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Procedia Earth and Planetary Science 9 (2014) 3 – 13
Procedia
Earth and Planetary Science

The Third Italian Workshop on Landslides

Effects of baffle transverse blockage on landslide debris impedance

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Abstract

Mitigation of landslide debris hazards sometimes requires the use of structural countermeasures such as baffles to minimise the destructive impact energy of a torrent. An array of baffles is a type of structure countermeasure frequently installed along the flow path to protect downstream facilities. They are currently designed using empirical methods since their interaction mechanism with landslide debris is not well understood. In this study, a 5 m long rectangular flume model is used to conduct experiments to investigate flow interaction between baffles and uniform dry sand. Dynamic similarity between model and prototype flows is achieved by adopting Froude scaling. The discrete element method (DEM) is then adopted to conduct numerical back-analysis of flume experiments to study the effect of varying transverse blockage on flow impedance. Results reveal that higher degrees of transverse blockages are more effective at developing upstream subcritical conditions which may develop into a granular jump and promote additional energy dissipation. An increase in the degree of transverse blockage from 20% to 37% provides up to 18% additional kinetic energy dissipation.

Selection and peer-review under responsibility of Dipartimento di Ingegneria Civile, Design, Edilizia e Ambiente, Seconda Università di Napoli.

Keywords: Landslide debirs; Flume modelling; Discrete element method; Transverse blockage

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1. Introduction

Debris flows occur in many parts of the world including Canada[1], Japan[2], and Hong Kong[3,4]. Severe loss of lives[5] and damage to infrastructure has been reported in literature. Both passive and active countermeasures are often adopted to mitigate this hazardous phenomenon[6]. Passive measures include detailed risk assessments[7], monitoring systems[8], and settlement relocation. However, passive measures alone may be inadequate and active measures are

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Selection and peer-review under responsibility of Dipartimento di Ingegneria Civile, Design, Edilizia e Ambiente, Seconda Università di Napoli.
doi:10.1016/j.proeps.2014.06.012

required. Active measures are structural impediments such as flexible barriers[9], check dams[10], slit dams[11], or an array of baffles[12,13,14,15]. The use baffles is particularly effective in impeding flow energy for debris flows[16,17], snow avalanches[18], and water discharge in hydraulic engineering[19]. The functionality of an array of baffles is to perturb the flow pattern such that flow slows down as it approaches each block and then accelerates towards the next row to accommodate the dissipation of flow energy upon impact. Figure 1 shows an array of rectangular and staggered landslide debris baffles positioned in front of a rigid barrier in the Lantau Islands, Hong Kong.

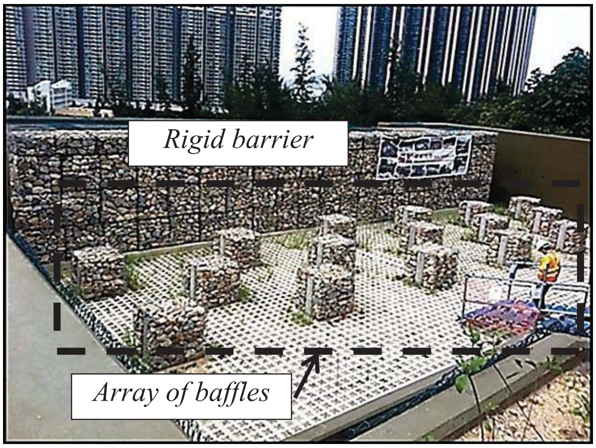

Fig. 1. Debris flow baffles in a deposition basin (Lantau Island, Hong Kong)

