Gravity-Driven Monodisperse Avalanches: Inertial- to Frictional-Dominated Flow

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Abstract
A set of experiments on avalanches—each one with a single particle size (monodisperse)—is presented. Experiments were performed with different flume lengths, inclinations, and roughness, for different avalanching masses and particle sizes. A transition from an inertial behavior to a frictional dominated one is observed at a particle size of 1 mm, in all cases. Taking into account the energy dissipated during each step of the avalanching process, we inferred a scaling function that allowed us to collapse all experimental data into a single curve. The transition from an inertial to a frictional dominated regime is explained in terms of the increasing number of particles per unit mass with decreasing particle size, for which the external shear activates a growing number of internal degrees of freedom in which the energy is dissipated. Molecular dynamic numerical simulations showed consistency with the suggested hypothesis of higher dissipated power for larger number of avalanching particles (smaller grain size).

Keywords Runout · Granular flows · Granular avalanches

1 Introduction

Rock avalanches have been studied intensively because of the intrinsic risk they represent for human settlements (Holub and Hübl 2008) and due to their importance in shaping the landscape (Geertsema et al. 2006). Model avalanches using monodisperse (Martínez et al. 2007; Goujon et al. 2003), bidisperse (Goujon et al. 2007; Bartali et al. 2020), and polydisperse grain size distributions (Bartali et al. 2015; Thornton et al. 2006) are fundamental in understanding parameters such as the runout of geological events and how these parameters are influenced by particle size, particle texture, and morphological characteristics.

Many experiments on rock avalanches at the laboratory scale, together with theoretical efforts, attempt to emulate, predict, and get scaling laws that allow us to compare different results and to interpret natural events (Pouliquen 1998; Roche et al. 2011; Campbell 2002). From the experimental point of view, flume lengths ranging from 1 m (Cagnoli and Romano 2010) up to 90 m (Iverson 1997), equipped with optical, load, and pressure sensors, as well as high-speed cameras, have been used in gathering valuable information on the flow kinematics and rheology (Bartali et al. 2012; 2015). These avalanche experiments were performed using masses as low as 0.030 kg of grains (Cagnoli and Romano 2010) up to 30 Tonnes (10 m³) of dry and wet materials (Iverson 1997), both natural as well as analogue (Manzella and Labiouse 2009).

Theoretically and numerically, the use of the continuous-medium hypothesis for solving the mass and momentum

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conservation equations should lead, in principle, to equivalent descriptions of the system. However, as the scale of the description approaches the micro-scale corresponding to a single grain characteristic length, the continuous-medium hypothesis becomes meaningless, as it cannot describe collisions among individual particles (the hypothesis of a continuous medium is opposed to the discrete nature of granular media). In numerical calculations using molecular dynamics, the computing power demands grow as a power law of the linear size; for instance, in 3D, halving the linear size of the particles requires eight time more particles, and, therefore, eight times more computing power, for the same mass. An analogous situation appears if we try to increase the complexity of the particle’s shape. From the theoretical point of view, the so-called Savage and Hutter model has been put forward by Kolumban Hutter since 1989 and further improved in collaboration with many other authors (for a review see Hutter 2005). It consists of a set of hyperbolic partial differential equations designed to predict the motion and deformation from initiation to runout along a concomitantly determined avalanche track along a prescribed topography.

Even though the theoretical model helps to simplify or reduce the number of parameters needed for describing granular flows, they could cause oversimplification in cases where new emerging phenomena occur. Examples of such emerging phenomena are stick–slip (Bartali et al. 2015) vs smooth sliding, fragmentation during the flow, or segregation by sizes during the avalanche, so natural events remain poorly represented by their model analogues.

