The paper was published in the proceedings of the 10th International Conference on Physical Modelling in Geotechnics and was edited by Moonkyung Chung, Sung-Ryul Kim, Nam-Ryong Kim, Tae-Hyuk Kwon, Heon-Joon Park, Seong-Bae Jo and Jae-Hyun Kim. The conference was held in Daejeon, South Korea from September 19th to September 23rd 2022.

Physical Modelling in Geotechnics

Influence of interstitial fluid on debris flow mobility: An experimental study

A. Bhatta & C.W.W. Ng
Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, HKSAR, China

C.E. Choi
Department of Civil Engineering, The University of Hong Kong, HKSAR, China

ABSTRACT: Estimation of debris flow dynamics is essential for the mitigation of debris flow hazards. The flow dynamics of biphasic mixtures are strongly influenced by their rheology but has received little attention. An experimental study was carried out to investigate the influence of interstitial fluid rheology on debris flow mobility in a 3.3 m long flume with 200 mm in width and 500 mm in height. Mixtures of sand with four different combinations of clay-water mixtures as the interstitial fluid were examined. Three dimensionless numbers, specifically the Froude number, Reynolds number and dimensionless yield stress were used to characterise flow dynamics.

Keywords: debris flows, rheology, flow propagation, energy dissipation.

1 INTRODUCTION

Debris flow is a steep creek hazard (Hungr *et al.,* 2014). Its flow mobility depends on the bed slope, solid concentration, fluid rheology, shear rate (Iverson *et al,* 1997).

Previous studies have suggested that the composition of a debris flow has a strong influence on its mobility, and thus the resulting impact mechanisms of protection structures. Ng *et al.* (2016) investigated the impact mechanism of dry granular and viscous flows and reported that dry sand flow exhibits a progressive deposition mechanism with a dead zone. In contrast, viscous liquid flow exhibits a vertical-jet like impact mechanism. Furthermore, physical tests conducted using dry granular flows (Faug, 2021) and water-sediment mixtures (Armanini *et al.*, 2020) show a conflicting dependence of the impact mechanism on the Froude number. Faug (2021) reports granular jump model for granular flow with Froude number larger than 5. On the contrary, Armanini *et al.* (2020) reports formation of jet for water-sediment mixture with Froude number larger than 3. Choi *et al.* (2015) investigated the flow behaviour for dry granular and water flows and concluded that Froude number of dry sand and water flows depends on whether energy dissipates from boundary shearing or in combination with internal friction. Based on the physical and numerical study of clay-water slurries, Jing *et al.* (2018) concluded that yield stress governs runout distance and viscosity governs lateral spreading. Nevertheless, the effects of the interstitial fluid rheology of on debris flow dynamics has yet to be elucidated.

This study aims to investigate the effects of interstitial fluid rheology on the debris flow mobility and flow dynamics. A series of flume tests are conducted, and the properties of the experimental debris flow are characterised along the flow length using dimensionless numbers.

2 PHYSICAL MODELLING

A laboratory flume is used to investigate the influence of interstitial fluid on flow mobility. Figure 1 shows the flume, which is 3.3 m long with a flow channel of 2.8 m and a storage container of 0.5 m. The flume is 0.2 m wide and 0.5 m high with transparent Plexiglas side walls and bed. The flume can be inclined to any desired angle and is equipped with instrumentation for flow velocity and flow depth measurement.

2.1 Scaling

Dimensionless numbers are routinely used in studying scale dependent processes by establishing similarity conditions between model and prototype length scales, timescales, and stress scales (Butterfield, 1999; Iverson, 2015). In debris flows, these dimensionless numbers are based on key physical parameters of the flow (Iverson, 2015; Zhou and Ng, 2010). Since the aim of this study is to investigate the influence of interstitial fluid rheology on flow mobility, three key dimensionless numbers are considered: Froude number, Reynolds number and dimensionless yield stress.

