INTERACTION OF DEBRIS FLOW WITH RIGID AND FLEXIBLE BARRIERS: CENTRIFUGE AND NUMERICAL SIMULATIONS

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Abstract: The dynamics of debris flow are governed by the interaction between its solid grains and the viscous interstitial fluid. However, understanding the effect of solid-fluid interaction for impact problems has proven to be quite the challenge since debris flows have poor temporal predictability and are scale-dependent. Existing frameworks characterising impact adopts macroscopic variables such as the Froude number without considering solid-fluid interaction. This has resulted in design approaches that rely much on empiricism and have also led to international recommendations, specifically pressure coefficients (α) that are mutually inconsistent. In this extended abstract, a series of centrifuge tests modelling the impact between debris flow and model rigid and a novel model flexible barrier are discussed. The solid-fluid interaction was investigated by varying the solid volume fraction of the flow to change the degree of grain contact stress. A large-nonlinear finite element model was then adopted to back-analyse centrifuge experiments to study the effects of the fluid viscosity on the dynamic response of a new model flexible barrier.

Keywords: debris flow impact; rigid and flexible barriers; centrifuge modelling; finite element modelling

INTRODUCTION

Debris flows are distinct compared to other geophysical flows, such as mud flows and debris floods, because of their strong dependence on the interaction between incompressible grains of soil and the viscous pore fluid (Iverson 2015). Solid-fluid interaction has profound effects on changes in pore pressures which in turn controls the mobility of the flow (Iverson 2003). For impact-related problems, solid-fluid interaction governs the degree of contact stresses between grains, which in turn dictates the impact mechanism (Choi et al. 2015a; Ng et al. 2016a) and loading distribution on a barrier (Song et al. 2017). Despite the importance of solid-fluid interaction, it is not considered in existing frameworks which characterise impact. The main challenges in understanding the fundamental mechanisms of impact of two-phase flows is the scale-dependency of debris flow. For instance, shallower flow depths that develop in bench-top experiments exhibit disproportionalities in viscous shearing and the ability to sustain pore pressures (Iverson 2015).

Existing frameworks characterising the impact of debris flow simply treat the flow as an equivalent fluid and do not consider solid-fluid interaction. Instead, impact is characterised macroscopically using the Froude number and the conservation of momentum (Cui et al. 2015).
The most commonly adopted momentum-based equation for estimating debris impact (WSL 2009; Kwan 2012) is given as follows:

\[ F_d = \alpha \rho v^2 \sin \beta \, hw \]  

(1)

where \( F_d \) is the bulk debris impact force, \( \alpha \) is the pressure coefficient, \( \rho \) is the debris density, \( v \) is the debris velocity, \( \beta \) is the angle between the barrier and impact orientation, \( h \) is the debris thickness and \( w \) is the channel width. However, it is clear from Eqn. (1) that the effects of solid-fluid interaction are not fundamentally considered.

To tackle this challenge and to enable a fundamental understanding of solid-fluid interaction and scale-effects in a systematic manner, the geotechnical centrifuge provides a suitable means. The centrifuge correctly captures the absolute stress state (Schofield 1980; Ng 2014) of a granular assembly and ensures the correct response in pore pressures. Also, by varying the particle diameter and fluid viscosity (Bowman et al. 2010), stress ratios in key dimensionless groups which describe the dynamics of debris flow can be systematically controlled (Iverson 1997).

In this extended abstract, a series of centrifuge experiments studying the impact of two-phase flows on rigid and flexible barriers are discussed. Numerical back-analyses using a large nonlinear finite element model was then used to back analyse centrifuge experiments to bear further insight on the influence of fluid viscosity on the dynamic response of a flexible barrier.

CENTRIFUGE MODEL TESTS AND FINITE ELEMENT MODELLING

Centrifuge modelling

The 400 g-ton Geotechnical Centrifuge Facility (GCF) at the Hong Kong University of Science and Technology was used to carry out the experiments. The beam centrifuge has an arm radius of 4.2 m (Ng 2014). All tests were conducted at a g-level of 22.4 inside a model container with plan dimensions of 1245 mm × 350 mm and a height of 851 mm. A 25° slope with a width of 233 mm and a length of 1000 mm was installed inside the model container. A storage container was mounted at the top of the model container to contain the debris material. Inside the storage container a helical ribbon mixer was installed to prevent the consolidation of the debris mixture in-flight. A hinged door is installed at its base of the storage container which is released in-flight by controlling a hydraulic actuator.