Experimental studies on monodisperse-sized model avalanches focus mainly on the velocity of particles moving in the flow—either those forming a gas-like phase (saltational particles at the avalanche front) or those in dense phases of the flow—and on the ordering acquired due to the uniform regular shape of model grains used in experiments (Drake 1990; Jalali et al. 2002; Campbell 2006; Goujon et al. 2007). On the other hand, segregation by kinetic sieving, in which small particles percolate towards the bottom in between large ones during motion, is the most notorious effect due to size differences among particles, and has been already investigated (Makse et al. 1997). In bidisperse granular avalanches, the dynamic behavior of constituent particles cannot be scaled up in any simple way (Gray and Ancey 2009). Theoretical and experimental work has shown that “size does matter”, since the scaling properties of the Hertz–Kuwabara–Kono model lead to a reduction of the restitution coefficient with decreasing particle size (Antypov et al. 2011). In this regard, the question arises on how particle size affects the behavior of the avalanche, as a whole, and its corresponding runout. Runout values larger than those expected from the simplest model of a solid sliding down a slope with friction have been observed and explained in terms of the dispersive stresses exerted by the fragmentation process and the differential spreading of the rear and frontal parts of the avalanche (Davies 1999). Such long-runout values are always related to fine particles, which are produced during the avalanche development by fragmentation and which, in turn, act as a lubricant among large particles, enhancing the vibrational fluidization of the granular avalanche. The large distance traveled by some observed landslides (Shreve 1987 in Drake 1990) has been attributed to a Leidenfrost-like effect (Eshuis et al. 2005), in which the avalanche body floats over a saltational layer of grains excited by the intense shear of the first layer in contact with the slope; however, this was never observed in the carefully controlled experiments performed by Drake (1990).

This simple question on how the particle size affects the runout of a dry granular flow is systematically addressed in this work on avalanches. We found a transition from an inertial-dominated regime (long runout) to a frictional-dominated regime (short runout) for which internal friction, rotation, and drag excited by the external shear dominates the flow. Furthermore, in this paper, we develop the basic concepts to understand the observed long runout of some geophysical granular flows in terms of their mobility, which in turn depends on the number of dissipative degrees of freedom that are activated during the motion.

2 Experimental Set-Up

We built two identical flumes 15 cm wide and 2.5 m long, as schematically shown in Fig. 1, followed by a deposition area 1.2 m wide and 1.8 m long that allows the sedimentation of longer runout avalanches. The first flume base and the deposition area was built using smooth medium-density fiberboard (MDF) sheets (15 mm thick) covered by vinyl white paint to give them some roughness. The walls of both sections were made with 6-mm-thick, 15-cm high, tempered glass.

The second flume base was covered by a very smooth Formica sheet, maintaining the same deposition area as described above. The slope of each flume was set to be variable, ranging from 0° to 50°, while the deposition area was maintained horizontal. The flume is supported by an open frame metallic structure 50 cm x 50 cm x 2.5 m.

The granular material starts running with null initial velocity, after the removal of a barrier placed at different positions (1 m, 1.5 m, and 2 m) from the break point, to simulate different flume lengths and to impart different gravitational potential energy to the granular mass. A set of two high frame rate (120 fps) video cameras (SONY HDR-XR150) complemented the system.

We used rough irregular granular volcanic material (andesite from the Nevado de Toluca volcano in Mexico,
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with density of 2.6 g/cm³) carefully sieved to obtain nine different grain sizes from 0.0625 to 16 mm mean grain diameter. We used standard sedimentological sieves specified in Wentworth (1922). All the material used was collected in the same area to ensure that the grain textural features, mineralogy, and their density were almost the same (Fig. 2b). The total mass of each granular class was 4 kg, and the calculated number of particles, in 4 kg of material, is shown in Fig. 2a. To assure uniformity in grain size, we sieved the same material twice. A grain size class is comprised of grains between two specific sizes determined by the mesh aperture. In our case, we used 62.5 µm, 125 µm, 250 µm, 500 µm, 1 mm, 2 mm, 4 mm, 8 mm, and 16 mm classes during our experiments.

3 Method

We performed experiments with dense, dry granular avalanches with the flume tilted 27°, 32°, 37°, and 42°. For each slope, we started the avalanches at 1 m, 1.5 m, and 2 m (upstream) from the break point. We released 4 kg, 2 kg, and 1 kg of granular material for each combination of slope and initial starting point, as can be seen in the flowchart shown in Fig. 3, to study the effect of initial potential energy, grain size, and mass on the avalanche’s runout. We also defined several parameters relating the distance traveled by the granular mass, until it eventually slows down and stops, forming the deposit on the horizontal deposition area, as can be seen in Fig. 1. The quantity called “run from break point” (RBP) is the distance from the break point of the flume to the tip of the massive deposit (disregarding all scattered particles). The total flow run is the distance traveled by the grains from the movable gate on the flume plus the RBP. The runout is the sum of the projection on the horizontal plane of the portion of the flume traveled by the grains and the RBP.

