A Numerical Study of Granular Surge Flow through a Row of Baffles

Une étude numérique des écoulements granulaires à travers une rangée de chicanes

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ABSTRACT: A numerical study that utilizes three-dimensional discrete element method was undertaken to investigate the impact process and the dynamic interaction between granular surge flow and baffles. In the numerical analyses, the granular flow medium and the baffles were modelled as frictional spherical discrete elements and rigid square objects respectively. The location, velocity and forces acting on the individual discrete elements during the impact and interaction process were captured and recorded in the analyses. A detailed assessment of the numerical output data indicates that a single row of baffles is effective in reducing the kinetic energy and discharge of the granular surge flow.

RÉSUMÉ : Une étude numérique utilisant une approche par éléments discrets en 3D a été mise en oeuvre pour étudier le processus d'impact et l'interaction dynamique entre un écoulement granulaire et des chicanes. Dans cette étude, le milieu granulaire a été modélisé par des objets sphériques et les chicanes par les objets carrés. Les grains comme les chicanes sont considérées comme parfaitement rigides. L'emplacement, la vitesse et les forces agissant sur les éléments discrets au cours du processus d'impact et l'interaction ont été ainsi calculés. Une évaluation détaillée des données de sortie indique qu'une seule rangée de chicanes est efficace pour la réduction de l'énergie cinétique et l'évacuation de l'écoulement granulaire.

KEYWORDS: baffles, granular flow, discrete element method, energy dissipation, impact pulse, discharge.

1 INTRODUCTION

Granular surge flows such as debris flows and snow avalanches are dangerous natural hazards. Baffles have been employed to dissipate the kinetic energy of such flows and reduce the entrainment of channel bed deposits. Rows of baffles could be constructed across the flow path in order to reduce the flow velocity, the entrainment potential and dynamic impact force on downstream structures. Baffles constructed across the debris flow path are potentially more advantageous than the conventional rigid debris-resisting barriers because baffles are generally easier to construct without the need for extensive site formation works. However, the dynamic interaction of granular surge flow with baffles is still an emerging area of research to both the academics and the practitioners.

Discrete element method was introduced in geomechanics by Cundall and Strack in 1979 and was later adopted as a research tool by other researchers (e.g. Muir et al., 2008; Sibille et al., 2008; Thompson et al., 2009). The discrete element method is an appropriate and useful tool for modelling debris flow and snow avalanche because of the granular flow nature (Zwinger 2000; Nicot 2004; Hutter et al, 2005; Pudasaini & Hutter 2007) of these phenomena. In a previous study by Law 2008, a series of flume model tests and three dimensional discrete element analyses were conducted to investigate the impact behaviour of granular surge flow on a rigid barrier. The study has been extended to investigate granular surge flow through a row of baffles. This paper focuses on the numerical study of the impact process and the dynamic interaction between baffles and granular surge flow using the discrete element method.

2 NUMERICAL STUDY

2.1 *Introduction*

The granular medium was modelled as incompressible frictional discrete elements and the planar rigid surfaces were used to model the baffles and the ground surface. In the analyses, the location and velocity of the individual discrete elements together with the forces acting on each element were captured and recorded in order to study the impact process and the dynamic interaction between baffles and granular surge flow. The displacement of individual discrete elements is independent of one another, and they only interacted when coming into contact with each other or with the baffles and other rigid boundaries. The motion of each discrete element was calculated on the basis of the forces acting on it by the Newton's laws of motion. The displacements and rotations of the discrete elements were computed in the numerical analyses.

2.2 *Numerical model setup and test procedure*

Figure 1 shows the geometry of the flow path and the baffles. The granular medium comprises a total of 30,000 spherical discrete elements and all the discrete elements have a uniform diameter of 0.05m. The material density of each discrete element is 2,650 kg/m^3. The discrete elements were not intended to simulate motion of individual particles in the granular medium. Instead, the macroscopic behaviour of the granular medium was represented by the contact behaviour between the discrete elements. Planar rigid surfaces were used to model the baffles and the ground surface.