On the model slope, either a rigid or a novel model flexible barrier, both 200 mm (model dimensions) in height, can be installed perpendicularly to study the interaction between different flow and barrier types. Figures 1a and 1b show the front view of the novel model flexible barrier and spring elements mounted used to replicate prototype cable load-displacement, respectively. Details of the novel model flexible barrier and the spring elements are discussed in Ng et al. (2016a). Load cells and laser sensors were installed to measure the axial load and cable displacement in each model flexible barrier cable. The rigid barrier was modelled as a 10 mm thick (model dimension) cantilevered steel plate. The rigid barrier was instrumented with load cells to study the distribution of impact pressure along the height of the barrier. Furthermore, impact kinematics for each test were captured using a high-speed camera capable of
capturing a resolution of 1300 × 1600 pixels at a sampling rate of 640 frames per second. Images were then used to carry out Particle Image Velocimetry (White et al. 2003) analysis to understand the impact kinematics.

Leighton Buzzard (LB) fraction C sand, with a particle diameter of about 0.6 mm, was used in the tests. The internal and interface friction angles of the sand are 31° and 22.6°, respectively. The viscous liquid has a specific viscosity of 11.3 Pa·s and a density similar to that of the LB sand (Ng et al. 2016a). A summary of the tests discussed in this extended abstract is given in Table 1.

**Fig. 1.** Model flexible barrier (Ng et al. 2016b): (a) front view of barrier; (b) spring elements at the back of the partition

**Fig. 3.** Large-nonlinear finite element model (LS-DYNA)
Large-nonlinear finite element modelling

A large-nonlinear finite element model software package in three-dimensions, LS-DYNA, was used to study the influence of flow viscosity on the dynamic response of a flexible barrier. LS-DYNA uses explicit time integration to study nonlinear flow problems and has been applied widely for stress and deformation analysis of structures subjected to impact. This approach provides a continuum numerical solution based on the conservation of energy and Newton’s laws of motion. The Arbitrary Lagrangian-Eulerian (ALE) formulation discretises the computational domain into a mesh of elements, which can move arbitrarily and optimise the shape of the elements, enabling large deformation of the debris flow.

The numerical model is shown in Fig. 3. The interaction of debris flow with a barrier requires a coupling technique to take into account the material internal stress changes and structural deformation upon impact. The interaction between the debris flow (ALE-based elements) and barrier and the channel (shell and beam elements) is modelled using finite-element contacts following the approach of Olovsson and Souli (2000 & 2001) and Hallquist (2006). Any penetration of the flow material into the barrier or channel results in a normal reaction force with the interface which is distributed evenly to both the flow and the barrier or channel base.

This LS-DYNA model has been benchmarked against several well-documented laboratory flows and field studies (Hallquist 2006; Koo 2015; Kwan et al. 2015). Test FL in this extended abstract was adopted to carry out numerical back-analysis and a parametric study to investigate the influence of fluid viscosity on the dynamic response of the flexible barrier. The flow viscosity was varied according to measurements of field debris flows (Iverson 1997), 0.001 Pa·s to 0.1 Pa·s. A summary of the numerical parameters adopted in the simulations are summarized in Table 2.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Description</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>RL</td>
<td>Rigid barrier + sand-liquid mixture</td>
<td>Viscous liquid (Solid fraction 0%)</td>
</tr>
<tr>
<td>RSL20</td>
<td>Rigid barrier + sand-liquid mixture</td>
<td>Solid fraction 20%</td>
</tr>
<tr>
<td>RSL40</td>
<td>Rigid barrier + sand-liquid mixture</td>
<td>Solid fraction 40%</td>
</tr>
<tr>
<td>RSL50</td>
<td>Rigid barrier + sand-liquid mixture</td>
<td>Solid fraction 50%</td>
</tr>
<tr>
<td>FL</td>
<td>Flexible barrier + liquid</td>
<td>Viscous liquid, viscosity 11.3 Pas</td>
</tr>
</tbody>
</table>

Table 2. Input parameters

<table>
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<tr>
<th>Component</th>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
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</thead>
<tbody>
<tr>
<td>Viscous flow</td>
<td>Density $\rho$</td>
<td>1580</td>
<td>kg/m$^3$</td>
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<tr>
<td></td>
<td>Viscosity $\eta$</td>
<td>11.3</td>
<td>Pas</td>
</tr>
<tr>
<td>Flexible cable</td>
<td>Stiffness $K_1$</td>
<td>$1.8 \times 10^6$</td>
<td>N/m</td>
</tr>
<tr>
<td></td>
<td>Stiffness $K_2$ (1 $k_c$)</td>
<td>$2.0 \times 10^5$</td>
<td>N/m</td>
</tr>
</tbody>
</table>