Froude number (Fr) (Eq 1) is the ratio of flow inertia and gravitational force (Choi *et al.,* 2015) or flow velocity and celerity (Chow, 1959). For sloping channel, velocity along the channel (v), depth perpendicular to the channel (h) and slope perpendicular component of

gravity ($g\cos\theta$) is used to calculate Froude number. Froude number is frequently used in physical modelling of debris flow to characterise flow dynamics and impact mechanisms (Choi *et al.* 2015; Faug, 2021; Armanini *et al.,* 2020). Hübl *et al.* (2009) reported that natural debris flows have Froude number ranging between 0.5 and 7.6.

$$Fr = \frac{v}{\sqrt{gh\cos\theta}} \tag{1}$$

Table 1. Test programme.

Test ID	Fluid: Clay (% by volume)	Fluid: Water (% by volume)	Solid (% by volume)
C1	5	95	36%
C2	10	90	
C3	15	85	
C4	20	80	

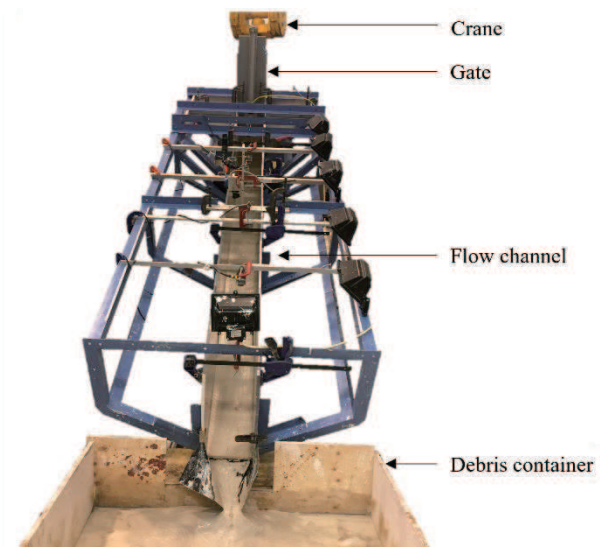

Fig. 1. Front view of flume model

Reynolds number (*Re*) defines whether the flow is governed by inertia or viscous stress (Eq 2; where ρ is flow density, R is hydraulic radius and μ_f is fluid viscosity). For open channel flows, laminar flow occurs when *Re* is less than 500 and turbulent flow occurs when *Re* exceeds 2000 (Chow, 1959).

$$Re = \frac{\rho v R}{\mu_f} \tag{2}$$

Dimensionless yield stress (N_{yield}) (Eq 3) is the ratio of fluid yield stress (τ_y) and basal shear stress (Shu and Zhou, 2006) or ratio of plug height and flow depth (Le Bouteiller *et al.*, 2021). N_{yield} describes the propensity of a yield stress fluid to flow under shear stress. $N_{yield} = 0$ refers to flow with no yield stress; N_{yield} between 0 and 1 suggests the formation of plug flow as the fluid flow occurs; $N_{yield} > 1$ implies that the driving shear stress is insufficient to make the yield stress fluid to flow from rest. In the case of moving fluid, $N_{yield} > 1$ arrests the motion of the fluid flow. For any flow-like landslide, initial N_{yield} evolves from a value less than unity and ultimately reaches to 1 (Coussot 2014) if the flow is not obstructed.

$$N_{yield} = \frac{\tau_y}{\rho g h \sin\theta} \tag{3}$$

2.2 Test setup and programme

Debris flow is modelled with a dam break initiation by opening a gate allowing 30 kg debris material to flow along the channel at an inclination (θ) of 26°. Five cameras are used to capture flow kinematics and determine spatial variation of flow depth and velocity along the flume. Four different clay-water compositions are used to model four different interstitial fluid rheology. The interstitial fluid rheology is measured with a rheometer and fitted with Herschel-Bulkley model. Toyoura sand at 36% by volume concentration is used as solid fraction. The test programme for this study is shown in table 1.