Debris flows have complicated flow and rheological behavior, hence studies pertaining to snow avalanche and hydraulic engineering are not suitable for investigating debris flow baffles. This paper serves as a continuation of previous investigations of landslide debris baffles using flume and DEM modelling[12,13,14,15]. Dry sand flows were scaled to characterize landslide debris using Froude (*Fr*) similarity. A *Fr* number of about 3 was targeted and from calibration experiments this was equivalent to flow depths of 80 mm with a frontal velocity of 2.7 m/s at a distance of 0.8 m downstream from the storage container. The geometric influences of the baffle height, longitudinal spacing between successive rows, and number of rows on flow impedance were examined. Previous investigations reveal that it is imperative to adopt baffles taller than the approach depth to ensure subcritical upstream conditions and to suppress overflow[13]. Successive rows staggered of baffles should be positioned as close as possible to promote the greatest energy dissipation from the deflection of granular jets[14]. It is evident that landslide debris baffles are highly effective at reducing frontal velocity by up to 36% and runout distances by up to 65%[15].

It should be pointed out that there are some fundamental differences in the design and use of slit dams and baffles. Slit dams comprise of a single row of densely spaced columns which aim to retain peak discharge volumes instead of baffles which impede flow energy while allowing debris to pass. Despite an extensive study on geometric effects and its influence on flow impedance, the significance of varying the degree of transverse blockage on flow impedance is still not well understood. In this study, the range of transverse blockage needed is to avoid simulating slit dams. In accordance to empirical design recommendations for debris flow retaining slit dams[20,21], an equivalent transverse blockage of at least 40% is required. Slit openings for landslide debris baffles should fall outside the following relationships for slit dams:

$$b \cdot d_{\max} < 2.0 \tag{1}$$

$$b \cdot w = 0.2 \div 0.6 \tag{2}$$

where b is the slit opening size, d_{max} is the maximum particle size, and w is the channel width. Along the transverse direction, the obstruction can be characterized by the degree of transverse blockage (T_b) and is given as follows:

$$T_b = b_s / w \times 100 \tag{3}$$

where b_s is the sum of each baffle width along the transverse direction. This study aims to investigate the influence of baffle transverse blockage on upstream Froude conditions and flow energy reduction.

2. Flume modeling

2.1. Flow characterization

Three types of similitude are required for modeling flow interaction, namely geometric, kinematic, and dynamic similarity. Geometric similarity is achieved adopting rectangular shaped baffles that are commonly used in the field, and characterizing the model dimensions relative to initial upstream flow conditions. Kinematic similarity describes the impedance resulting from baffle interaction, which is unknown, and examined this study. Dynamic similarity is achieved by using the Froude number (Fr) which governs the similitude of forces in gravity-driven flows in open channels. The Fr number is the ratio of inertial forces to the gravitational forces and is defined as follows:

$$Fr = v \Big/ \sqrt{g h_a} \tag{4}$$

where v = frontal velocity before impact (m/s), g = gravitational acceleration (m/s^2), and h_a = approach flow depth (m).

Debris flow can be characterized with approach Froude numbers ranging from 0 to 4.5 based on field observations[22,23]. A Froude number of about 3 is adopted for this study and is equivalent to prototype debris flow events with an approach velocity of 10 m/s and an approach flow depth of 1 m[12,13,14,15].

2.2. Flume model

Figure 2 shows the flume model used to investigate landslide debris interaction with baffles. The rectangular flume model is 5 m in length and has a base width of 0.2 m[12,13,14,15,24]. The channel inclination is set to 26° for this study and was selected based on calibration exercises used to characterize the appropriate upstream flow conditions for achieving Froude similarity upon interaction with the baffles. Finally, debris is stored at the most upstream end of the flume inside a 0.08 m^3 storage container.

2.3. Instrumentation

Figure 3 shows two identical high speed cameras used to capture both the plan and side view of the flow interaction. The full resolution capacity of the cameras is (329 × 475) and the cameras can capture up to 204 frames per second. Moreover, ten photoconductive sensors are installed along the base of the channel at 500 mm intervals to measure the frontal velocity of a flow. These photoconductive sensors are light sensors. When debris passes over each sensor, a signal is sent to a data logger. With the known spacing between successive sensors and the difference in time when a signal is generated and received, an average frontal velocity of the torrent along the transportation zone can then be deduced. Since the voltage received is a function of the thickness of sand over each photoconductive sensor, each photoconductive sensor is calibrated and the flow front is defined as a thickness of 5 mm in this study.

