The Rosetta Stone Project – Integrating experimental results on debris flow mechanics across the scales: first results

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Abstract

Debris flows are an increasing global hazard. However, despite separate advances in the geotechnical engineering, fluid mechanics, granular physics, and earth sciences communities a holistic understanding of the mechanics of these complex flows remains elusive. The "Rosetta Stone" international debris flow experimental network (2017-2020) was established to address these shortcomings. The project aims to conduct physical tests with common material characteristics, informed by monitored field events, that will lead to improved numerical models to enhance societal safety. Advantage is taken of the carefully developed field monitoring and / or experimental apparatuses available at five institutes – these involve the Illgraben debris flow field monitoring site in Switzerland, a large scale indoor flume for experiments up to a cubic metre, two small scale flumes, including one designed for transparent soil for internal flow investigations, a large vertical rotating drum for steady flows and transitions, and a wide rotating drum for unconfined flows and roll wave development. Tests are being conducted using identical materials on particle sizes distributions that range from fully monodisperse (single sized particles) to well graded. Results are being shared and interpreted according to the different paradigms adopted within each network discipline (namely, geotechnics, geophysics, geology, fluid mechanics, and granular physics). Final results will be communicated via an open-access repository in order to enable better prediction of debris flow behaviour by improved validation and calibration of numerical models. This paper focuses on the initial set up and arrangement of the network and preliminary results in terms of velocity profiles for the monodisperse case.

1 INTRODUCTION

Debris flows are a common and particularly hazardous type of rapid landslide (Hungr et al., 2001). They occur in most hilly or mountainous regions of the world, triggered typically when loose sediment is entrained by rain or meltwater. Both likelihood of occurrence and consequences may increase in future years as climate changes and populations expand into upland and hillslope areas.

The behaviour of debris flows is extremely complex. This is due both to segregation of particle sizes, where the larger particles push to the surging front during downslope motion (Johnson et al. 2012), and to size effects, where larger flows are able to develop and sustain pore fluid pressures that can reduce interparticle friction and hence produce longer runout (Iverson, 2015). While there are many competing numerical models that attempt to account for these influences, these are poorly validated due to a lack of high quality, quantitative data from realistic, well-defined materials. The models lack predictive power and are unreliable for assessing risk and hazard under a changing climate and land use.

The objective of this network is to bring together a diverse team of international research groups in civil engineering, physics and geological disciplines to perform a combined physical study of debris flow material behaviour at different scales by which validation and calibration of numerical models may be achieved, creating a "Rosetta Stone" for communication between the disciplines.

2 METHODOLOGY

2.1 Context

From an analysis of debris flows at the Illgraben site in Switzerland (which represents the field scale), we consider the project in terms of decreasing experimental scales (Iverson, 2015). Hydraulic, granular and geotechnical scaling principles have been used to produce appropriate parameters for common inputs to the experiments.

2.2 Particle size distributions

Particle size segregation is a key mechanism that results in the high mobility of debris flows, however, for simplicity it is common to utilise uniform particle gradings in many experimental campaigns (Choi et al. 2014; Larcher et al 2017; Leonardi et al, 2015). Few experimental studies have compared directly the behaviour of monodisperse and well graded flows conducted in the same apparatus and across different apparatuses. This combined study aims to do this.

The research network commenced in August 2017 with a visit to the highly instrumented torrent site at the Illgraben in Switzerland. This torrent experiences annual debris flows with volumes of 50,000m^3 - 150,000m^3. Examination of debris flows at field-scale enabled a representative particle size distribution and fluid rheology to be selected to create a common "recipe" for the following experimental work.