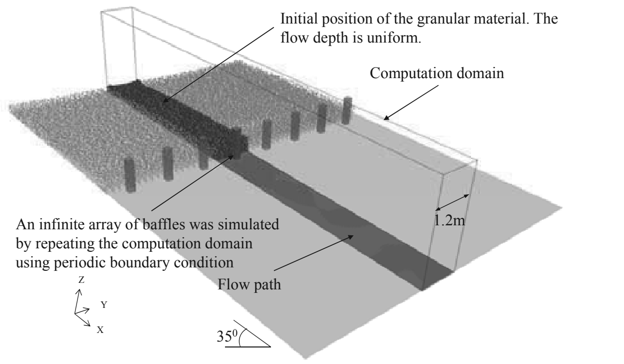

Figure 1. Numerical model setup

The length and width of the computation domain were 15m and 1.2m respectively. The slope gradient was chosen to be 35^0. The plan area and the height of the individual baffle were 0.2m x 0.2m and 1m respectively. The baffle was located in the middle of the flow path. The periodic boundary condition (PBC) was applied along the y-direction (Figure 1) of the computation domain. With the PBC, discrete elements leaving one side of the computation domain in the y-axis will emerge on the opposite side with the same dynamic properties, such as velocity, force, etc. This boundary condition helps to reduce the computation time since the impact of granular flow medium on an array of baffles could be simulated using a single baffle and a reduced number of discrete elements (i.e. only the dark particles shown in Figure 1 need to be modelled). With reference to Chen 2009, a baffle spacing of 1m and the ratio of baffle spacing to element diameter of 20 were adopted in the analysis to prevent clogging of the discrete elements between the baffles.

Each numerical analysis is divided into two stages, namely the initial stage and the impact stage. At the initial stage, the granular medium comprising an assembly of discrete elements with random packing was placed on a rigid surface inclined at 35^0 as shown in Figure 1. The individual discrete elements stabilized itself under the action a body force, which was equivalent to gravity and acting perpendicularly downwards at the ground surface. The body force acting on the individual discrete elements was rotated to the vertical direction in the next stage to enable the granular medium to flow downslope under the action of gravity and impact the baffles. The initial thickness of the granular medium was uniform and chosen to be 0.5m before impacting on the baffles. At the impact stage, the granular medium was given an initial velocity of 8 m/s. The corresponding Froude number of the initial flow condition is close to 4 which fall within the range of Froude number of debris flow events reported by Hubl et al 2009.

2.3 *Contact law applied in numerical model*

The local rheology of the flow material was simulated by applying the contact law in the numerical model. The linear Hookean stiffness model was adopted for the discrete elements and the rigid planar surfaces in the numerical analyses. According to Crosta et al. 2001, the contact stiffness of the discrete element has negligible influence on the computed mobility of granular material. Given that the chosen stiffness value have only minimal influence on the computed result, the discrete element and wall stiffness used were both chosen to be $1x10^8$ (N/m) such that the elements almost behave like a rigid body.

The relative translational and rotational motions between the discrete elements are mainly resisted by contact friction. The macroscopic friction angle of dry sand was measured to be 35^0 (Teufelsbauer et al. 2011, Chiou 2005, Pudasaini et al 2005 and 2007, Pudasaini and Hutter 2007). Based on field and laboratory tests conducted by Chau et al. 2002, Azzoni and Freitas 1995 and Robotham et al. 1995, the coefficient of restitution was chosen to be 0.5.

According to Calvetti and Nova 2004, the macroscopic friction angle of the granular medium is typically much less than 30^0 irrespective of the value of the contact friction angle adopted on spherical discrete elements without rolling resistance. Calvetti et al 2003 and Tamagnini et al 2005 emphasized the need to inhibit particle rotations and calibrate the particle contact friction angle based on the desired value of the macroscopic friction angle of the granular medium.