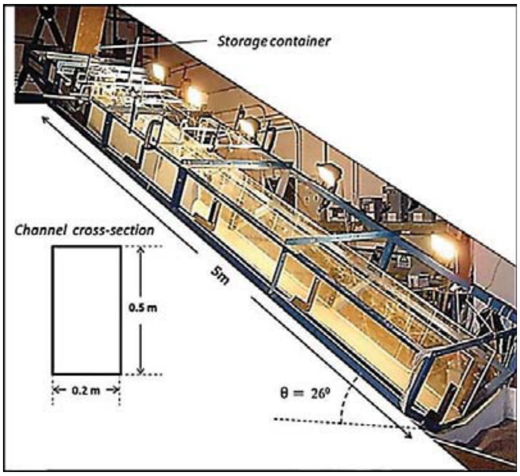

Fig. 2. Flume model

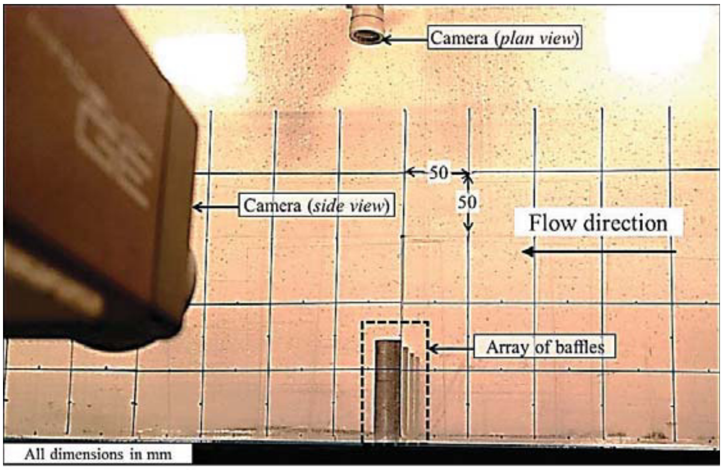

Fig.3. Side view of a typical model setup

2.4. Test programme and material

Four baffle configurations are examined in this study, including three different degrees of transverse blockages, and a control test. The degree of transverse blockages was varied as 20% (see Fig. 4a), 30% (see Fig. 4b), and 37% (see Fig. 4c). The baffle height is selected depending on the upstream approach flow depth (ha). Since the approach flow depth of 80 mm was adopted for each test to achieve a *Fr* number of 3.0[12,13,14,15], single row arrays of 1.5ha tall baffles were adopted for each configuration. Table 1 gives a summary of the test configurations examined in this study.

2.5. Model setup and testing procedures

In order to understand the complex flow mechanisms, it is imperative to understand the most fundamental flow cases (dry granular materials) before investigating multi-phase flows. Hence, dry Leighton Buzzard (LB) Fraction C sand composing of fairly uniform grains with diameters between 300 μm and 600 μm was used in this study. A mass of 100 kg of sand with an initial bulk density of 1680 kg/m^3 was used for each experiment. The initial debris mass was determined from calibration experiments to achieve Froude similarity.

Individual model aluminum baffles are installed on the base of the channel to form the appropriate baffle configuration. The first row of baffles is positioned 800 mm from the storage container. This length is determined to accommodate the appropriate upstream flow conditions using Froude scaling. Once the baffles are prepared, instrumentation and lighting are prepared.