3 RESULTS

3.1 Frontal velocity and maximum flow depth

Figure 2 shows measured frontal velocity (v) and maximum flow depth (h) for the test with sand and 5% clay-water mixture (Test C1). The frontal velocity is determined from the videos captured by the top view cameras and maximum depth is obtained from the videos captured by the side view cameras. The frontal velocity and maximum flow depth are evaluated for a section of the flume located between 0.5 m and 2.5 m from the gate. The flow velocity and flow depth measurements obtained from video analysis are averaged across a window of 0.1 m. These averaged flow velocity and flow depth values are then used in subsequent dimensionless analyses.

The flow front velocity increases and maximum flow depth decreases as the flow propagates farther from the gate. Potential energy of the debris material drops and gets converted into kinetic energy as the flow progresses downstream. The drop in potential energy does not fully get converted into kinetic energy as some part of the energy gets dissipated due to internal and boundary friction shearing (Choi *et al.,* 2015). The flow depth decreases with distance from gate due to flow spreading along the channel as previously observed by Choi *et al.* (2015).

The flow front velocity and maximum flow depth are used to scale experimental debris flow using dimensionless numbers and compare mobility of flow with different interstitial fluid. Similar approach is used to obtain spatial variation of flow front velocity and maximum depth along the flume length in all other tests.

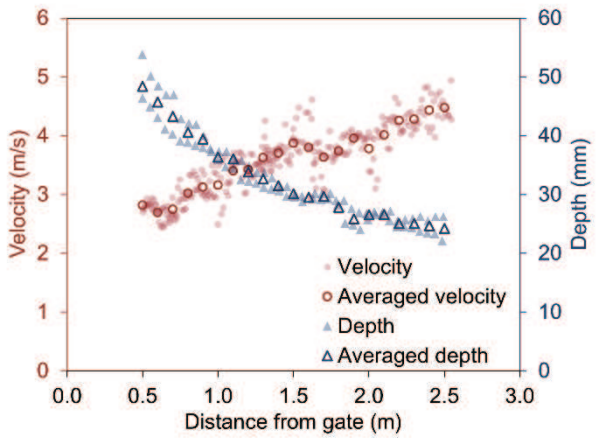

Fig. 2. Variation of flow front velocity and maximum depth for debris with 5% clay-water as interstitial fluid (Test C1).

3.2 Comparison of key dimensionless numbers

Figure 3 shows the change in three dimensionless numbers along the channel length for all four test cases. The fitted lines for each case are also plotted for clear visualisation. For each test, Fr>1 i.e., the flow is governed by inertia (Fig 3a). The Froude number increases for all test cases as the flow travels along the channel. However, the rate of increase in Froude number differs depending on the composition of the interstitial fluid. The increase in difference in Froude number from 0.8 to 2.2 as the tested flows travel 2 m downstream highlights the influence of interstitial fluid on flow mobility.

Figure 3b shows the change in the Reynolds number along the channel. Since the Reynolds number can vary several orders of magnitude (Chow, 1959), the Reynolds number is plotted on a log scale. It can be observed that the flow with 20% clay-water mixture (Test C4) as the interstitial fluid lies in transitional regime while all other mixtures are in turbulent regime. Based on figures 3a and 3b, all flows except test C4 are supercritical-turbulent (Chow, 1959).

Figure 3c shows the change in dimensionless yield stress in log scale along the flow channel. Increasing the dimensionless yield stress along the flow channel is due to flow thinning, which reduces the applied shear stress. All tested flows exhibit an exponential increase in dimensionless yield stress with increase of propagation distance. Flow characterisation using the above three dimensionless numbers show that inertial stresses are governing the dynamics of sand-clay-water mixture flows.