In the numerical analyses, a rolling resistance term was added in the calculation of rolling motion of discrete elements. The rolling resistance was calculated using a directional constant torque model elaborated by Ai et al 2011. The model applies a constant torque on a particle to represent the rolling friction. The direction of the torque was always against the relative rotation between the two contact entities. The torque between two in-contact spheres i and j can be expressed as:

$$M_r = -(\omega_{rel} / |\omega_{rel}|)\, \mu_r R_r F_n \quad (1)$$

$$\omega_{rel} = \omega_i - \omega_j \quad (2)$$

where ω_i = the angular velocities of sphere i;
ω_{rel} = the relative angular velocity between two elements;
μ_r = the rolling friction coefficient;
F_n = the normal contact force; and
R_r = the radius of the discrete element

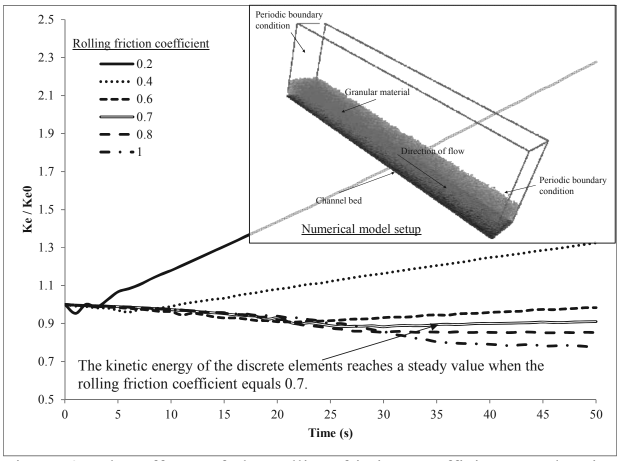

Figure 2. The effects of the rolling friction coefficient on the time history of the computed kinetic energy

A calibration exercise was carried out to identify the appropriate rolling friction coefficient for the numerical study. Figure 2 shows the numerical setup for the calibration work. The simulation box boundary was periodic in nature in order to allow the granular material to transport on the incline indefinitely. The granular material was given an initial velocity of 8m/s. By adopting a macroscopic friction angle of 35^0 (i.e. same as the channel inclination), a coefficient of restitution of 0.5 and trying different rolling friction coefficients (i.e. μ_r = 0.2, 0.4, 0.6, 0.7, 0.8 and 1) in the calibration exercise, the granular flow would eventually reach a steady kinetic energy.

Figure 2 shows the time history of the kinetic energy (k_e) of all discrete elements relative to the computed k_e at time zero (k_{e0}). The k_e is the sum of kinetic energy of all discrete elements. Based on the results of the calibration exercise, the granular flow could attain a steady velocity when the rolling friction coefficient reached a value of 0.7, which was chosen to be the appropriate rolling friction coefficient for the numerical study. The input parameters adopted is summarized in Table 1.

Table 1. Parameters adopted in the numerical study

Parameter	Magnitude
Slope angle	35^0
Baffle dimension	0.2m x 0.2m x 1m
Particle diameter	0.05m
Density of each particle	2650kg/m^3
Particle and wall stiffness	1x10^8 (unit)
Contact friction angle	35^0
Coefficient of restitution	0.5
Rolling friction coefficient	0.7
Approaching velocity	8m/s

3 COMPUTED RESULTS

3.1 *Flow Profile*

Figure 3 shows the plan and side view of a number of snapshots recorded in the numerical analyses. The time difference between each snapshot is 0.012 second. The darker the particle colour, the lower was its velocity. A velocity reduction of the discrete elements immediately behind the baffles was observed on plane and Section A-A as shown in Figure 3.

In Figure 3a, at time = 0s, the particles at the front of the flow were just in contact with the baffle. In Figure 3b, at time = 0.012s, the dark region signified the slowing down of the discrete elements behind the baffle after impacting it. The boundary of the dark region where the momentum of the discrete elements was reduced by the baffle is marked by a white dashed line.