Table 1. Physical and numerical test plan

Test ID	Baffle height (h_a)	Number of rows	Degree of transverse blockage (%)
Control	1.5h_a	1	0
H15_R1_T2			20
H15_R2_T3			30
H15_R3_T37			37

Upon preparation of the baffles and instrumentation, the storage container door is secured with the activation of the magnetic lock at the base of the door. Two springs attached to the door are then loaded. The systematic layering sand is conducted to reach the target volume. The flume is then gradually inclined to 26°. The spring loaded storage door is released by deactivation of the magnetic lock and the door is caught by a hook mechanism at its highest point of accent to allow the sand to freely flow outside of the storage container. Sand surges downslope through the baffles and is collected at the most downstream end of the flume. More details of the model setup and test procedures are discussed in previous publications[13,15].

3. Discrete element method (DEM)

Flow interaction with an array of baffles is highly incoherent during flume experiments and it is difficult to quantify the energy dissipation, hence the DEM was adopted to simulate the kinematics of granular flow in this study. The open-source software package Large scale atomic/molecular massively parallel simulator Improved for General Granular and Granular heat transfer simulations (LIGGGHTS) was used. Further details on the DEM method are discussed in previous publications[14,22].

3.1. Numerical model and input parameters

The numerical model adopts identical channel and baffle configuration as each flume experiment. Planar rigid walls are used to simulate the baffles and channel bed while periodic boundaries conditions (PBCs) are used for the side walls. To eliminate the unrealistic particle arrangement at the wall boundary caused by the constraint of particle sizes in discrete element simulations[25], the PBCs are adopted. 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 just before impact.

In this study, a total of 65,000 discrete elements with a diameter of 5mm were used. The other parameters used for each simulation is summarised in Table 2. It should be pointed out that there are three major limitations in 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 simulated, some input parameters pertaining to these motions are difficult to determine and quantify accurately and reliably. More details on the numerical model, boundary conditions, and input parameters are discussed in a previous publication[14].