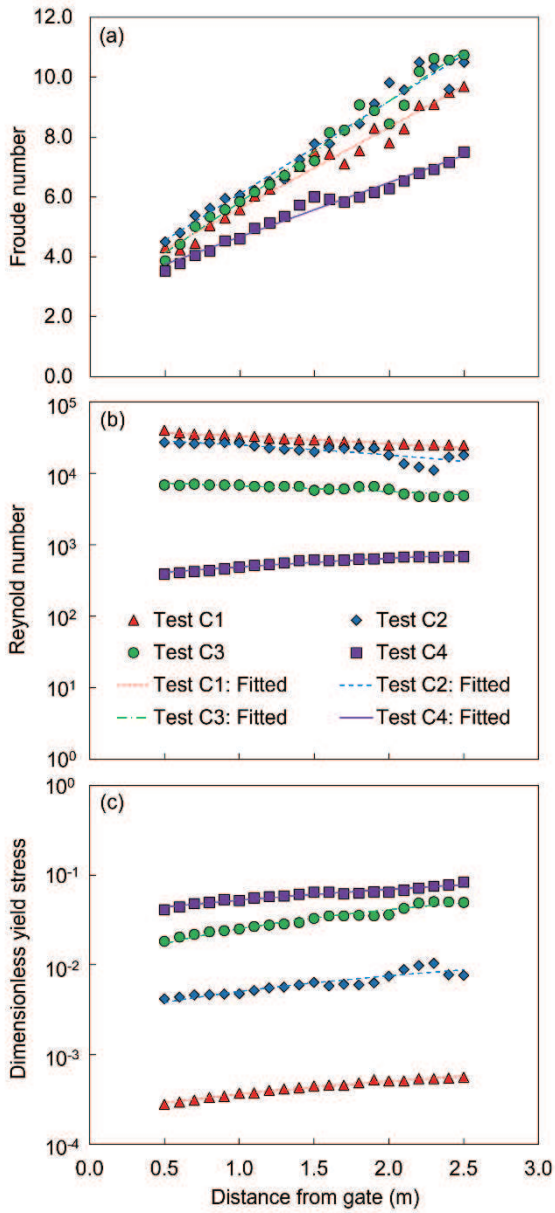

Fig. 3. Flow characterisation along the channel length using (a) Froude number, (b) Reynolds number, and (c) Dimensionless yield stress.

3.3 Normalised energy and energy dissipation

In addition to three dimensionless numbers, the normalised energy (E_{norm}) is used to investigate the change in calculated energy ($E_{calc,}$ Eq 4) along the channel length. The normalised energy is defined such that it becomes unity at a sloping distance of 0.5 m from the gate for all four tests. The calculated energy at any location is the total head at that location. The total head is the sum of elevation, pressure head and velocity head (Eq 4). The datum for elevation head is located at a sloping distance of 2.5 m from the gate with the flume inclined at 26°. Vertical component of flow depth (h) is used to calculate pressure head following the approach used in seepage analysis in infinite slope (Craig, 2004).

$$E_{calc} = \left[z + h\cos\theta + \frac{v^2}{2g}\right] \quad (4)$$

Figure 4 shows the variation of normalised energy for four tests along the channel length. The fitted lines for each case captures linear trend of energy dissipation along the channel. Test results show that the normalised energy of sand-clay-water mixture in general decreases with increase in clay content. This added reduction in normalised energy can be attributed to higher viscous dissipation for the fluid with higher Reynolds number (Fig 3b). The influence of clay concentration in tests C1 and C2 is not obvious and test C1 is observed to have higher dissipation compared to test C2. This is because the fluid density decreases with decreasing the clay concentration, and the solid grains settle more quickly, and shear frictionally compared to interstitial fluid with higher clay concentration. It is found that for test C4, (i.e., 20% clay-water mixture as interstitial fluid) 54% of the initial energy is lost during the flowing process down the channel.

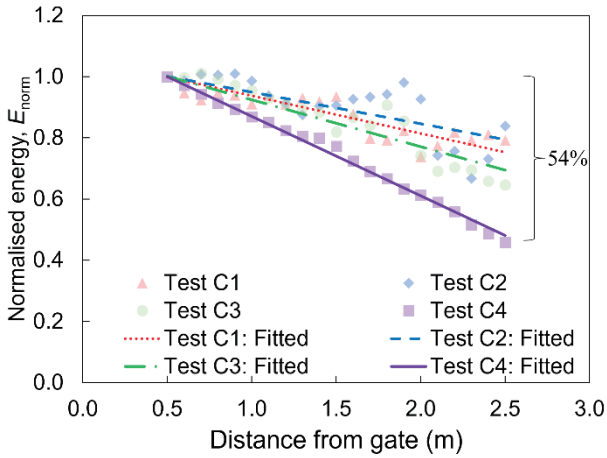

Fig. 4. Variation of normalised energy along the channel length.

