang et al. 2019), although it is observed that such conditions are generally applied to quasistatic problems (e.g., Ng et al. 2015b; Wang et al. 2019). It was found that the boulders had always stopped moving by the time this threshold was reached.

2.7. Test plan
The baffle array was based on the configuration discussed in Kwan et al. (2018). Baffles with sides of 1.0 m and heights of 1.5 m on the upstream face were installed. Rows of baffles had a spacing of 1.5 m (Kwan et al. 2018). Three rows of baffles were selected as per Law et al. (2015). Rows of baffles were staggered (Cosenza et al. 2006; Teufelsbauer et al. 2011; Choi et al. 2014, 2015a; Ng et al. 2015a; Law et al. 2015; Wang et al. 2017a, 2017b; Bi et al. 2018a, 2018b; Kwan et al. 2018; Kim et al. 2019; Fei et al. 2020; Li et al. 2020). Furthermore, a range of lateral baffle spacings of \( 1 < s/b < 4 \) was investigated, covering the range mentioned in Kwan et al. (2018). Table 4 summarises the test plan.

3. Interpretation of results
3.1. Observed flow kinematics

Figure 6 shows side and top-down views of the channel and barrier. The array of baffles is installed on the slope in Fig. 6a and in the horizontal channel in Fig. 6b. The spacing \( s/b \) is 1 in both cases.

In Fig. 6a(i), boulders have been entrained by the flow front. Figure 6a(ii) shows pile-up and overflow for the bulk granular assembly occurring; all of the boulders have impacted the baffles, albeit different rows. Figures 6a(iii–vi) show that the bulk granular assembly continues to flow downstream, whilst the boulders have become trapped. Evidently, the baffles are successful at regulating the outflow. Figure 6a(vi) shows the boulders being filtered by the baffles.

In Figs. 6b(i) and 6b(ii), the boulders and flow are moving downstream towards the baffle array. Figure 6b(iii) shows the boulders impacting the first row of baffles. At the same time, granular jets (e.g., Hákonardóttir et al. 2003b) pass between the baffles. Pile-up is observable in Figs. 6b(iv) and 6b(v), with two boulders overtopping the first row of baffles. Figure 6b(vi) shows the simulation after the material has come to rest. The remnants of granular jets are visible between the final row of baffles and the barrier, but no boulders have reached the terminal barrier.

Overall, Fig. 6 shows that baffles on the slope and on the horizontal may both be effective at reducing the impact load on the barrier due to boulders. The baffles installed on the slope appear to be effective at flow regulation, as a large volume of granular material passes through them. In contrast, a much smaller volume of material passes the baffles in the horizontal channel due to the dissipation of flow kinetic energy at the transition between the slope and the horizontal plane.

3.2. Flow velocity and flow rate of material passing through an array of baffles

Figure 7 shows averaged velocities for flow material passing through arrays of baffles, normalised by average velocities for flows without obstacles. Figure 7a shows that this normalised velocity increases as \( Fr \) increases and as \( s/b \) decreases. The increase with \( Fr \) is because of the increasing importance of overflow. The dependence on overflow is qualitatively inferable from the formulations for pile-up height for flows impacting a rigid barrier given in Jóhannesson et al. (2009), Choi et al. (2015c), and Iverson et al. (2016). As such, studies or recommendations that give baffle height solely in terms of the flow depth (e.g., Hákonardóttir et al. 2003b; Choi et al. 2014; Kwan et al. 2018) may potentially lead to designs that lead to overflow. Thus, \( Fr \) must also be considered in the design of baffles.

Assuming steady-state conditions are applicable, it is expected that the flow velocity should increase as the baffle spacing is
Fig. 5. Numerical setup for the simulations with both a fine granular assembly and a set of perched boulders. The length of the flat section on which the boulders are initially perched is 1 m. Separate cases are run where the baffle array is placed on the horizontal channel (parts (a) and (c)) and the slope (parts (b) and (d)). [Colour online.]

Table 4. Test plan.

