Mobility of long-runout rock flows: a discrete numerical investigation

L. Staron
CNRS-Université Pierre et Marie Curie, Paris VI, Institut Jean le Rond d’Alembert, 4 place Jussieu, case 162, 75252 Paris Cedex 5, France.
E-mail: staron@lmm.jussieu.fr

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SUMMARY
In the perspective of studying the mobility and deposit geometry of long-runout flows, discrete numerical simulations of model granular avalanches over simple topography are performed. Analysing the behaviour of the ratio $H/L$ depending on the parameters varied in the simulations, we show its poor sensitivity to the topographic parameters, namely the initial height of the flowing mass and the slope. On the contrary, a correlation between $H/L$ and the frictional properties of the material is established. However, the existence of variations of the effective friction induced by the dynamics are not reflected by the value of $H/L$. As an alternative to the $H/L$ description of the flow behaviour, we propose a new scaling for the runout distance taking into account the lateral extension $L_0$ of the relief. Forming the normalized runout $L/L_0$, and defining the aspect ratio $a$ of the topography, we show the dependence of $L/L_0$ on $a$, thus generalizing previous analysis of Martian data. Analysing the correlation between the normalized runout and the front velocity for the numerical simulations, we show how $L/L_0$ depends both on the frictional properties of the material and on the dynamics of the flow. This result suggests the necessity of evaluating the lateral extension of the relief $L_0$ in the case of natural flows, in order to define a ‘horizontal travel index’ including the topography in an attempt to better understand the flow dynamics. Analysing the deposit for both simulations and real flow data we evidence a common behaviour suggesting that the geometric factors prevail over the differences in topography irrespective of the details of the flow context and conditions. We moreover assert the relevance of discrete simulations to the discussion of real cases.

Key words: Numerical solutions; Fracture and flow; Friction.

1 INTRODUCTION
In spite of the quantity of research dedicated to rock avalanches and more generally dry debris flows, the behaviour of those remarkable geological events remains a debatable and challenging issue. More specifically, the high mobility characterizing them and allowing the material to reach unexpectedly long runouts is so far essentially unexplained. While different mechanisms were proposed to account for this mobility, involving either fluidization by trapped air (Kent 1966; Shreve 1966) or by acoustic energy (Melosh 1979), lubrication by melted material (Erismann 1979) or more simply by a basal shear layer (Campbell 1989), none of them has been universally acknowledged as being fundamental in the dynamics of long-runout dry flows. An important obstacle for identifying the mechanisms of lubrication or fluidization is the suddenness and destructive power of geological flows which prevent monitoring and direct measurements. As a result, the corpus of data available mainly consists of accurate descriptions of the deposits. However, relating the shape of the deposit to the physical properties of the flow is not straightforward. Accordingly, the evaluation of the mobility can hardly be more then a crude geometrical characterization. Meanwhile, the great variety of material involved, the various triggering mechanisms and the differences in topography severely complicate attempts of generalization. In this context, little is known about dry flows mobility. The simplest approach to evaluate the latter is to identify it with the ratio of the initial height to the final runout distance, relying on the assumption that the potential energy initially available is dissipated by friction force along the runout irrespective of the path followed by the material. The effective friction thus quantified tends to obey an inverse correlation with the volume of the flowing material (Heim 1932). However, while this correlation remains unexplained, no other was clearly evidenced which could lay the basis of a physical understanding of flow mobility.

Considering the difficulties of studying real natural phenomena, simple models of granular flows are expected to bring important insights (Cleary 1993; Campbell 1995; Hutter & Kock 1995; Straub 1997; Hungr & Evans 2004). In this spirit, laboratory experiments of the collapse of columns of grains onto horizontal planes have brought forward a new scaling law for the runout distance (Balmforth & Kerswell 2004; Lajeunesse et al. 2004; Lube et al. 2004). This scaling only involves the aspect ratio of the initial column before collapse, and is robust against the column volume, the
grains properties and the nature of the substrate. Very interestingly, this scaling law could be successfully confronted with Martian data, and the landslides of Valles Marineris proved to behave in a way similar to the laboratory columns (Lajeunesse et al. 2006). However, these results cannot be easily applied to other landslides for which the aspect ratio of the initial mass prior to the flow is difficult to evaluate, and for which topography is likely to play a role. Yet, it seems reasonable to assume that similar scaling could be evidenced in the general case of a granular mass flowing over a simple relief.

