Downstream Frontal Velocity Reduction Resulting from Baffles

Effets des déflecteurs dans la réduction des vitesses frontales dans un écoulement descendant.

Choi C.E., Ng C.W.W.
Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology
Kwan J.S.H., Shiu H.Y.K., Ho K.K.S., Koo R.C.H.
Geotechnical Engineering Office, Civil Engineering and Development Department, HKSAR

ABSTRACT: Debris flows occur in mountainous regions during rainfall and can result in disastrous consequences to downstream facilities if appropriate mitigation measures are not taken. Common mitigation measures include flow impeding structures within the flow path. An array of baffles is a type of flow impeding structure used primarily to reduce the mobility of landslide debris. However, they are usually designed on an empirical and prescriptive basis and the degree of impedance resulting from an array of debris flow baffles is not well understood. This paper presents a series of systematic flume tests examining the influence of baffle row number on reduction of debris frontal velocity. Photoconductive sensors installed at the base of the flume channel have been used to measure the average frontal velocity of the debris flow downstream of the array of baffles. Results show that one row is ineffective in reducing the debris frontal velocity. Two to three rows of baffles exhibit notable frontal velocity reduction.

RÉSUMÉ : Les coulées de granulaires représentent un risque majeur en régions montagneuses en période de fortes pluies et peuvent avoir des conséquences désastreuses pour les installations en aval si des mesures appropriées ne sont prises. De telles mesures comprennent la construction de déflecteurs à matériaux sur le parcours des coulées avec pour objectif principal est de réduire la mobilité de la masse granulaire en mouvement. Cependant, la construction de ces déflecteurs repose sur des hypothèses empiriques. La contribution exacte des déflecteur est mal comprise à l'heure actuelle et elle est difficile à évaluer précisément. Cet article présente une série de tests expérimentaux ayant pour objectif d'évaluer l'influence de l'augmentation du nombre de déflecteurs sur la réduction de la vitesse frontale de la coulée granulaire. Des capteurs photoconducteurs placés dans le fond du canal de test ont été utilisés pour mesurer la vitesse frontale moyenne des grains en aval des déflecteurs installées. Les résultats révèlent qu'au moins deux à trois rangées de déflecteurs sont nécessaires pour avoir une réduction significative de la vitesse frontale de l'écoulement.

KEYWORDS: physical modelling; flume; debris flow; baffles; landslide mitigation measures

1 INTRODUCTION

Ground mass detached from landslide source travels down hillside under gravitational actions. Landslide debris can have high mobility and can result in serious consequences to downstream facilities. Velocity of debris fronts can reach up to 30 m/s (Costa 1984; Rickenmann 1999) with peak discharges several times greater than floods occurring in the same catchment (Hungr et al. 1984). In order to mitigate this hazardous phenomenon, debris-resisting structures are often used as defence measures to retain landslide debris and impede debris mobility (Mizuyama 2008). Defence measures may include the rigid and flexible barriers (Wendeler et al. 2007), levees, slit dams (Watanabe et al. 1980), and arrays of baffles.

The primary function of baffles is to impede the flow pattern such that flow slows down after it passes through the baffles (USFHA 2006). Baffles can be installed upstream of barriers to reduce the impact resistance required by the barriers and to promote lateral dispersion of flow in deposition basins (Cosenza et al. 2006). Figure 1 shows rectangular gabion baffles installed in front of a rigid barrier in Lantau Island, Hong Kong. Baffles are usually designed by empirical and prescriptive methods and their fundamental impedance capacity is not well understood.

Similar studies on snow avalanche impeding obstacles report that an individual row of obstacles can dissipate energy by 20% and an additional row contributes to 10% extra energy dissipation (Hakanordottir et al. 2001). Salm (1987) reports that the degree of impedance can be estimated based on the consideration of the cross-sectional blockage over the channel area. However, the above criteria are applicable only for snow avalanches because the flow regimes characterising avalanche and debris flow are quite different (see Sect. 2.1 for further details). This study aims to examine the reduction of downstream debris frontal velocity resulting from an array of baffles. The influence of the number of staggered rows of baffles on downstream debris frontal velocity is investigated.