In addition, and to enable validation of apparatuses along with calibration of newly installed sensors for sharing of techniques, a material with monodisperse (uniform) particle sizes has been selected to use for all the experiments. This material (Denstone 3mm ceramic beads by Saint-Gobain) has several advantages: (1) the material is identical (material, size and shape characteristics) in all tests across all apparatuses (except for the transparent flume housed at Sheffield which, necessarily, must use glass particles); (2) the material is somewhat rough so that re-use does not alter its surface properties, unlike as can occur when using glass ballotini; (3) particles are near-spherical so that results can be subsequently modelled using discrete element methods; (4) while monodispersity does not lead to true debris flow behaviour and inherent evolution of material response (due to lack of particle size segregation), the constitutive behaviour remains very simple throughout the flow and enables direct comparison to both previous experimental work and the simplest of numerical models for validation purposes.

2.3 Fluid

The content and constituent of fluid is a key variable in determining the mobility of debris flow (Kaitna et al., 2017, Parsons et al., 2001). Once again, it is relatively common to carry out experiments on dry flows in order to simplify the experimental set up and interpretation, however, fluid saturation aids the promotion of pore pressure and dampens particle collisions (Armanini, 2013). Hence, from both a continuum and discrete modelling perspective, the inclusion of fluid in experimental work on debris flows is crucial. In this combined study, both dry and fluid saturated flows are being considered. In general, water is used as the fluid, with oil being used for the glass-fluid transparent flows. In the tests described in this paper, only dry results are given.

2.4 Mass

The flow mass can greatly determine the mobility of a debris flow. Larger flows travel further by dint of both the actual volume of material involved and by the accumulation and maintenance of elevated pore pressures within the flow during motion, which serves to reduce frictional particle contacts and potentially aid lubrication. The different scales at which experiments are conducted in the network enables the issue of flow mass to be considered carefully – both for tests conducted within a specific apparatus and between experimental configurations.

In future work, the role of size of flow on mobility and on pore pressure development will be examined with respect to fluid saturated flows. In the experiments described in detail here, dry masses are used.

2.5 Measurements

A crucial element of this study is that the data collected should be comparable. Specifically, flow heights, velocity profile distributions, deposit geometries, basal pressures and solid concentrations are being recorded – where applicable in each experiment.

2.6 Field to lab scale

2.6.1 Illgraben debris flow site

In the field of natural hazards research, the WSL is internationally known for a strong focus on understanding the flow processes of rapid mass movements such as avalanche and debris flow processes through collection of data at full-scale field research sites, such as the Illgraben debris flow observation station. The Illgraben is a highly instrumented torrent site located in the canton of Valais in Switzerland. This torrent experiences annual debris flows with volumes of 50,000m^3 - 150,000m^3.

WSL installed a new force plate for the Illgraben channel at end of February 2019 – the previous one (McArdell et al., 2007) having been destroyed by a debris flow event. The new force plate is 2 m long (in the flow direction), 4 m wide, and weighs about 3 tons. It allows the vertical and horizontal forces in the flow to be measured at up to 9600 Hz. It has been dimensioned to measure flows as deep as 5 m.

Figure 1. Illgraben check dam and monitoring point, Switzerland – Rosetta Network team on right for scale.

Approximately 65 debris-flow and similar debris-flood events have been observed passing over the force plate. The old Illgraben observation station (force plate operational between 2004 – 2017) was somewhat less reliable than the new version, so some of the data sets are incomplete and e.g. front velocity, flow depth, or video recordings are missing. From the 65 events, the median depth at the front of the flow is 1.5 m (range: a few dm up to 3 m), the median front velocity is 3.4 m/s (<1 up to 10 m/s), and the median Froude number is 0.85 (<0.2 up to 3).

Based on a combination of previously published grain size analyses from the Illgraben and on photogrammetric analysis of images, Uchida et al (2019) estimate that the median particle size is at least 10 mm, although qualitative estimates of the front of the flows (e.g. McArdell et al., 2007) suggest a value somewhat larger than 10 mm. Analysis of the video recordings indicate that particles with diameters exceeding 3 m are regularly transported at or near the front of many events.

2.6.2 Queen's University large scale flume

Large scale instrumented flume tests are being conducted at Queen's University on flow volumes most closely approximating field-scale debris flows (up to 1 m^3 source volume). The 2.1 m wide flume has a 6.8 metre long inclined portion at 30° from horizontal and a 33 m long horizontal runout section (Bryant et al, 2013) – Figure 2.