<table>
<thead>
<tr>
<th>Series</th>
<th>Baffle array location</th>
<th>Baffle spacing (s/d_{\text{Boulder}})</th>
<th>No. of rows of baffles</th>
<th>Barrier?</th>
<th>Channel length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granular flow only</td>
<td>—</td>
<td>—</td>
<td>0</td>
<td>No</td>
<td>5, 9, 11, 17, 23, 29, 35, 41, 47</td>
</tr>
<tr>
<td>Granular flow + boulders</td>
<td>—</td>
<td>—</td>
<td>0</td>
<td>Yes</td>
<td>5, 9, 11, 17, 23, 29, 35, 41</td>
</tr>
<tr>
<td>Sloped channel</td>
<td>1, 2, 4</td>
<td>3</td>
<td>Yes</td>
<td>7, 8, 9, 11, 17, 23, 29, 35, 41</td>
<td></td>
</tr>
<tr>
<td>Horizontal channel</td>
<td>1, 2, 4</td>
<td>3</td>
<td>Yes</td>
<td>7, 8, 9, 11, 17, 23, 29, 35, 41</td>
<td></td>
</tr>
</tbody>
</table>

decreased (Choi et al. 2015a). This is because constrictions tend to maintain a constant overall flow rate \(Q\), according to \(Q = UA_{\text{flow}}\), where \(A_{\text{flow}}\) is the cross-sectional area of the flow. This effect diminishes as \(Fr\) becomes lower due to the lack of momentum driving the flow through the slits between baffles. Other studies such as Hákonardóttir et al. (2003b) and Choi et al. (2014) reported net reductions in velocity (see also Table 2). The apparent differences with results from this study may be because of the way that \(Fr\) is characterised: the velocity and flow depth vary continuously across the length of each flow (Ng et al. 2019); so direct comparisons of velocity and \(Fr\) are not always straightforward.

Figure 7b shows that after the third row of baffles, the velocity reduction is almost identical to that in Fig. 7a. This is because the increase in flow velocity due to the effects of the constriction is attenuated when the discharge impacts the staggered baffles in the next row, offsetting an increase in velocity due to gravitational acceleration. Figures 7c and 7d show that for baffles in the horizontal channel, the effect on the flow velocity due to the constriction size still seems to hold, with more narrowly spaced baffles producing higher velocities relative to an open channel. However, in contrast to Figs. 7a and 7b, increasing \(Fr\) reduces the relative velocity. For \(s/d = 4\) and \(Fr = 3.4\), the relative velocity is around unity, but for \(Fr = 4.9\), the relative velocity drops to 0.5. This is because of the influence of the transition (from the slope to the horizontal channel) on the flow velocity. For lower values of \(Fr < 4\) for channels without baffles, flows become completely arrested on the horizontal channel shortly after the transition from the slope. Evidently, the baffles make little difference. In contrast, for higher \(Fr > 4\), the flow keeps moving downstream even after the transition. This suggests that the beneficial effects of baffles for reducing the flow velocity increase with \(Fr\). As such, baffles should be given higher priority during engineering design if higher \(Fr\) values are anticipated, site constraints notwithstanding.

For comparison, Salm (1987) reported that energy dissipation due to baffle-like obstacles is 50% of the transverse blockage, implying a velocity reduction of between 10% for \(s/d = 4\) and 30% for \(s/d = 1\). Jóhannesson et al. (2009) suggested that a single row of baffles should reduce the flow velocity by 20%, with two rows of baffles reducing it by a further 10%, based on physical experiments using snow where \(3 < Fr < 6\). Ng et al. (2015) reported a reduction in velocity of between 30% and 60% for dry sand flows impacting three rows of baffles for \(Fr \approx 3\). Kim et al. (2019) reported a velocity reduction of between 45% and 70% for two-phase flows impacting one to four rows of baffles for \(Fr \approx 6\). Wang et al. (2017a, 2017b) reported velocity reductions of 3% to 39% for two-phase flows impacting three rows of baffles for \(Fr \approx 4\). The wide range of reduction factors reported is interesting, and is probably caused by a range of factors including \(s/d\) and \(Fr\) (see the range of values recorded in Table 2).

Figure 8 shows the normalised peak outflow rate for different cases. The normalised peak outflow rate implicitly accounts for the effects of the transverse blockage on the amount of material that flows downstream. The peak outflow rate for cases with baffles is normalised by that for flows without obstacles at a given static monitoring section (indicated in the insets). Figures 8a and 8b correspond to monitoring regions behind the first and third rows of baffles, respectively. Two sets of lines are shown on each graph, corresponding to (i) different ratios of \(s/d\) and (ii) different positions of the baffle array.

Figure 8a shows that immediately after the first row of baffles, the normalised peak outflow rate increases with \(Fr\) for \(Fr > 3\), regardless of \(s/d\) and the placement of the baffle array. This is due to overflow that occurs for \(Fr > 3\). The normalised peak outflow...
rate for baffles on the slope is generally lower than for baffles in the channel for a given value of $s/d$. This reflects that the transition to the horizontal section of channel causes a substantial dissipation of energy (see also Fig. A1). This dissipation of energy accounts for much of the reduction in the peak outflow rate. This is why the reduction in the outflow rate due to the presence of baffles is less obvious for the horizontal section of the channel than the slope, at least for $s/d$ values of 2 and 4.