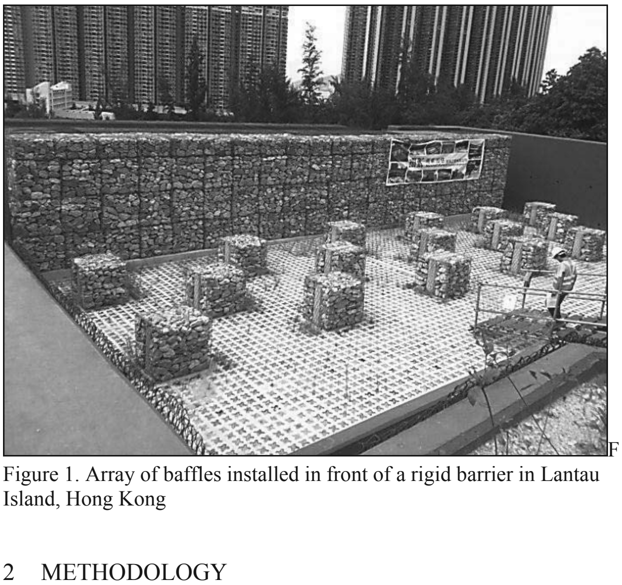
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Figure 1. Array of baffles installed in front of a rigid barrier in Lantau Island, Hong Kong

2 METHODOLOGY

2.1 *Scaling*

Three types of similitude are required for modelling debris flow-baffle interaction; they are (i) geometric similarity, (ii) kinematic similarity, and (iii) dynamic similarity. For simplicity, geometric similarity is achieved by normalising model dimension by the flume channel width and debris flow depth (more details presented in Sect. 3). Kinematic similarity describes the impedance resulting from baffle interaction which is unknown and constitutes the objective of this study. Dynamic similarity is attained by adopting the Froude number, F_r, which governs the behaviour of gravity-driven flows in open channels. The F_r number is the ratio of inertial forces to the gravitational forces and is given as follows:

$$F_r = \frac{v}{\sqrt{gh}} \qquad (1)$$

where v = frontal velocity (m/s), g = gravitational acceleration (m/s^2), and h = debris flow depth (m).

Debris flow can be characterised with approaching F_r which ranges from 0 to 4.5 (Arrattano et al. 1997, Hubl et al. 2009) based on field observations. An $F_r \approx 3$ is adopted for characterising the approaching flow in this study. This corresponds to debris flow event with an approaching velocity of about 10 m/s and flow depth of about 1 m. Details of the scaling process and control test are discussed by Ng et al. (2012).

2.2 *Flume model*

Further to flume experimental studies of debris flow mechanisms (Law et al. 2008, Zhou et al. 2009) at the Hong Kong University of Science and Technology (HKUST), a new five metre long rectangular flume (see Figure 2) with a channel base width of 0.2 m and height of side walls of 0.5 m was developed for this study. Based on calibration exercises, an inclination angle of 26° is used (Ng et al. 2012) to match an $F_r \approx 3$. Instrumentation and lighting are mounted on the external frame surrounding the flume. Debris material is contained in a storage container located at the most upstream end of the flume. The storage container has a maximum storage volume of 0.08 m^3 and is equipped with a spring-loaded door secured by a magnetic lock. At the most downstream end of the flume is a deposition container for collecting debris materials.

2.3 *Instrumentation*

Ten photoconductive sensors are installed throughout the base of the flume at intervals of 0.5 m. When debris passes over the sensor, a signal is sent to the data logger at that particular instant. With the known spacing and difference in time at which signals are received between two sensors, the average debris frontal velocity can be deduced along the entire transportation zone. The uncertainty of photoconductive sensors is estimated to be ± 0.05 m/s.

Laser sensors are mounted over the top of the channel to capture centreline flow depths at specific locations along the flume. Furthermore, high speed cameras are installed above and at the side of the flume to capture the flow dynamics during interaction with the array of baffles. The full resolution capacity of the cameras is 1024 × 1024 pixels and with a potential frequency of 759 frames per second.