In Fig. 4, we show the different deposits (and their RBP values) obtained by an avalanching mass of 4 kg of grains traveling 2 m down the flume, which was tilted 37° with respect to the horizontal deposition surface for eight different granulometric classes. In that picture, the regression of the deposit toward the break in slope, as the grain size diminishes, is quite clear. Large particle deposits (at left side

Fig. 1 Flume schematic and variable definitions. Total flow run (red dashed line) is the sum of flume length (FL) plus the run from break point (RBP). Runout is the sum of \( H_{\text{max}} \sin\alpha \) and RBP (color figure online)

Fig. 2 a Number of particles calculated, of each grain size, contained in 4 kg of material. b Example of the grains (binarized from a picture) used to perform the experiments. Finest particles (< 1 mm) were omitted in the picture due to their small size

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of the Fig. 4) are produced at long distances from the breaking point, while small size particles produce deposits standing partially on top of the incline of the flume (right side pictures of Fig. 4). The difference in RBPs, which is 73 cm for avalanches with grain sizes between 16 and 1 mm, becomes only 16 cm for avalanches with grain sizes between 1 mm and 62.5 microns. For avalanches with particles smaller than 1 mm, the deposit material accumulates over the flume in larger proportion as the particle size used is reduced. In other words, the rearward part of the avalanche is deposited and travels shorter distances from the starting point as the particle size is reduced.

It should be remarked that many geometric characteristic parameters of the deposit, such as the runout, flow run (distance from the gate to the front of the deposit along the avalanche trajectory), the length of the deposit, the RBP, or its average height, are related in a complex way to the rate at which kinetic energy is acquired and lost during the

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**Fig. 3** Flowchart of all experiments performed

**Fig. 4** Examples of typical deposits obtained for an avalanche of 4 kg of material running down a flume 2 m long, 0.15 m wide, and tilted 37°. The grid is 5 cm by 5 cm. The yellow arrows show the RBP of each deposit. The number on the upper left corner of each picture is the grain size of the avalanching material (color figure online)
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13 flow development. In this sense, the position of the front of the deposit is always related to the above-given geometrical parameters of the deposit, reaching shorter traveled distances as the flow becomes more dissipative. In other words, as the flow dissipates more energy, with respect to the initial gravitational potential energy, during its way down the flume, the granular material is deposited at shorter positions and the total flow run and the tail of the deposit acquire smaller values. The deposit could be partially located on top of the lower part of the flume, as shown in right side pictures of Fig. 4 for 0.5, 0.25, 0.125, and 0.0625 mm grain sizes, and its shape could be complex.

The length of the deposit, its height profile, and frontal and rearward shapes acquire complex shapes that are difficult to characterize and are hardly reproducible. Due to these facts, we focused on the behavior of the position of the front of the avalanche deposit, which shows a very good reproducibility for different values of particle size, flume inclination, flume length, and inclination and roughness of the flume. Moreover, the position of the front of the deposit or RBP, represents a good measure of the residual energy at the end of the slope.

For each experiment, we focused on the total flow run and the run from break point (RBP), which, for both, were larger for the coarsest particles than for the smallest ones. In all cases, we disregarded all the scattered particles in front of the massive deposit. It is worth noting that the deposit consisted, of a distal cloud, of scattered particles and a closer dense body of the deposit, for which particles are clustered together, forming a massive body everywhere thicker than a single monolayer (see Fig. 4 for 4 mm in size where the distal scattered front is marked).

To facilitate the measurement of the main features of the deposit, a 5 cm by 5 cm grid was painted over the sedimentation or deposition area. All measurements were made using image processing. Each set of experiments was performed at least five times to verify reproducibility. Error bars in Fig. 5 represent the standard deviation of data. It can be seen that the maximum errors are close to 10% in only two cases, while in most other cases, they are so small that they cannot be seen in the plots, showing good reproducibility.

The realization of the experiment proceeds as follows: the angle of the flume is selected and fixed, and then the granular material is loaded at the selected distance from the break point, held in place by a gate that can be removed manually. Since the buffer memory of the camera is only 4 s, a micro-switch connected to the gate triggers the camera when the gate is removed, starting the avalanche and allowing video recording of the event. These high frame rate (120 fps) videos are later converted into a sequence of frames and used to measure the velocity of the flow front (at the brake in slope). The velocity of the flow front is determined by the distance traveled by the front in sequential frames and dividing by the time between selected frames. A last set of experiments was performed replacing the rough-base flume by the one with a smooth Formica sheet and maintaining the deposition area with the same roughness, to determine the total flow run and the RBP changes due to different friction coefficients between the flume and the granular material or

![Fig. 5](image_url)

**Fig. 5** a Experimental results of mean total flow run obtained with the avalanche mass set to 4 kg and the flume length equal to 2 m. Error bars are the standard deviation obtained after repeating experiments five times for each grain size and for each flume tilt (most of them are smaller than the symbol showing the mean value). b Total flow run plotted as a function of the flow front velocity. The velocity is the mean value of the massive flow front (dense granular flow frontier) measured on the last 50 cm of the flume (up-slope from the break point). The mean values of the flow front velocity are determined after running five experiments of each grain size.
the effect of the basal friction coefficient of the flume on the mobility of the avalanche.