INTERPRETATION OF RESULTS

Impact pressure distribution

Figure 4 shows a comparison of the measured peak impact pressure distributions along the rigid barrier for flows with varying solid fraction. The solid fraction by volume was varied as 0 (test RL), 0.2 (test RSL20), 0.4 (test RSL40), and 0.5 (test RSL50). Reference lines are shown for...
comparison with existing design recommendations from China (SWCB 2005; MLR 2006), Canada (Hungr et al. 1984; VanDine 1996), and Japan (Watanabe 1981; NILIM 2007). The peak pressure shown as the pressure coefficient ($\alpha$) from Eqn. 1. A horizontal reference line is also shown to highlight the uniform impact distribution with flow thickness $h$ that is generally assumed in international guidelines.

Results reveal that the measured pressure distributions can be characterised using triangular pressure distributions. It is also evident that $\alpha$ is dependent on the solid fraction of the flow. With an increasing solid fraction, a triangular distribution is more pronounced and $\alpha$ increases. The increase in $\alpha$ is attributed to static loading at the base of the barrier from granular deposits during the impact process. The wedge-like granular deposit is called a dead zone (Fig. 5). This dead zone serves two purposes, firstly it contributes a static loading concurrently with dynamic loading. Secondly, the dead zone redirects the momentum of subsequent flow vertically along the barrier face. The redirection of momentum is crucial for reducing the impact loading on the rigid barrier.

A comparison of measured pressure profiles show differences with design recommendations from around the world. Most obviously, the shape of the pressure distributions are quite different. The triangular distribution measured from the centrifuge tests are quite different compared to the uniform distribution assumed in Eqn. 1. More importantly, the formation of a dead zone for debris flows is a key aspect of solid-fluid interaction with the barrier that cannot be captured using Eqn. 1. Another key difference between the measured results and existing design recommendations is that $\alpha$ values can exhibit a disparity of up to 2 times. Most concerning of all is that there is a very wide range of $\alpha$, although generally on the conservative end of the spectrum, that appear to be mutually inconsistent with each other. It is clear that the further research is warranted to improve the characterisation of impact with the consideration of solid-fluid interaction.

Influence of fluid viscosity on impact

Figure 6 shows the influence of viscosity on the peak impact pressure. The peak impact pressure is represented using $\alpha$ from Eqn. 1. The target Fr range, 3 to 4.5, in this parametric study is for the most part dynamically similar. The typical range of viscosity for natural debris flows ranges from 0.001 to 0.1 Pa·s (Iverson 1997). Simulations clearly show that viscous shearing effects for debris flows have an insignificant effect on the macroscopic flow dynamics. The insignificant contribution of viscous shearing in altering the flow dynamics is consistent with that reported by Choi et al. (2015b) for small-scale flume tests studying the mobility of single-phased flows. Furthermore, results demonstrate that the pressure coefficient of each viscous flow falls around unity. By contrast to the two-phase flows (Fig. 5), viscous flows lack a solid component, and thus their pressure coefficients are generally quite similar. It can also be deduced that effect of viscous shearing alone has little influence on the dynamic response of a flexible barrier.
Fig. 4. Peak impact pressure profiles

Fig. 5. Impact kinematics analysed using PIV (test RSL50)
SUMMARY

Centrifuge experiments and numerical simulations modelling the interaction between debris flow and barriers were discussed in this extended abstract. Contrary to existing design approaches, which treat the flow macroscopically, it is imperative to consider the interaction between the solid and fluid phases to properly estimate the impact pressure distribution acting on the barrier. The pressure coefficient ($\alpha$) used in momentum-based design approaches is dependent on the solid fraction of the flow. It is also evident that the wide range of recommended $\alpha$ values in literature is not only mutually inconsistent but highly-conservative. In some guidelines, the recommended $\alpha$ values are almost twice as large as that measured from the centrifuge experiments. Furthermore, the effect of viscous shearing alone has negligible influence on $\alpha$. This further corroborates that the design on barriers against debris flows, more specifically $\alpha$, is fundamentally dependent on the solid volume fraction of the flow.

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REFERENCES


Song D, Ng CWW, Choi CE, Kwan JSH & Koo RCH (2017) Influence of debris flow solid fraction on rigid barrier impact. (submitted to *Canadian Geotechnical Journal*).


White DJ, Take WA & Bolton MD (2003) Soil deformation measurement using particle image velocimetry (PIV) and photogrammetry. *Géotechnique* 53(7) 619-631