3 TEST PROGRAMME

A series of four flume experiments are presented in this paper. The details of experiments are given in Table 1. The four experiments consist of one control experiment without baffles in the channel to serve as reference and the three baffle configurations which vary in number of staggered rows (one to three rows). All experiments have been repeated to ensure repeatability. For simplicity, a single baffle height of 0.75 times the approach debris flow depth (h = 80 mm) is adopted for all configurations. Details on the approach debris flow depth are discussed by Ng et al. (2012). The degree of transverse blockage is selected as 30% in this study. The degree of transverse blockage is defined as the sum of obstruction in the transverse direction divided by the width of the flume channel. According to Ikeya and Uehara (1980) and Watanabe et al. (1980), slit dams function primarily to retain flow material through the mechanism of arching, while baffles primarily impeded the flow mobility. Slit dams entail an equivalent degree of transverse blockage of greater than 40%, therefore the degree of transverse blockage selected in this study (i.e. 30%) is appropriate for modelling debris flow baffles.

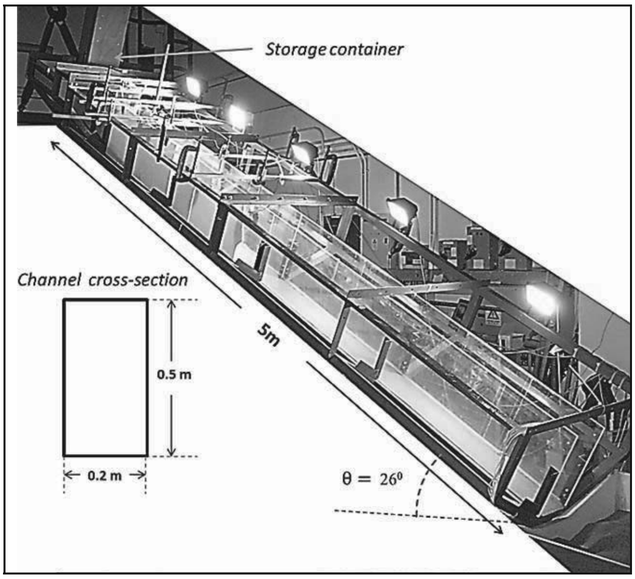

Figure 2. Flume model setup

Table 1. Test programme

Test ID	*Baffle height (h)*	*Transverse blockage (%)*	*Number of rows*
H0_R1	0	0	0
H075_R1	0.75*h*	30	1
H075_R2	0.75*h*	30	2
H075_R3	0.75*h*	30	3

h: approach flow depth (80 mm)

The arrangement of full and half sized baffles used to create a staggered formation as shown in Fig. 3. The dimensions of full baffles are 20 mm × 20 mm × 60 mm, and the dimensions of half baffles are 20 mm × 10 mm × 60 mm. The spacing between successive rows is selected to be 50 mm or 0.25 times the width of the flume channel. This spacing is selected based on recommendations by Hakonardottir et al. (2001) that baffles should be placed as close together as possible to promote the deflection and interception of discharge from the slits of the previous row.

4 EXPERIMENTAL RESULTS

5.1 *Flow dynamics*

As a flow front impacts an array of baffles, streams of debris material discharge through the slits and part of debris also runs up along the upstream vertical face of the baffles simultaneously. The debris run up eventually exceeds the baffle height and some materials become airborne. Synchronously, material is deposited upstream of the baffles. The upstream flow eventually rides over the deposited material and cascades over the array of baffles. There are essentially two components of downstream discharge, namely discharge through and overtop of the baffles, both of which combine and propagate downslope after the landing of overflow trajectory.