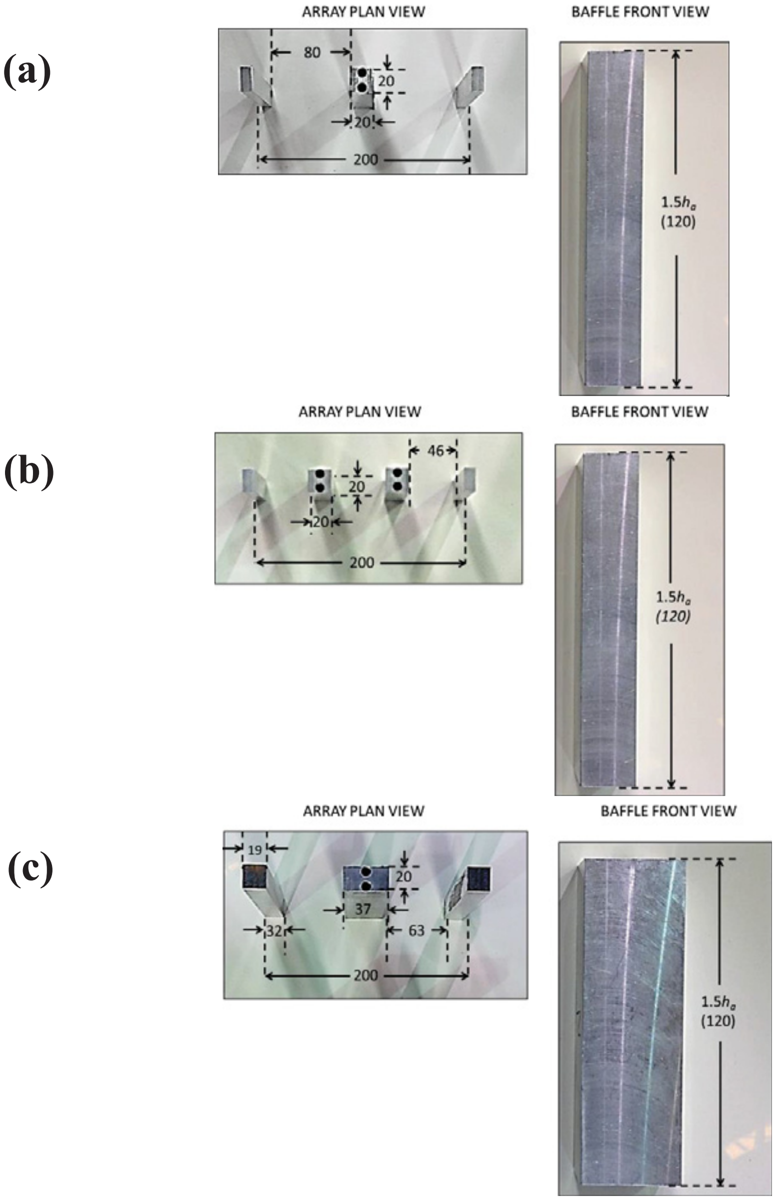

Fig. 4. Baffle array layout and dimensions (all dimensions in mm): (a) 20 % transverse blockage**; (b)** 30 % transverse blockage; (c) 37% transverse blockage

3.2. Numerical test plan and simulation procedures

A series of four numerical simulations with different baffle configurations were conducted to back analyze the physical model tests. The influence varying the degree of transverse blockage on flow mechanisms is investigated. Details of each configuration are given in Table 1.

Each numerical simulation begins with 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 and a measured frontal velocity of 2.7 m/s is then applied to the wedge of discrete elements. The flow is initiated and the flow dynamics are monitored. Monitoring sections are used to capture the velocity, flow depth, Froude number, and kinetic energy of each discrete element.

Table 2. DEM input parameters

Input parameter	Value (*units*)
Number of discrete elements	65, 000
Particle diameter	0.005 (*m*)
Particle stiffness	1×10^8 (*N/m*)
Discrete element friction angle	35°
Coefficient of restitution	0.5

3.3. Model calibration

To ensure that input parameters and modeling techniques are appropriate for simulating the interaction of granular flow against an array of baffles, flume experiments are used to calibrate the DEM model. The numerical model has previously been calibrated in a previous publication[14]. Figure 5 shows a comparison of flow dynamics from flume experiments and DEM simulations for test configuration with a single row of baffles with 30% transverse blockage. The observed flow interaction from flume experiments is captured with a high speed camera mounted overtop (shown on the left of the figure) and a similar view of the computed discrete element simulation is shown on the right. It is evident that the numerical model captured reasonably well the recorded flow dynamics during the flume test. This provides the confidence in subsequent numerical back-analyses.

4. Interpretation of Flume and DEM results

4.1. Observed interaction mechanisms

Figure 6 shows a typical flow interaction captured from flume experiments using high speed imagery. A side view of a $1.5h_a$ single row array with 37% blockage is shown. The flow with a frontal velocity of 2.7 m/s (measured using photoconductive sensors) approaches the array of baffles at t = 0 s (see Fig. 6a). As the flow impacts the array of baffles, run-up is observed along the upstream face of the baffles (see Fig. 6b). Debris accumulates upstream of each baffle to form dead zones (see Fig. 6c). The debris continues to impact the array of baffles and enlarges the dead zones (see Fig. 6d). Between t = 0.20 s and 0.25 s, a granular jump forms. A granular jump acts as a wall of sand behind the baffles that further dissipates flow energy as oncoming flow impacts the granular jump (see Figs. 6e and 6f). A granular jump theoretically develops at critical conditions, or when supercritical flow transitions into the subcritical flow regime.

4.2. Computed upstream Froude conditions

Figure 7 shows a comparison of upstream Froude conditions for different transverse blockages during the DEM simulations. Single row arrays of $1.5h_a$ tall baffles with transverse blockages of 20%, 30%, and 37% are included. The control test (unobstructed channelized flow with an initial Froude number of about 3) is shown for reference. The computed Fr number for each time step is taken as the average of all spherical discrete elements with their centroids falling within a distance of 50 mm upstream of each array. A horizontal reference line at $Fr = 1$ is shown to distinguish transition from supercritical to subcritical flow conditions, and the potential development of a granular jump as discussed in section 4.1.