Notably, the relationship between $s/d$ and the peak normalised outflow rate is opposite to that between $s/d$ and the normalised averaged outflow velocity (see Fig. 7). This is because although the slits cause some material to be accelerated, the actual volume of material passing downstream is rather limited, especially for $s/d = 1$. This also suggests why flow velocities appear to increase in this study, but decrease in others (see Hökansson et al. 2003b; Jóhannesson et al. 2009; Ng et al. 2015a; Kim et al. 2019; Wang et al. 2017a, 2017b): for the flow as a whole interacting with baffles, the average velocity for the flow material decreases, but the frontal material passing through the slits accelerates. This explains why staggered rows of baffles are required to intercept this accelerated material.

Figure 8b shows that the peak normalised outflow rate diminishes as flow material passes through additional rows of baffles. For baffles placed on the horizontal plane and $s/d = 1$, the discharge rate is less than 10% of the flows in channels without obstacles. For baffles on the slope, the same $s/d$ reduces the discharge rate by between 25% and 40%. This suggests that the transition and the baffle array together cause a greater degree of energy dissipation than either one on its own, after the flow has passed three rows of baffles. This underscores the importance of accounting for the effects of a transition from the slope to the horizontal, which current international guidelines do not explicitly consider (VanDine 1996; Kwan et al. 2018; see Table 1). The increasing reduction in outflow rate as the flow passes more and more rows of baffles also emphasises the need for multiple rows of staggered baffles.

3.3. Mesoscopic behaviour of flows passing through baffle arrays

Filtering boulders fundamentally depends on mesoscopic interactions. Quantities such as the Savage number $N_{Sav}$ (Iverson 1997) differentiate between governing mechanisms of mesoscopic grain interaction, specifically frictional and collisional regimes. However, $N_{Sav}$ is primarily applicable to flows in channels without obstacles, where the grain size is approximately monodisperse.

Instead of the Savage number $N_{Sav}$, a simple metric of contact durability (Goodwin and Choi 2020) was adopted to characterise
the mesoscopic flow behaviour. The contact durability gives the proportion of contacts between grains that are maintained from one time step to the next. Lower values correspond to more frictional flows, whilst higher values correspond to more collisional flows. The calculation process is given in Appendix B. In Fig. 9, the contact durability for flows interacting with a baffle array is normalised by that of the durability of the flow in a channel without obstacles. Sub-unity indicates that flows in channels without obstacles behave more frictionally than flows interacting with baffles, unity indicates similar flow regimes, whilst super-unity indicates that flows in channels without obstacles behave more collisionally than flows interacting with baffles. The abscissa is given as normalised time: the characteristic timescale is the baffle array length divided by the pre-impact flow velocity $U$.

For baffles on the slope, the normalised contact durability is initially sub-unity, as grains scatter collisionally after initially impacting the baffles. Thereafter, the value rises: baffles constrict the flow, mobilising frictional shearing. Nonetheless, the normalised contact durability is unity for $Fr = 3.34$ and only slightly super-unity for $Fr = 4.37$. For baffles on the horizontal plane, however, the normalised contact durability rises by more than three times after four normalised time units as the baffles cause the flow to become arrested. This is consistent with the reduction in relative velocity and outflow rate for baffles on the horizontal plane shown in previous figures.

3.4. Reduction of peak load on the terminal barrier due to the presence of an array of baffles

For engineering design, the peak impact loads on a terminal barrier for a variety of $Fr$ and $s/\delta$ are of primary interest. Peak loads comprise both continuum and discrete components. The peak loads are normalised by the theoretical static load $Bkgh^2$ (Faug 2015). This also enables theoretical reference lines to be shown: assuming the flows behave as continua, all terms from eq. 1 can be scaled by the theoretical static load (Faug 2015):

$$\frac{F}{Bkgh^2} = 1 + \frac{\alpha U^2}{kgh}$$

Equation 6 can then be rewritten in terms of $Fr$:

$$\frac{F}{F_{\text{static}}} = 1 + \frac{\alpha}{k} Fr^2$$

where $B$ is the channel width, $k$ is an earth-pressure coefficient, $\rho$ is the flow density, $g$ is gravitational acceleration, $h$ is the flow...
depth, \(a\) is an impact coefficient, and \(Fr\) is the Froude number. The coefficient \(a\) is suggested as being as high as 2.5 in Kwan (2012) to account for the presence of boulders less than 0.5 m in diameter. Although the boulders in this study are larger than 0.5 m, in this discussion they are grouped into \(a\) for the purposes of easily comparing the effects of different baffle configurations. Taking \(k\) as unity, lines for \(a/k\) based on eq. 7 from 0.5 to 5.0 are shown in Fig. 10.