Transient flow profiles have been determined via multiple high speed camera placements along the transparent walls. Outputs include front velocity and flow velocity profiles. The basal fluid pressures are measured with a network of ten sensors. Finally, the deposit geometry is captured using terrestrial LiDAR.

Figure 2. Large scale flume at Queen's University, Kingston.

2.6.3 University of Sheffield small scale flumes

At smaller scale, this research uses two flumes at Sheffield University. The first (2 m long and 100 mm wide) is designed to enable different basal roughness to be easily altered and, in the project experiments, uses the same basal roughness and scaled geometry as the Queen's University flume and the same materials as for the other flumes and drums (Figure 3).

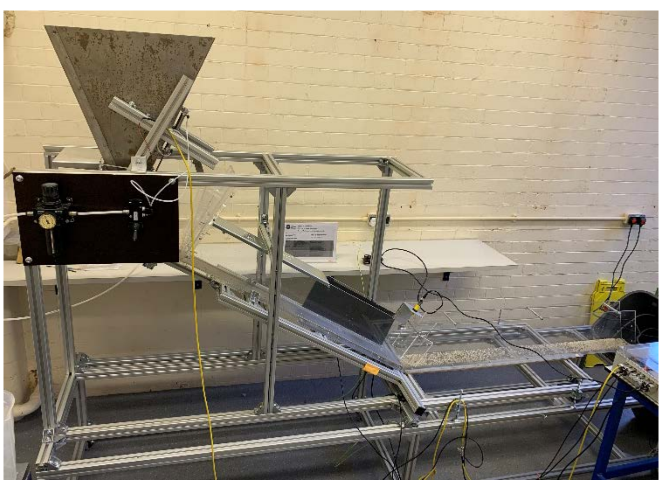

Figure 3. General arrangement of small flume, University of Sheffield.

The second flume is a transparent soil debris flow flume (2 m long and 150 mm wide) (Sanvitale & Bowman, 2017) which uses glass particles and an optically matched oil to replace soil and water allowing internal particle mechanisms to be viewed away from the sidewall influences. This is case however, the fluid used has a higher viscosity (16 cSt) and lower density (0.846 g/L) than water, while the glass spherical particles have a different surface roughness than either Denstone or real soils. To examine the influence of these differences on the behaviour of the flows, three flow conditions will be examined to compare with the other network flow apparatuses: dry flows, fluid saturated flows with water, and with oil.

Test outputs from both apparatuses include: external and internal (for the transparent flume) flow velocity profiles, granular temperature, particle solid concentration, basal pore pressure, deposit geometry and distribution.

2.6.4 BOKU large rotating drum

The large 2.43 m diameter, 0.45 m wide rotating drum at BOKU Vienna enables steady and non-uniform flows at different velocities as the rotational speed is altered (Kaitna and Rickenmann, 2007). Flow masses can be varied up to approximately 50kg and can either be dry, partially dry or fluid saturated.

Test outputs include flow geometry, basal normal stress and pore fluid pressures as well as the torque at the axis of the drum. Additionally, the flows are recorded through the transparent side wall with a high-speed video camera at a frame rate of 1500 fps.