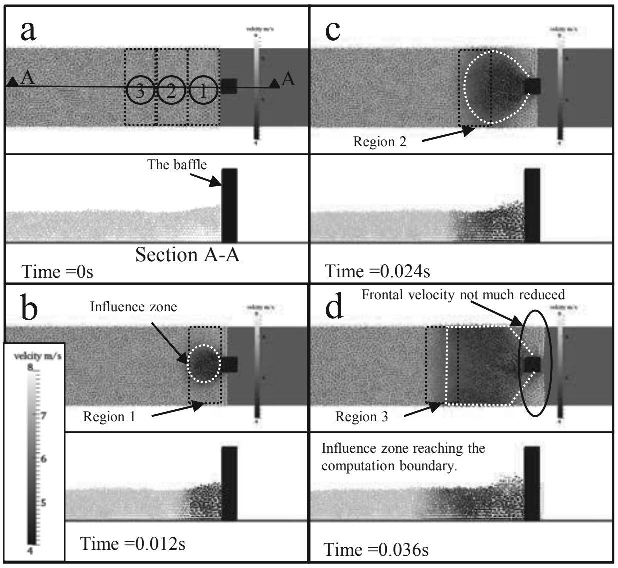

Figure 3. The snapshots showing the change of particle velocity during impact. The time difference between each snapshot is 0.012 second.

In Figure 3c, at time = 0.024s, the size of the dark region increased in size, and the dark region reached the computation boundary in Figure 3d. This indicates that the reduction of the momentum of the discrete elements behind each baffle was no longer localized, but a continuous zone of momentum reduction behind the row of the baffles. The presence of such a momentum reduction zone suggests that most discrete elements passing through the baffles will be decelerated by the flow resistance provided by the baffles. The only exception was the frontal discrete elements located between the baffles. As highlighted in Figure 3d, the velocity of the frontal discrete elements between the baffles was not reduced by the baffles. It is noted from the side view snapshots that the flow depth right behind the baffle increases at the time of frontal impact. The deceleration of the discrete elements was observed to be uniform over the flow depth.

In order to capture and record the dynamic behaviour of the discrete elements behind the baffles, three measurement regions (i.e. region 1, 2 and 3) as shown in Figure 3a were established. Each measurement region was 0.4m in length in the longitudinal direction. The unbalanced force, kinetic energy and discharge rate of the discrete elements within the measurement regions in the first 0.14 seconds of the impact process were recorded and presented as follows.

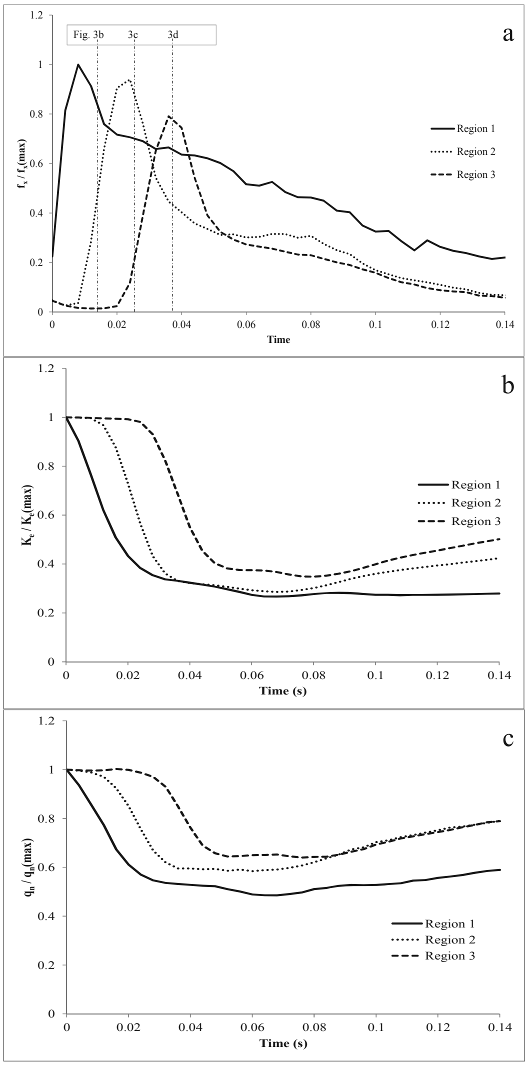

Figure 4. The computed f_x, k_e and q_n of discrete elements located in region 1, 2 and 3 (please refer to Figure 3a for the location of the regions).