Figure 10a shows normalised peak impact loads for \(s/d < 4\) for baffles installed on the slope. \(Fr\) corresponds to the value at the flow front, before impact with the baffle array (see Appendix A). The load on the barrier for \(s/d = 4\) lies outside even the bound of \(a/k = 5.0\). This suggests that \(s/d = 4\), the upper bound mentioned in both MLR (2004) and Kwan et al. (2018), may not be suitable for the purpose of filtering boulders. At most, such a baffle spacing could be adopted for moderate flow rate regulation (see Fig. 8).

For the smallest baffle spacing considered, \(s/d = 1\), the computed impact load on the barrier is bounded by \(a/k = 0.5\), implying that the coefficient \(a\) in eq. 1 could be reduced for a sufficiently narrow baffle spacing. A coefficient of 0.5 is five times less than that currently suggested for rigid barriers resisting flows with a smaller boulder size of less than 0.5 m (Kwan 2012), implying that the thickness of the barrier could potentially be reduced by a factor of five. The cost savings from the reduction in materials used in the barrier would more than offset those used for the baffles, which generally have a much smaller total volume than terminal barriers (Kwan et al. 2018).

Figure 10b shows similar data as Fig. 10a, but for baffles on the horizontal channel. The impact force due to the boulders on the barrier for \(s/d = 4\) increases with \(Fr\). The impact forces are higher
than the theoretical lines for $\alpha/k = 2.5$ because overflow also increases with $Fr$, implying that this configuration of baffles is ineffective at reducing load on the terminal barrier. For $s/\delta = 1$, the impact forces lie within the bound $\alpha/k = 0.5$, suggesting that the baffles are successfully able to filter the boulders across a range of $Fr$. It is worth mentioning that $s/\delta = 1$ was able to filter at least 80% of the boulders for all cases run (i.e., at least 80% of the boulders were not able to pass out of the baffle array). A ratio of $s/\delta = 2$ filtered at least 60% of the boulders, whilst $s/\delta = 4$ filtered at least 20%.

In summary, baffle spacings at the upper bound of $s/\delta = 4$ (mentioned in both MLR 2004 and Kwan et al. 2018) are less appropriate for filtering boulders compared to narrower spacings. It is expected that for high values of $s/\delta$, extra rows of baffles would be required to attain the same trapping efficiency as for lower $s/\delta$. Furthermore, baffles on a slope have shown to be less effective at reliably filtering boulders than baffles in a horizontal channel, for given values of $Fr$ and $s/\delta$.

4. Conclusions

Current recommendations suggest that the ratio between baffle spacing $s$ and boulder diameter $\delta$ can be in the range $1 < s/\delta < 4$. However, there is minimal guidance on the optimal placement of baffles or what conditions enable boulders to be filtered. As such, it is unclear how the impact loading requirements for terminal barriers could be reduced.

The discrete element method (DEM) was used to investigate (i) the placement of the baffle array relative to a rigid barrier and...
(ii) the baffle spacing relative to the boulder diameter (s/δ). The key conclusions from the simulations performed in this study are as follows:

1. For a baffle spacing of s/δ = 1, the impact coefficient α for the terminal barrier can be reduced to 0.5 for baffles on the slope, or even less for baffles on a horizontal plane, from a nominal value of at least 2.5 for a rigid barrier without baffles. This is because closely spaced baffles enhance contacts between grains and dissipate flow kinetic energy. For the upper bound of s/δ = 4 mentioned in existing guidelines, the equivalent α can be as high as 5 or more, indicating that such a configuration is unable to filter boulders.

2. Three rows of baffles on a horizontal plane are more effective at reducing flow discharge compared to three rows of baffles on slopes. For s/δ = 1, the third row of baffles on the horizontal plane reduces the peak discharge by up to 90% relative to a channel without obstacles, whereas the same array of baffles on the slope reduces discharge by up to 75%. This reflects the beneficial effects from the transition between the slope and the horizontal, which enhances the dissipation of flow kinetic energy in concert with the baffle array — more so than either the baffle array or the transition would achieve on their own. Furthermore, increasing s/δ causes the peak discharge to increase proportionately more for baffles on the slope than for baffles on a horizontal plane. The maximum reduction in the peak discharge is up to four times more for baffles on the horizontal plane than a similar array on sloping terrain, compared to channels without baffles.