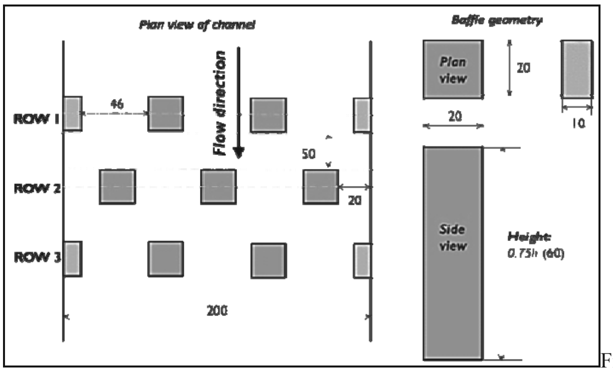

Figure 3. Baffle arrangement and dimensions (all dimensions in mm)

5.2 *Frontal velocity*

The measured debris frontal velocity profiles of different tests are compared and shown in Fig. 4. The measured debris frontal velocity is plotted against normalised distance travelled along the transportation zone (N_d), which is the ratio of distance travelled by the debris front along the 5 meter flume. The debris flow direction is from left to right on x-axis and the location of the baffles along the transportation zone is shown as a vertical dashed line.

The frontal debris velocity profile of the control test (H0_R0) is shown as a reference for comparison purposes. The debris frontal velocity of the control test rapidly increases upon release from the storage container. At $N_d = 0.2$, a steady debris flow profile develops, beyond $N_d = 0.6$, the debris frontal velocity begins to decrease. A similar debris velocity profile is observed in the experiment of one-row baffle test (H075_R1). However, for the two-row and three-row baffle tests, a prominent debris velocity reduction at the immediate downstream of the baffle groups was observed. The velocity profile rapidly decreases to less than 2 m/s after which it gradually increases beyond $N_d = 0.3$.

Results show that one row of baffles (H075_R1) exhibits negligible reduction in frontal debris velocity and the propagation of the front is similar to unobstructed flow (H0_R0). Obvious reduction in debris frontal velocity is observed in the test with two rows of baffles (H075_R2) at the location immediately downstream of the baffle group. This may be attributed to the second row of staggered baffles intercepting the discharge from the slits of the first row which dissipates energy by disrupting streamlines of the flow (USFHA 2006). The provision of an additional row of baffles (i.e. the third row; test H075_R3 refers) exhibits a frontal debris velocity reduction of 47% at $N_d = 0.3$ relative to the control experiment, whereas two rows of baffles (H075_R2) only exhibits 30% reduction of frontal debris velocity relative to the control experiment at $N_d = 0.3$. Moreover, the higher frontal velocity reduction may be attributed to an additional third row of baffles which intercepts discharge from the second row and disrupts streamlines. Beyond $N_d = 0.4$, two rows (H075_R2) and three rows (H075_R3) baffle groups exhibit a similar gradual increase in frontal debris velocities. An increase in frontal debris velocities may be attributed to subsequent excessive overflow of material due to the use of shorter baffles (0.75 times the approach flow depth) in this study. Overflow of debris in test H075_R1 is captured from high speed imagery at the side of the flume model and is shown in Fig. 5. Overflow does not experience impedance and launches downstream (Barbolini et al. 2009) to increase the momentum and thus the frontal velocity of the flow. Overflow is hazardous particularly in situations where its trajectory is not easily predicted. Johannesson (2001) surveyed a torrent which had been deflected by a dam at Flateyri in north-western Iceland and observed that the deflected stream came to rest 100 m further downslope than the un-deflected part. The mechanism of overflow appears to be significant and results from this study require further interpretation.