4 Results and Discussion

All the experiments presented in this section were performed by changing only one variable at a time, maintaining all the others as constant. We show and discuss in this section the most significant phenomenological results and present arguments of plausibility supporting our hypothesis to explain the observed phenomena for the different experimental conditions explored.

4.1 Constant Mass, Variable Flume Slope

This set of experiments was done releasing 4 kg of particles of each grain size (62 µm to 16 mm) with null initial velocity. The granular material was loaded at the top of the flume at a distance of 2 m from the break point, creating a monodisperse avalanche for each grain size. As can be seen in Fig. 5, the distance traveled by the avalanche from the starting point to the tip of the deposited body—hereafter, total flow run (see Fig. 1)—is a function of the particle size for all flume slopes.

In Fig. 5, the most striking feature is the appearance of a flowing regime change, shown as a sudden increase of the slope for all plots, around a particle size of 1 mm. This change of regime represents the most important finding of this experimental study and is a robust phenomenon as we will show. The trend of these plots, in which larger grains produce larger total flow runs, can be understood as a consequence of competing trends. On one hand, each particle acquires kinetic energy in the gravity field, but on the other hand, part of this energy is lost due to mutual collisions and friction against the flume or other particles. The rate of change of the flow run with respect to the change in particle size for particles smaller than about 1 mm is always smaller than the rate of change for particles larger than 1 mm.

We propose the hypothesis that the regime change could be explained if the rate of kinetic energy acquisition from gravity, for particles larger than 1 mm, is greater than the rate of energy loss due to their mutual interactions (inelastic collisions and friction caused by the external shear), giving rise to an inertial regime. As the rate of kinetic energy acquisition becomes equal or lower than the rate at which energy is lost—for particles smaller than 1 mm—the avalanche behavior is dominated by internal friction until the flow will eventually halt (most of the time, for avalanches of small particles, a tail of particles is left deposited on the flume up-slope). For particles larger than 1 mm, the relatively small number of particles per unit mass and their higher mass (inertia) allows them to run faster (see Fig. 5b), leading to a gravity-driven inertial flow regime. On the other hand, for finer avalanches, the number of particles per unit mass is much larger and, consequently, their mutual interactions per unit time dissipate energy at a higher rate. As the particle size is reduced, the number of particles per unit mass grows, thus the kinetic energy acquired per unit time is rapidly dissipated by a much larger number of mutual interactions, leading to the development of a very low velocity flow (Fig. 5b).

The analysis of the plot in Fig. 5 reveals a smooth but clear transition in the behavior of the granular flows: the total flow run increases with particle size, obeying an exponential law, as can be seen from the straight lines that are linear fits (shown as a guide for the eye) to the corresponding experimental points in Fig. 5a, performed with the purpose of qualitatively showing the sudden increment in slope. In Fig. 5b, the change in the slope of the total flow run vs velocity of the front is even clearer since both axes, total flow run and avalanche front velocity, are linear, showing how large particles preserve much more energy for moving along the deposition zone after the end of the flume, and this excess energy grows faster with growing particle size.

4.2 Constant Mass, Variable Flume Length

These sets of experiments were performed to show that the initial potential energy of the granular mass does not modify the double regime of the flowing masses, which occurs when the slope of the total flow run vs grain-size curves changes at a grain size near to 1 mm. Particles were placed at three different points on the flume (2 m, 1.5 m, and 1 m) from the break in slope. The mass of each run was maintained at a constant (4 kg). In Fig. 6, we show the results corresponding to tilt angles 32° and 37° of the flume. As expected, the maximum distance traveled is proportional to the initial starting point of the avalanche. Comparing these plots with those shown in Fig. 5, it can be seen that the flow behavior is similar, showing that particles larger than 1 mm move in an inertial-dominated regime and finer particles move dominated by frictional forces in a more viscous-like manner. It should be noted that the slopes of the fits are very similar, as if, specifically, the curves were shifted vertically by the same amount as the difference between their respective starting points.