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References


Appendix A

The flow front governs interaction between flows and obstacles (Ng et al. 2019), so a measuring section that moves and deforms with the frontal 10% of the flow was adopted for characterising flow properties:

\[ h = \frac{2}{N_{gr}} \sum_{i=1}^{N_{gr}} h_i \]  
\[ U = \frac{1}{N_{gr}} \sum_{i=1}^{N_{gr}} U_i \]  
\[ Fr = \frac{U}{\sqrt{gh \cos \theta}} \]  
\[ \nu = \frac{N_{gr}(4/3)\pi^3}{hB^3_{mon}} \]

where \( N_{gr} \) is the number of particles in the measuring volume; \( h_i \) is the height of the centroid of particle \( i \); \( U_i \) is the velocity of particle \( i \); \( r \) is the particle radius; \( B \) is the channel width; and \( L_{mon} \) is the length of the measuring section, which can vary during outflow. Equation A1 finds the flow depth by doubling the average flow depth. (This is preferable to using a simple maximum value, which is easily distorted by saltating particles.) Equation A2 is a mean of the particle velocities in the monitoring region. In eq. A3, a Froude number is computed for all the particles in the measuring region based on eqs. A1 and A2. Equation A4 obtains the volume fraction by dividing the total volume of the particles within the monitoring region by the estimated bulk flow volume.

The flow depth, velocity, Froude number, and solid volume fraction for six open-channel flows with varying channel length \( L \) are shown in Fig. A1. Figure A1a shows an example of how \( Fr \) at the flow front changes as the flow moves down the channel; \( L \) was 11 m. \( Fr \) at the flow front increases from just over 2 after the perch to a maximum of around 4 at the transition point between the sloped channel and the horizontal channel. \( Fr \) then decreases in the horizontal channel at two distinct rates. The initial steep drop occurs due to energy dissipated through impact with the horizontal channel. The secondary drop occurs due to shearing with the base of the horizontal channel. For this case, \( Fr \) measured at the position where the first row of baffles would have been on the horizontal plane was measured to be around 3.3. \( Fr \) of 3.3 can also be found on the sloped channel, 4.4 m away from the start of the channel. This point is selected for the first row of baffles on the slope to ensure dynamic similarity for comparing cases where the array is on the slope and on the horizontal.

This exercise was repeated for several different channel lengths using open channels (Fig. A1b). \( Fr \) values for three locations are shown: at the transition between the slope and the horizontal, at the start of where the array of baffles would have been placed on the horizontal channel, and where the barrier would have been. It is worth noting that the \( Fr \) values attained are within the nominal range for debris flows suggested by Hübl et al. (2009). Figure A1c shows the position for the start of the baffle array on the slope as determined from \( Fr \) curves (e.g., Fig. A1a), to ensure that cases with baffles on the slope and on the horizontal are dynamically comparable. Figure A1d shows the velocity and flow depth at the flow front for different \( Fr \) values.
Appendix B

Figure B1a is modified from Goodwin and Choi (2020) and shows the algorithm used for determining contact duration. LIGGGHTS saves contact data for every particle in the simulation domain at a specified interval, including the IDs of particles in contact, as well as their spatial position. The algorithm firstly imports the contact data and then sorts contacts by their position along the channel; only the frontal 10% of particles are retained. This is equivalent to having a monitoring section that moves and deforms with the flow.

For each time step considered, pairs of IDs of particles that are in contact are recorded. This list of ID pairs is then compared against the particles in contact at the next time step. The number of ID pairs (i.e., contacts) that exist in both lists are divided by the total number of contacts in the first list. This gives a number between zero, meaning no sustained contacts, and unity, meaning all contacts are sustained.

Figure B1b shows an idealized 2D schematic of this process for a small number of particles across two time steps. In the region shown, at the first time step, there are seven pairs of particles in contact. The contact IDs (2–5, 4–5, 5–6, etc.) are recorded. At the second time step, there are also seven contacts, of which five also appeared in the previous time step. The contact durability for this region would therefore be computed as 5/7 = 0.71. (Note that for the actual simulations, the domain is 3D.)
Fig. B1. Calculation of contact durability (see Fig. 9). (a) Algorithm for contact duration (modified from Goodwin and Choi 2020); (b) idealized two-dimensional schematic of particle contacts for two time steps (also modified from Goodwin and Choi 2020). Numbers in black indicate particle ID, whilst numbers in red indicate pairs of particles in contact. [Colour online.]