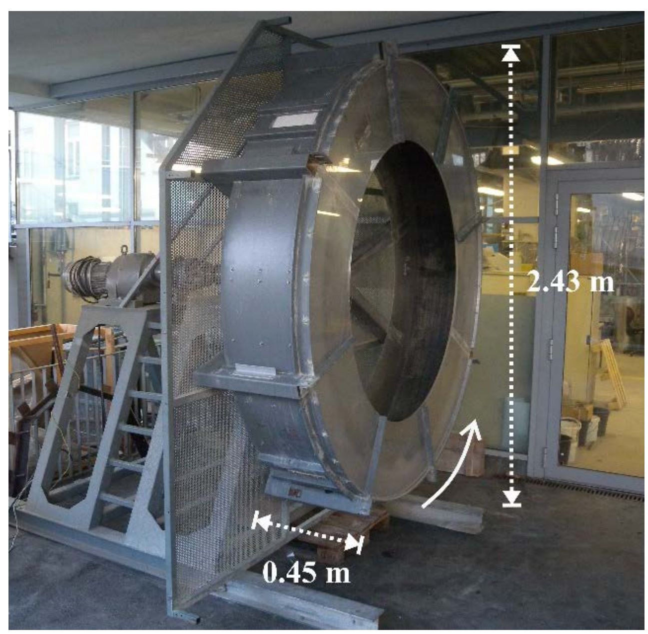

Figure 4. Rotating drum setup at IAN-BOKU, Vienna.

2.6.5 Durham University rotating drum

A new 2 m wide, 2.5 m diameter rotating flume apparatus has recently been commissioned at Durham University. In contrast to the rotating drum at BOKU, flows are not constrained laterally so that a 3D profile develops at the surface.

The geometry assures relatively simple interpretation and enables the study of roll waves and surges to provide sensitive tests of numerical models (Kowalski and McElwaine, 2013).

3 RESULTS

3.1 Experimental work carried out to date

3.1.1 Monodisperse – comparison of velocities

Our preliminary study shows the importance of experimental arrangement and size on the outcomes derived from experiments on simple monodisperse dry granular flows.

Figure 5 shows the results of five tests carried out on the Queen's large flume, with volumes from 0.2 m^3 to 1.0 m^3 and three tests on the Sheffield small flume, set at the same slope angle of 30°, with masses from 0.001 m^3 to 0.004 m^3 (1L to 4L) using the same 3 mm diameter particle materials and a relatively low basal roughness due to the use of an aluminium base in both experimental suites. Data are presented in terms of recorded velocity against flow height for the peak flow height, taken at the downstream end of each flume.

In Figure 5, data are presented in terms of v/v_{mean} to enable focus upon the profile of the velocities. Figure 6 then shows normalized velocity distributions according to normalization by √(gh).

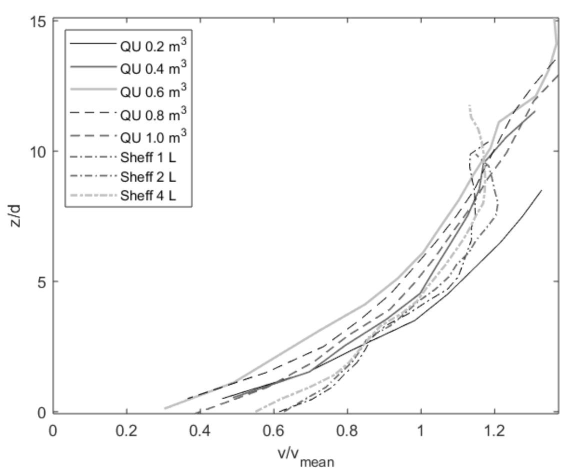

Figure 5. Dry flows of 3mm ceramic particles for flume tests. Downstream velocity profile at sidewall normalized by mean flow velocity against flow height normalized by particle size.

A number of observations can be made: First, Flow thicknesses vary from approximately 8 to 15 particle diameters with most flows having normalized thickness z/d between 10 and 14, across both flumes. Second, in terms of v/v_{mean} against nomalised flow height z/d, the data from the two flumes are quite consistent with a concave upward profile at peak flow and a degree of slip at the base. There is a greater proportion of slip velocity at the base of the flume for the small scale experiments (approximately v/v_{mean} = 0.6) than for the large flume experiments (v/v_{mean} = 0.4). In addition, the flow profile is more plug-like with less shearing in the small flume flows than for the larger flume.