For clarity, we only show results corresponding to the flume tilted 32° and 37°, because the avalanche behavior for
4.3 Constant Flume Length, Variable Avalanche Mass

To study if the distance traveled by a granular flow depends on its mass, we performed a set of experiments modifying the mass of the avalanche, maintaining all other variables the same. If we compare the total flow run (Fig. 7a–c) for experiments performed with a tilt angle of 37° and a starting point set at 1 m, 1.5 m, and 2 m, it can be seen that all the values of the maximum distance traveled by the avalanche are almost the same for a given grain size, regardless the mass of the avalanche. The maximum difference in total flow runs, for masses between 1 and 4 kg, is less than 8%. Changing the avalanching mass fourfold causes a minor or insignificant change in the total flow run, keeping all the other parameters constant (grain size, flume length, and flume base, and deposit area roughness).

The transition from an inertial to a frictional dominated regime is still evident at grain sizes of about 1 mm. The fact that the total flow run is independent of the avalanche mass shows that the work done by frictional forces grows with the avalanching mass, as in the case of standard Coulomb’s dry friction between two sliding solid surfaces. However, one may have expected that the Coulomb’s dry friction coefficient between the avalanche and the flume would be reduced for smaller particles, and thus, so the work done by friction, producing larger values of the RBP as the particle size is reduced. This assumption goes contrary to our observations.

The fact that the total flow run is independent of the avalanche mass indicates that both acquisition and loss of energy are specific quantities (per unit mass), but there is no easy explanation of the dependence of the flow run on the particle size. Thus, an inherent internal mechanism dependent on the number of particles per unit mass is required to explain both: a flow run (a) independent of the mass but (b) strongly dependent on the number of particles per unit mass (particle size).

The proposed mechanism is that the number of dissipative inter-particle interactions (proportional to the number of particles per unit mass), excited by the external shear, accounts for the dissipated energy in a given time interval, and thus, this dissipated energy will be a specific quantity strongly dependent on particle size. Therefore, the total flow run will have the same dependence on particle size, but will be independent of the total avalanche mass. In this respect, our physical picture of the work done against dissipative forces in a granular flow is more closely related to the mechanism of energy dissipation in a viscous fluid (internal shear), than to that of the energy dissipated by a solid object sliding down an incline. In this sense, the power dissipated by inter-particle collisions depends on the number of these interactions per unit time and, consequently, on the number
of particles per unit mass. Therefore, the power acquired by gravity minus the power dissipated by internal interactions would strongly depend on the particle size, but not in the avalanche mass. Notice that the particle–particle interactions are excited by the shear with the flume (external shear).

4.4 Effect of Flume Roughness

We show here the effect of the flume base roughness (not changing the roughness of the deposition area) on the distance the avalanche can travel. It can be seen in Fig. 8 that, as expected, a smoother flume base offers a lower basal friction coefficient leading to a longer distance traveled by the avalanche.

Avalanches sliding over the Formica sheet have a longer total flow run compared to those moving over a rougher painted wood base, meaning that grains acquire more velocity before they encounter the break in slope. It is interesting to see that, regardless the flume slope (27° and 37°) and the very different roughness of the flume base, the distance traveled by the avalanche shows again an increment in its slope at a grain size near 1 mm.
4.5 Total Flow Run and Number of Particles of the Avalanche

Data in all the figures presented above show consistently that there is a change in the flowing regime of the avalanche when the grain size crosses the 1 mm size threshold. As it will be shown in Sect. 4.6, this is due to an increment in the energy that can be dissipated in a given time interval, for a given mass of particles, when they are small. Measuring the kinetic energy acquired by the flow will provide the change in gravitational energy minus the dissipated energy due to friction and internal collisions. Thus, the energy that has been dissipated during the avalanche flow, by a given mass of small or big particles, at the break point, can be evaluated by measuring the final velocity there.

In Fig. 9, the total flow run has been plotted as a function of the number of particles estimated for an avalanche of 4 kg for different particle sizes. As the number of particles grows, so does the number of inter-particle dissipative interactions (collisional or frictional processes) and, thus, the energy dissipated during the avalanche displacement. This leads to a decrease in the total flow run as the number of particles grows, which is in agreement with our hypothesis that the power dissipated by the avalanche should depend on the number of interactions (number of particles) and the intensity of such interactions (shear rate). The origin of the change in the growing rate of total flow run as a function of particle size is still obscure, but we conjecture that this change in slope should occur when the rate at which potential energy is transformed into kinetic energy approaches the power dissipated by these internal interactions. Thus, further theoretical and experimental works are needed to shed some light on the mechanisms involved behind this transition.