The computed results reveal that a single row with 20% transverse blockage is ineffective in developing upstream subcritical conditions. It should be noted that upstream subcritical conditions are imperative to developing a potential granular jump which may lead to additional energy dissipation. As the transverse blockage is increased to 30%, a distinct transition from supercritical flow to subcritical flow is observed directly upstream of the array of baffles. Further increasing the degree of transverse blockage to 37% exhibits more rapid development of subcritical conditions. The shorter the duration to develop subcritical upstream conditions, the more effective the baffles are at arresting the impact energy.

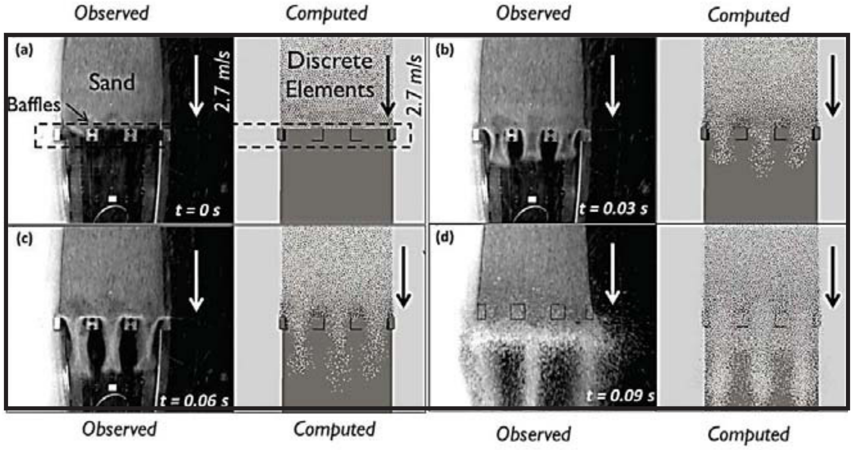

Fig. 5. Comparison of flume experiments and computed flow dynamics: (a) $t = 0$ s; (b) $t = 0.03$ s; (c) $t = 0.06$ s; (d) $t = 0.09$ s.

4.3. Computed downstream energy dissipation

Figure 8 shows a comparison of computed downstream normalized kinetic energy profiles for varying degrees of transverse blockages. The kinetic energy (E_k) for each time step is calculated as the average kinetic energy of all spherical discrete elements with their centroids falling within a distance of 50 mm downstream of each array. Each calculated E_k is then normalized by the approach kinetic energy before impact E_a, which E_a is determined from Froude scaling with a frontal velocity of 2.7 m/s (as measured from flume experiments) before impact. The control test kinetic energy profile is shown for reference.

It can be seen from the figure that as the debris particles (discrete elements) exit the single row arrays, the kinetic energy increases beyond control test conditions for a short duration. The increase in kinetic energy is attributed to discrete elements squeezing through reduce cross-sectional area and increasing in velocity (reminiscent of a nozzle). It is evident that the higher degrees of transverse blockages lead to the greater energy dissipation. An increase in the degree of transverse blockage from 20% to 37% leads to 18% more energy dissipation for the interaction duration captured. Consistent with the computed results shown in Fig. 7, a higher degree of transverse blockage also exhibits more effective development of the critical upstream conditions.