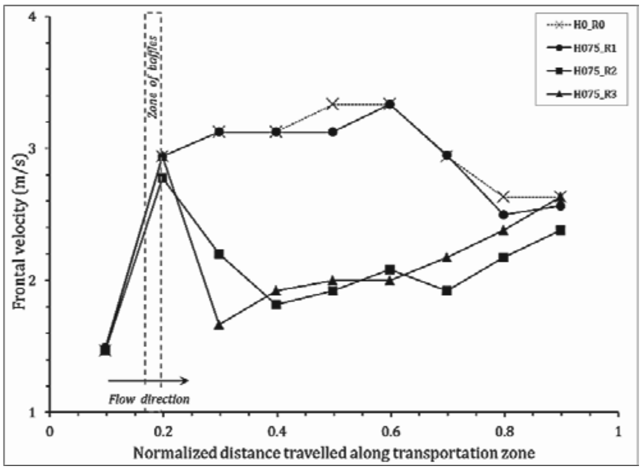

Figure 4. Comparison of measured frontal velocity

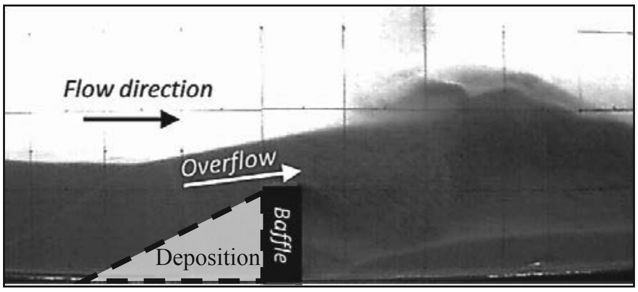

Figure 5. Observed overflow dynamics (test H075_R1)

5.3 *Preliminary Particle Image Velocimetry (PIV) analysis*

A preliminary Particle Image Velocimetry (PIV) analysis has been carried out to investigate the flow dynamics and quantify the flow velocity by interpreting the results of the flume test using the Particle Image Velocimetry package (geoPIV) developed by White et al (2003). This package is developed based on close-range photogrammetry techniques capable of tracing movements of soil grains captured in high-resolution images. It produces displacement and velocity vectors of the soil grains.

Typical flume test results for three rows of baffles produced by geoPIV are presented in Figure 6. It shows the flow dynamics of the debris upon hitting the baffles. Details of debris run-up against baffles, deposition behind baffles and filling up of the baffle zone and the subsequent overflowing from the crest of baffles were captured. In general, the preliminary results of the calculated velocity vectors by PIV method are consistent with the measured debris frontal velocity by the instrumented photo-sensors. Further PIV analysis will be carried out in the next stage of interpretation of the experimental study.

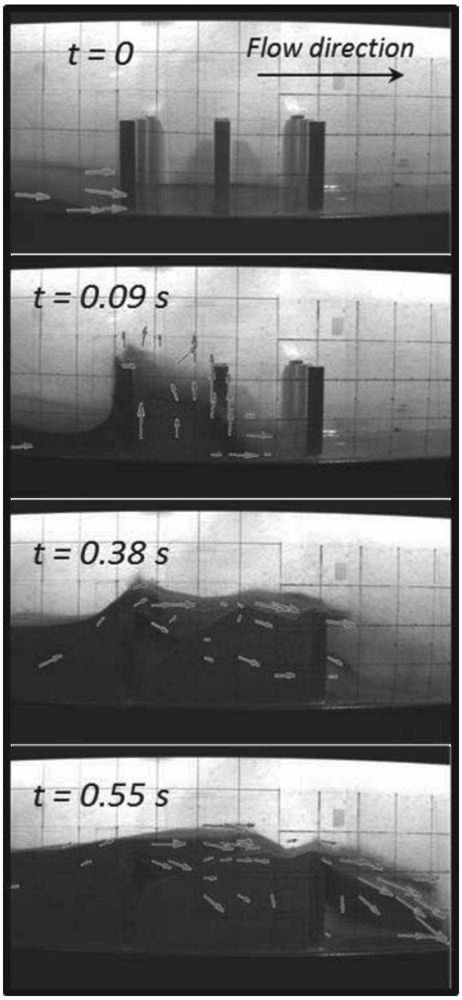

Figure 6. Preliminary results using PIV method

5 CONCLUSIONS

A series of systematic flume experiments modelling debris-baffle interaction has been conducted. The influence of increasing the row number on frontal debris velocity is presented and some preliminary conclusions are drawn as follows:

1. One row of baffles exhibits negligible reduction of frontal debris velocity compared to unobstructed channelised flow.
2. Two and three rows of baffles result in reduction of frontal debris velocities immediately at the downstream from the array of baffles. Increasing the number of staggered rows of baffles disrupts streamlines and intercepts discharge from slits of the previous row of baffles which dissipates energy and reduces the frontal debris velocity.
3. Overflow resulting from the use of baffles may result in subsequent increase in frontal velocity downstream and warrants further studies.

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