4.6 Numerical Simulations

We performed two-dimensional molecular-dynamic simulations of avalanching dumbbell-like particles consisting of two overlapped discs. Both discs have the same radii $\sigma$ and a center separation equal to the radius (see Fig. 8d). Normal dissipative interactions were calculated using the spring–dashpot model (Schäfer 1996), and tangential friction forces were obtained by a Cundall–Strack model (Cundall 1979). Coefficients of restitution for grain–grain collisions and for grain–flume collisions ($\epsilon_{gg}$ and $\epsilon_{gf}$) were 0.4 and 0.25, respectively. Static friction coefficients for grain–grain interactions and for grain–flume interactions ($\mu_{gg}$ and $\mu_{gf}$) were, respectively, 0.4 and 0.92, which were chosen in agreement with granite–granite and granite–wood values of such coefficients (see for example Lajtai and Gadi 1989).

Each simulation was run keeping the total mass and the flume inclination constant (4 kg and 39°, respectively). Ten simulations were performed beginning with 128 particles, having a disc radius of $\sigma=4$ cm. For the next simulations, the radii $\sigma$ were reduced by a factor of $\sqrt{2}$, i.e. the total number of particles was duplicated, thus keeping the total mass constant. Therefore, the rest of the simulations had a total number of particles of 256 ($\sigma=2.828$ cm), 512 ($\sigma=2$ cm), 1,024 ($\sigma=1.414$ cm), 2,048 ($\sigma=1$ cm), 4,096 ($\sigma=0.707$ cm), 8,192 ($\sigma=0.5$ cm), 16,384 ($\sigma=0.354$ cm), 32,768 ($\sigma=0.25$ cm), and 65,536 ($\sigma=0.177$ cm).

At the initial conditions, all the grains are placed in a square lattice above the flume and to the left of the vertical gate. The material is then released and allowed to drop and come to a complete rest in the space between the flume and the vertical gate (Fig. 10a). Afterwards, the vertical gate is removed (it is just eliminated from the configuration), and the released grains travel down the flume making the avalanche (Fig. 10b) until they fully stop their movement and come to rest on the horizontal deposition area (Fig. 10c).

During the avalanche process, the instantaneous total energy of the grains, i.e. the sum of potential energies and rotational and translational kinetic energies of all the grains was calculated every 10 ms. From this, the average dissipated power was calculated as the difference between two successive values of the total energy divided by the 10 ms time interval.

The results of the simulations are shown in Fig. 11, which shows a clear tendency for higher instantaneous dissipated power for smaller particle size, and so is strikingly consistent.
with the experimental results observed through total flow run measurements and the proposed model of increased dissipation with an increasing number of collisions per unit time, associated with the increased number of particles per unit mass. Even though we found good numerical evidence supporting our proposed hypothesis of higher dissipation capacity for a more finely divided granulate, due to limited computing power, we were unable to explore the behavior of particle sizes below 1 mm, since the computing time and storage capacity increases quadratically with the inverse of the radius, making the calculations unfeasible for very small particles, as can be inferred from the sequence of numbers of particles shown in Fig. 11.

4.7 Experimental Scaling

To rescale the experimental data in such a way that all curves collapse into a single one, we propose to plot the total flow run divided by the gravitational potential energy plus a linear combination of the angle $\alpha$ and the particle size $\phi$, represented by the function $\Lambda(\alpha, \phi)$ in Eq. 1. (see discussion below)

$$\Lambda(\alpha, \phi) = \frac{RBP + L \cos \alpha}{L \sin \alpha} + k\alpha + \phi,$$

where $RBP$ is the distance traveled by the avalanche over the horizontal deposition area, measured from the break in slope to the tip of the massive section of the deposit (disregarding scattered particles, Fig. 4); $L$ is the flume length, and $\alpha$ is the flume inclination, in radians. The values of $k$ and $\phi$ (in Eq. 1), which are dimensionless free parameters, were determined experimentally and are shown in Table 1. It can be noted, from Table 1 that the value of $k$ remains almost constant for each grain size, so we decided to use the mean