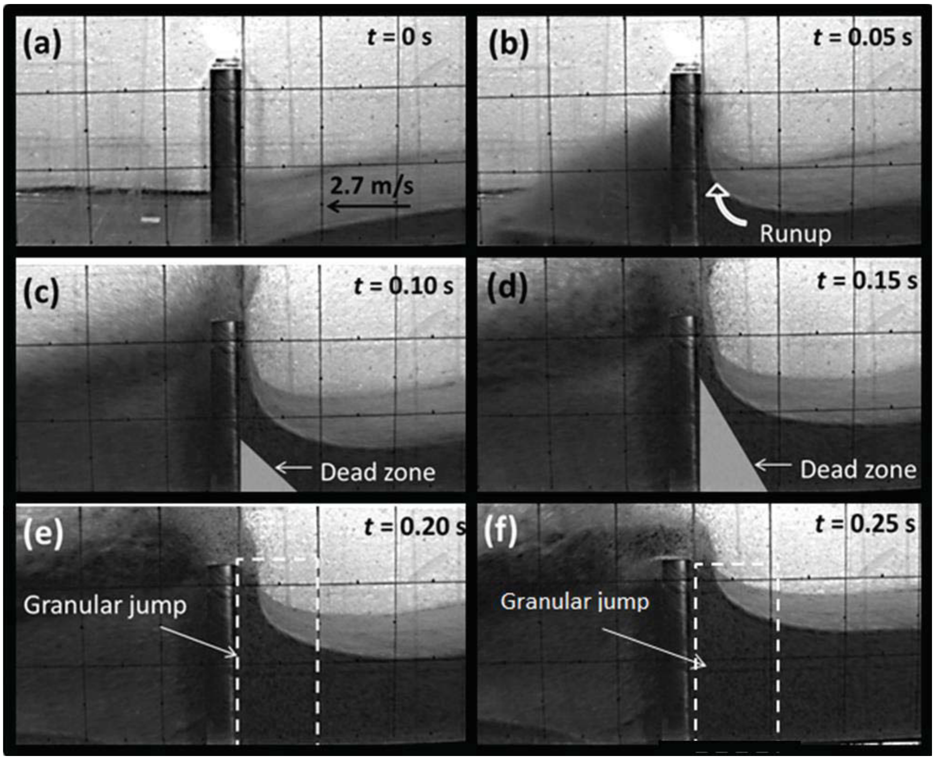

Fig. 6. Observed flow interaction (test H15_R1_T37): (a) $t = 0$ s; (b) $t = 0.05$ s; (c) $t = 0.10$ s; (d) $t = 0.15$ s; (e) $t = 0.20$ s; (f) $t = 0.25$ s

5. Concluding remarks

Modelling procedures for flume experiments using dry sand and the Discrete Element Method (DEM) were presented. The DEM was used to back-analyze physical model tests to investigate the influence of varying the degree of transverse blockage on flow impedance. Some preliminary findings can be drawn as follows:

a) Complex flow and impact mechanisms were observed and characterised by run-up phenomenon along the upstream face of the baffles, formation of dead zones and granular jumps. A granular jump acts as a wall of sand behind the baffles that further dissipates flow energy as oncoming flow impacts the granular jump, which theoretically develops at the critical conditions, or when supercritical flow transitions into the subcritical flow regime.
b) Higher degrees of transverse blockages are more effective at developing upstream subcritical conditions which may develop into a granular jump and promote additional energy dissipation. The baffle array with 20% transverse blockage is ineffective at developing subcritical upstream conditions in the duration captured for this study.
c) Higher degree of transverse blockages leads to lower downstream kinetic energy. Increasing the degree of transverse blockage from 20% to 37% provides up to 18% additional kinetic energy dissipation for the duration captured.