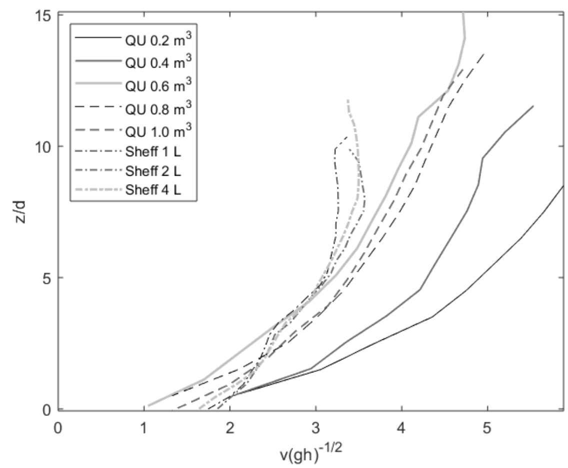

Figure 6. Dry flows of 3mm ceramic particles for flume tests. Downstream velocity profile at sidewall normalized by √(gh) against flow height normalized by particle size.

The use of √(gh) to normalize velocity results (i.e. Froude scaling) shows resultant v/√(gh) values that are relatively high for the small volume flows (0.2m^3 ad 0.4 mm^3) conducted on the large flume at the measurement point (values are approximately 2 at the base, peaking to between 5 and 6 at the top of the flows). For the larger flows on this flume, the equivalent values range from approximately 1 at the base to 4.5 at the top. For the small flume flows, data are quite consistent across the three volumes considered with v/√(gh) ranging from 1.8 at the base to around 3.5 at the top; which are consistent with data derived from other physical experiments, being slightly larger than typical values from the field (up to Fr <=2 based on front velocity, Hübl et al., 2009). This reflects the somewhat more "plug-like" behaviour of these flows in comparison to the greater shearing that occurs in the flows conducted on the larger flume.

3.1.2 Drum flows

Experiments were also conducted on the IAN-BOKU drum using dry Denstone monodisperse mixtures of 3 mm ceramic beads at mean velocities of 0.2, 0.4, 0.6, 0.9 and 1.2 m/s, with test masses ranging between 12 kg and 49 kg.

The velocity profiles for the largest mass at 49kg are given in Figure 7, normalised by the rotational base velocity. The flow profiles are notably different from the flume flows, presenting a concave downwards aspect that is reminiscent of flows over erodible beds. In this case, the flow thickness varies with rotational speed (or base velocity, which is a proxy for slope angle) from 16 to 21 particle diameters, with thinner flows occurring at higher base velocity.

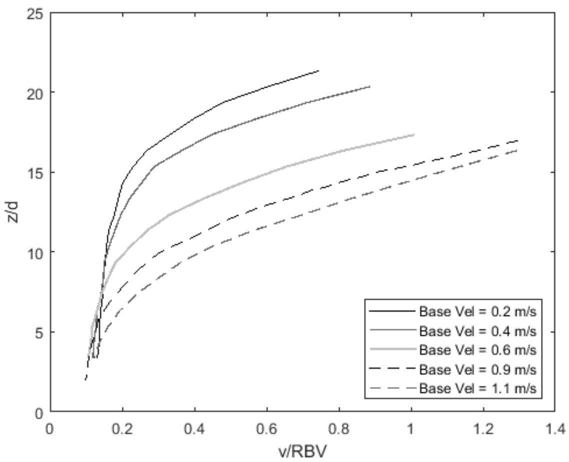

Figure 7. Dry flows of 3 mm ceramic particles for drum experiments. Velocity profiles for 49kg normalized by rotational base velocity.

3.2 Future work

Results will be interpreted numerically using models at both micro (local) and macro-scale (bulk). This should enable comparison between local modelling schemes espoused by granular fluids researchers, and those in which approximations are made as most commonly used by practising engineers.

Questions to be answered include: How well can scaled experiments represent large scale debris flows? What assumptions can be made to simplify their analysis towards hazard modelling and engineering decision making? What complex processes should we not ignore?

Finally, direct comparison with numerical models associated with straight conveyors and flumes will place the rotating drum flows in relation to more "simple" geometric configurations, closing the loop on how these different flows behave and how we can best described them.

4 ACKNOWLEDGEMENTS

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