<table>
<thead>
<tr>
<th>Grain size (mm)</th>
<th>$k$</th>
<th>$\phi$</th>
</tr>
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<tbody>
<tr>
<td>16</td>
<td>0.026</td>
<td>-0.053</td>
</tr>
<tr>
<td>8</td>
<td>0.029</td>
<td>-0.122</td>
</tr>
<tr>
<td>4</td>
<td>0.028</td>
<td>-0.140</td>
</tr>
<tr>
<td>2</td>
<td>0.027</td>
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<tr>
<td>1</td>
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</tr>
<tr>
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<td>0.027</td>
<td>-0.244</td>
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<td>0.25</td>
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<tr>
<td>0.0625</td>
<td>0.027</td>
<td>-0.253</td>
</tr>
</tbody>
</table>

Fig. 10 Simulated avalanche a at the initial condition, b while progressing, and c at the final deposition. d Shows a sketch of the two-dimensional grains made by two overlapping discs of radius $\sigma$ with their centers one single radius apart. Frictional interactions and partially elastic collisions among particles were simulated using the Cundall–Strack and the spring–dashpot models, respectively.

Fig. 11 Total dissipated power as a function of time during the avalanche progress. The first total number of particles considered, $N=128$, corresponds to a particle diameter, measured along the longest axis—$D=12$ cm. For each successive simulation, the particle diameter is reduced by a factor of $\sqrt{2}$ down to $D=0.53$ cm ($N=65536$).

Table 1 Experimentally obtained values of the terms $k$ and $\phi$ used in the scaling law proposed
value which is 0.026 in the scaling function $\Lambda$, for all grain sizes.

We propose a physical interpretation for Eq. 1, in which the first term represents the fraction of work done by frictional forces along the total flow run with respect to the total energy acquired in the gravity field, while the second term, $ka$, represents the fraction of energy lost by the avalanche at the slope change. This energy loss will be higher for higher angles and can be interpreted as a “collective restitution coefficient” or the fraction of kinetic energy lost by the avalanche body during a “collision” event against the deposition zone. Finally, the last term, $q\phi$, corresponds to the fraction of work done by frictional forces at the deposition zone during deceleration of the moving body (already positively accounted for in the $RBP/L \sin \alpha$ term).

The term $ka$ that accounts for the energy loss at the break in slope depends not only on the slope change, but on the particle size as well, due to the fact that a larger number of dissipative interactions will be induced by the kink on a more finely divided avalanche material as discussed previously.

From a simple energy balance, the run from break point (RBP) times the internal dissipative forces (assumed constant for each grain size) should be equal to the kinetic energy lost at the deposition zone. This work is related to the rate at which energy can be dissipated into internal degrees of freedom, i.e. the material’s dissipating capacity under shear. On the other hand, the same internal frictional forces, inside the avalanche, are excited by the shear stress exerted by the flume on the avalanche. This shear stress is proportional to the component of the force perpendicular to the flume surface ($mg \cos \alpha$) and, consequently, the energy lost during the downwards motion is proportional to the length of the flume times the cosine of $\alpha$. In this sense, normalizing the total flow run with respect to the potential energy available at the beginning of the avalanche ($mgL \sin \alpha$), would lead the first term on the right-hand side of Eq. 1, to have a constant value for each particle size.

- Fig. 12a shows the data transformed by means of applying Eq. 1 for different tilt angles ($27^\circ$, $32^\circ$, $37^\circ$, and $42^\circ$) at constant mass and flume length (4 kg, and 2 m respectively) in which a reasonably well collapse of the curves can be seen. This set of experiments show the worst collapse among all different panels in Fig. 12; however, the maximum difference is still less than 10% which accounts for the robustness of our model represented by Eq. 1.
- Fig. 12b shows curves for inclination $32^\circ$, 4 kg avalanching mass, and flume lengths set to 1 m, 1.5 m, and 2 m.
- Fig. 12c show curves for inclination $37^\circ$, 4 kg avalanching mass, flume lengths set to 1 m, 1.5 m, and 2 m. $\Lambda$ values collapse much better in these Fig. 12b, c than for Fig. 12a, with the maximum difference between them being less than 4% for each grain size.
- Fig. 12d shows the same low difference (less than 4%) between curves corresponding to avalanching masses of 1 kg, 2 kg, and 4 kg, when the flume length is 2 m, 1.5 m (Fig. 12e), and 2 m (Fig. 12f).