3.2 *Unbalanced force on discrete element close to the baffle*

The unbalanced force (f_x) is the sum of the unbalanced force of all discrete elements in the flow direction. When the granular flow approaches the baffles, a change in the normalized unbalanced force (f_x/ $f_{x(max)}$) with time is an indication of the internal stress experienced by the discrete elements due to the dynamic impact on the baffles. Figure 4a shows the relationship of (f_x/ $f_{x(max)}$) with time in region 1, 2 and 3. The built up and decline of f_x were recorded in the three measurement regions 1, 2 and 3 and presented in Figure 4a.

From Figure 4a, the duration of the peak f_x acting on the baffle was less than 0.01s, and the sequential peak f_x observed in all the three measurement regions had indicated the propagation of impact pulses in the opposite direction of the flow during frontal impact of granular flow on the baffles. By comparing Figure 3 and Figure 4a, it is observed that the discrete elements located close to the edge of the dark region had the peak f_x. The impact pulse is therefore correlated to the propagation of the dark region where the discrete elements reduced their momentum notably. As the f_x decreased steadily with time after impact, the post-peak f_x was found to be less than 30% of the peak f_x after about 0.14s. This finding suggests the highly transient nature of the impact.

3.3 *Energy dissipation and discharge*

Figure 4b shows the relationship of the normalized kinetic energy (k_e/ $k_{e(max)}$) of the discrete elements with time in region 1, 2 and 3. The solid line, dotted line and dashed line represent the computed k_e/ $k_{e(max)}$ in region 1, 2 and 3 respectively. The k_e is the sum of the kinetic energy of all the discrete elements in a region. From Figure 4a and Figure 4b, it can be observed that k_e decreased much more rapidly with time than f_x. In region 1, k_e reduced to 30% of the peak k_e after less than 0.02s while f_x requires about 0.14s to reduce to 30% of its peak f_x. The magnitude of k_e rose gently following the rapid reduction.

Figure 4c shows the mean discharge rate (q_n) of the discrete elements relative to the maximum computed q_n ($q_{n(max)}$) in region 1, 2 and 3. Similar to the trend of k_e, the normalized discharge rate reduced with time. The reduction of the discharge rate was less rapid in comparison with the reduction of k_e shown in Figure 4b. A rising trend of q_n is observed following the reduction. It is interesting to note that both the k_e and q_n rose following the sharp reduction of their values. It is inferred that the deceleration effect caused by the baffles are more significant during the first impact (i.e. time before 0.04 second for regions 1 to 3) at which the impact pulse propagated along these regions. The trend of kinetic energy of these regions beyond 0.14 second is likely to be affected by the presence of various deposition mechanisms, such as runup, reflected wave, jet and hydraulic jump, etc (Armanini and Scotton 1993; Armanini 1997; Sun and Law 2012). Further research will be carried out to study the influence of these mechanisms on the computed kinetic energy and discharge. Based on the above observations of the first impact process, the baffles reduced the kinetic energy and the discharge of the discrete elements behind them effectively.

4 CONCLUSIONS

In this study, the three-dimensional discrete element method was used to analyse a granular surge flow through a row of baffles. The analysis focused on the short moment at which the first impact of the discrete elements on the baffles took place. The propagation of impact pulses in the upstream direction was observed at the moment of impact. The magnitude of the impact pulse decreased with the distance upstream from a row of baffles. The deceleration of the discrete elements was uniform over the flow depth at the moment of impact. More than half of the kinetic energy of the discrete element right behind the row of baffles was dissipated in less than 0.02s. The kinetic energy of the granular medium behind the row of baffles decreases more rapidly with time than the unbalanced force. Based on the findings of the analysis, a single row of baffles is effective in reducing the kinetic energy and discharge of the granular surge flow at the moment of impact.

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