4 CONCLUSIONS

Inertial stresses dominate the dynamics of debris flow compared to fluid viscous stress and gravitational stress. Reynolds number and dimensionless yield stress vary exponentially during flow propagation downslope. The difference in Froude number widens along the flow length which highlights the influence of interstitial fluid rheology on debris flow mobility.

The interstitial fluid rheology affects energy dissipation during flow propagation. In fact, sand-clay-water mixture with 20% clay concentration can lose around 54% of energy while travelling 2m distance.

Future research is required to further verify and expand the possibility of characterising debris flow dynamics based on interstitial fluid rheology.

ACKNOWLEDGEMENTS

The work described in this paper was supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (AoE/E-603/18). A. Bhatta acknowledge support from the Hong Kong PhD Fellowship scheme provided by the RGC of HKSAR, China.

REFERENCES

Armanini, A., Rossi, G. & Larcher, M. 2020. Dynamic impact of a water and sediments surge against a rigid wall. *Journal of Hydraulic Research.* 58(2), 314-325.

Butterfield, R. 1999. Dimensional analysis for geotechnical engineers. *Géotechnique* 49(3), 357-366.

Choi, C. E., Ng, C. W. W., Au-Yeung, S. and Goodwin, G. R. 2015. Froude characteristics of both dense granular and water flows in flume modelling. *Landslides* 12(6), 1197-1206.

Chow, V. T. 1959. Open channel hydraulics McGraw-hill. *New York*, 26-27.

Craig, R. F. 2004. *Craig's soil mechanics*. CRC press.

Faug, T. 2021. Impact force of granular flows on walls normal to the bottom: Slow versus fast impact dynamics. *Canadian Geotechnical Journal*. 58(1), 114-124.

Hübl, J., Suda, J., Proske, D., Kaitna, R. & Scheidl, C. 2009. Debris flow impact estimation. In *Proceedings of the 11th International Symposium on Water Management and Hydraulic Engineering, Ohrid, Macedonia*, vol. 1, pp. 1.

Hungr, O., Leroueil, S. & Picarelli, L. 2014. The Varnes classification of landslide types, an update. *Landslides* 11(2), 167-194.

Iverson, R. M. 1997. The physics of debris flows. *Rev.Geophys.* 35(3), 245-296.

Iverson, R. M. 2015. Scaling and design of landslide and debris-flow experiments. *Geomorphology* 244, 9-20.

Jing, L., Kwok, C. Y., Leung, Y. F., Zhang, Z. & Dai, L. 2018. Runout scaling and deposit morphology of rapid mudflows. *Journal of Geophysical Research: Earth Surface* 123(8), 2004-2023.

Le Bouteiller, C., Chambon, G., Naaim-Bouvet, F. & Mathys, N. 2021. Hydraulics and rheology of natural hyperconcentrated flows from Draix-Bleone observatory, French Alps. *Journal of Hydraulic Research*. 59(2), 181-195.

Ng, C. W. W., Song, D., Choi, C. E., Liu, L., Kwan, J. S. H., Koo, R. & Pun, W. K. 2017. Impact mechanisms of granular and viscous flows on rigid and flexible barriers. *Canadian Geotechnical Journal* 54(2), 188-206.

Ng, C. W. W., Choi, C. E. & Goodwin, G. R. 2019. Froude characterization for unsteady single-surge dry granular flows: Impact pressure and runup height. *Can.Geotech.J.* 56(12), 1968-1978, 10.1139/cgj-2018-0529.

Shu, J. & Zhou, J. G. 2006. Characteristics of a hydraulic jump in Bingham fluid. *Journal of Hydraulic Research.* 44(3), 421-426.

Zhou, G. G. & Ng, C. W. 2010. Dimensional analysis of natural debris flows. *Canadian Geotechnical Journal* 47(7), 719-729.