Collapsed curves show that the transition from an inertial dominated to a frictional dominated regime (an increment in the slope in all plots) always takes place at the same particle size (1 mm), independently of the flume length (avalanche releasing point), the tilt of the flume, and the total flowing mass. Growing $\Lambda$ values with growing particle size is a clear indication that the number of frictional interactions or inelastic collisions per unit time, which is larger for finer particles, is responsible for this increase in dissipated power.

The proposed scaling function, when used for different roughness of the flume, fails to collapse the data into a single curve, due to the fact that the scaling function is proportional to the frictional forces exerted on the avalanche. Different shear stresses would lead to different internal frictional forces, and thus, non-collapsing curves, as can be seen in Fig. 13a, where we plot the scaling function to the experimental results shown in Fig. 8a (mass = 4 kg, flume length = 2 m and flume tilt = $27^\circ$). In Fig. 13b, we show the plot of the scaling function applied to results shown in Fig. 8b (mass = 4 kg, flume length = 2 m and flume tilt = $37^\circ$).

5 Conclusions

We studied the total flow run of dense, dry, monodisperse granular flows, using natural volcanic clasts, to better understand natural geophysical flows. We performed systematic, comprehensive measurements to find out the dependence of total flow run on particle size of the avalanching material, total flowing mass (1, 2, and 4 kg), and general parameters of the flume: tilt ($27^\circ$, $32^\circ$, $37^\circ$ and $42^\circ$), length (2, 1.5 and 1 m), and the flume base material (rough painted wood and smooth Formica).

We showed that the flow exhibits a robust transition in the sense that monodisperse avalanches containing particles with mean diameters larger than 1 mm move predominantly in an inertial-dominated regime, while granular flows containing only particles finer than 1 mm, move in a collisional- and frictional-dominated regime.

We attribute this transition to the dissipative capacity of the bulk material, that is, the instantaneous power directed to non-translational degrees of freedom within the avalanching...
Fig. 12 Proposed scaling law applied to experimental results obtained with the rough painted wood flume base. 

a Grain size from 62.5 μm to 16 mm mean diameter, constant mass (4 kg), constant flume length (2 m), and variable flume tilt (27°–42°).

b Grain size from 62.5 μm to 16 mm mean diameter, constant mass (4 kg), constant flume tilt (32°), and variable flume length (1 m, 1.5 m and 2 m).

c Grain size from 62.5 μm to 16 mm mean diameter, constant mass (4 kg), constant flume tilt (37°), and variable flume length (1 m, 1.5 m and 2 m).

d Grain size from 62.5 μm to 16 mm mean diameter, constant flume length (2 m), constant flume tilt (37°), and variable avalanche mass (1 kg, 2 kg and 4 kg).

e Grain size from 62.5 μm to 16 mm mean diameter, constant flume length (1.5 m), constant flume tilt (37°), and variable avalanche mass (1 kg, 2 kg and 4 kg).

f Grain size from 62.5 μm to 16 mm mean diameter, constant flume length (1 m), constant flume tilt (37°), and variable avalanche mass (1 kg, 2 kg and 4 kg).

Fig. 13 Proposed scaling law applied to experiments with different flume basal friction. 

a Comparison between the values of the scaling law applied to experiments performed with the smooth flume base (Formica) and the rough one (painted wood). Constant avalanching mass (4 kg), constant flume length (2 m), constant flume tilt (27°).

b Same as above, but the flume tilt was changed to 37°.
material (noise, heat, etc.), simply because the finer divided or fragmented the avalanching material is, the larger amount of degrees of freedom is added to the system. These degrees of freedom work as escape routes for energy injected by gravity. We hypothesize that when the dissipating energy rate, which depends inversely on particle size, approaches the value of the energy injected per unit time to the avalanche by gravity, the motion changes from being driven by gravity and inertia to be strongly determined by internal frictional forces (inter-grain frictional and inelastic collision interactions).

By doing an energy balance of the avalanche processes, from start up to deposition of the flow, we developed a scaling law that allows us to collapse all experimental results into a single curve. The scaling found is independent of the total mass of the flow, showing that the energy lost by the avalanche depends only on particle size. Furthermore, the transition prevails irrespective of the changes done to all other variables during the experiment, showing the robustness of the phenomenon.

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Compliance with Ethical Standards
Conflict of interest The corresponding author hereby declares that there is no conflict of interest whatsoever in this publication, relating either to any of the authors involved in the present research, or to any other third party.

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