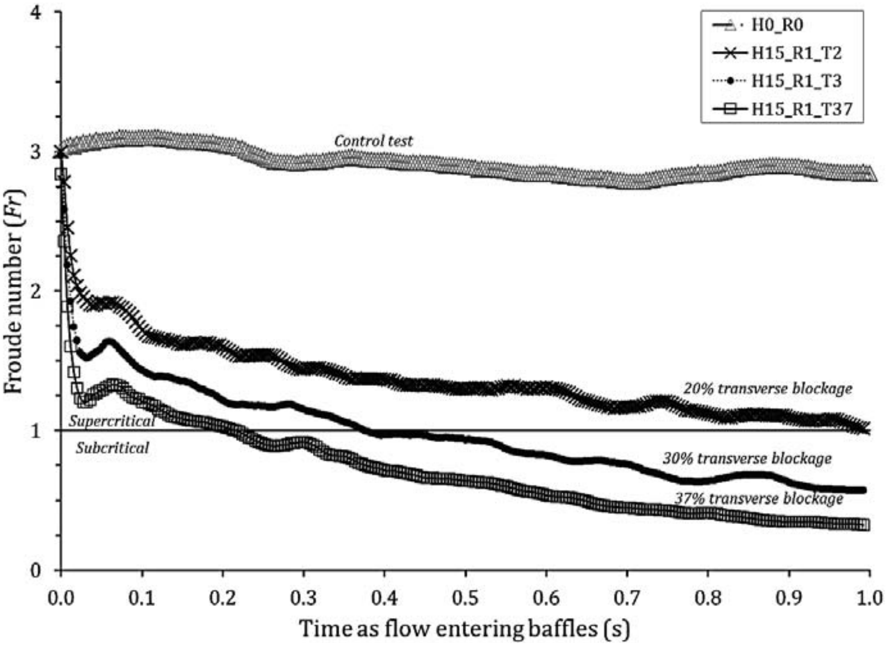

Fig. 7. Comparison of computed upstream Froude conditions for varying transverse blockages

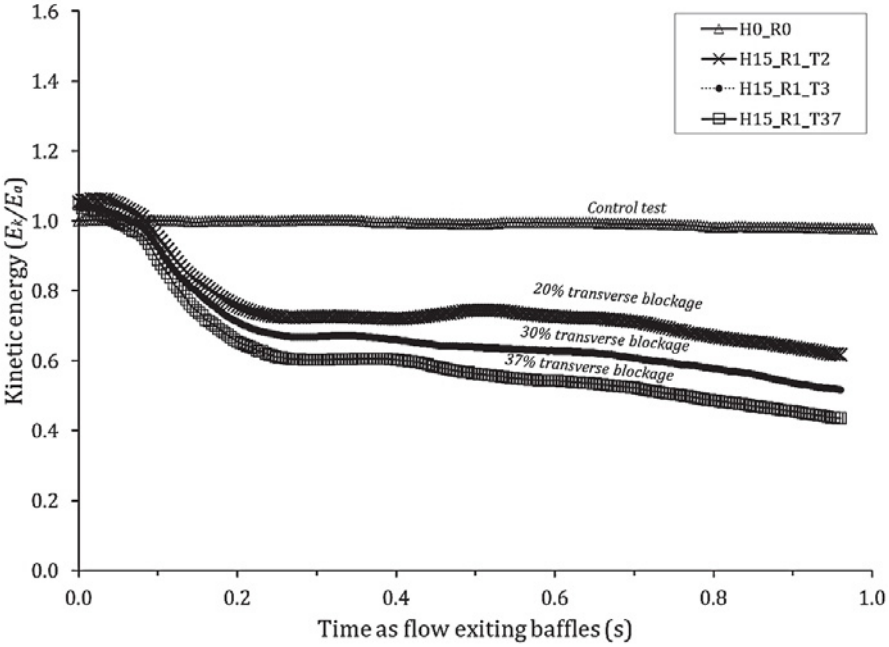

Fig. 8. Comparison of computed kinetic energy profiles for varying transverse blockages

Acknowledgements

The authors would like to acknowledge the financial support from research grant (HKUST9/CRF/09) provided by the Research Grants Council and the Geotechnical Engineering Office of Civil Engineering and Development of the Government of the HKSAR. This paper is published with the permission of the Head of the Geotechnical Engineering Office and the Director of Civil Engineering and Development, Government of the Hong Kong SAR, China.

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