In the perspective of studying the runout and deposit of dry flows in relation to simple scalings as observed in (Lajeunesse et al. 2006), discrete numerical simulations of model granular avalanches over simple topography are performed. The objective of this investigation is twofold. We first investigate whether the scaling shown in (Lajeunesse et al. 2006) can be generalized, and whether it can be related to the frictional properties of the flow, its dynamics and the characteristics of the final deposit. Meanwhile, we question the significance and relevance of the ratio $\frac{H}{L}$ as a quantification of the flow mobility. Then, systematically confronting our results to real flow data, we discuss the reliability of discrete numerical simulations to study geological cases.

The numerical method applied for this study is the non-smooth contact dynamics (Moreau 1994), which proved to reproduce accurately the behaviour of simple granular systems when confronted to laboratory experiments (Staron & Hinch 2005). We are thus confident that the results presented hereafter are a realistic picture of the behaviour of model granular flows. Details of the algorithm and of the numerical setup are presented in Section 2. At this stage, comparison with Martian (Quantin et al. 2004) and terrestrial (Nicoletti & Sorriso-Valvo 1991) data allow us to check that simulations are relevant to the discussion of real cases.

Characterizing the mobility of the flow is the subject of Section 3. We show the poor sensitivity of the ratio $\frac{H}{L}$ to the topographic parameters, namely the initial height of the flowing mass and the slope. Alternatively, we propose in Section 4 a new scaling for the runout taking into account the topography and generalizing the scaling observed in (Lajeunesse et al. 2006). Analysing the front dynamics in Section 5, we show that the new runout scaling is tightly related to the flow dynamics as well as to the frictional properties of the material. Evaluating an effective coefficient of friction $\mu_e$ from the work actually performed by the grains, we establish a correlation between $\mu_e$ and $\frac{H}{L}$. Meanwhile, we give evidence of variations in $\mu_e$ induced by the dynamics, hence not reflected by $\frac{H}{L}$. Analysing the shape of the deposit for both simulations and real flow data in Section 6, we evidence a common behaviour suggesting that the geometric factors prevail in the spreading dynamics irrespective of the details of the flow context and conditions. This suggests the first order role of geometric factors in flow behaviour. We moreover assert the relevance of discrete simulations to the discussion of real cases. The results are discussed in Section 7.

2 THE NUMERICAL EXPERIMENT

2.1 Algorithm and setup

Using the contact dynamics algorithm (Moreau 1994), we simulate the flow of 2-D rigid circular grains interacting through collisions and long-lasting contacts. The grains size is uniformly distributed in an interval such that the ratio of the maximum to the minimum diameter is 1.5. This slight size dispersity prevents the grains from obeying the unrealistic limit case of crystal-like geometrical ordering. However, it is not sufficient to discuss the influence of size segregation onto flow dynamics. In the following, $D$ denotes the mean grains diameter ($D = 0.05$ m).

The contact dynamics explicitly models the behaviour of each individual grains following the classical equations of the dynamics. The interactions between the grains consists of a simple Coulomb friction law involving the coefficient of intergran friction $\mu$, and of a hard-core repulsion law. Energy exchanges during collisions are controlled by a Newton coefficient of restitution $e$. While $\mu$ and $e$ are microscopic parameters characteristic of the contact scale, they control the ability of the flow to dissipate its energy at a macroscopic scale. Numerical experiments performed using contact dynamics (Staron & Hinch 2007) have shown that the influence of the value of $e$ is very weak as long as $e$ remains smaller than 0.8; for larger values, clouds of bouncing grains form, and we no longer are in the case of dense granular flows. Hence in the simulations presented in the following, $e$ was set to 0.5 and its influence was not studied. Varying the dissipative flow properties was achieved by changing the value of the intergran friction $\mu$, which was set alternatively to 0.01, 0.1 and 0.5. No interstitial fluid is considered at all, which implies that any effect of trapped air cannot be accounted for. Moreover, our simulations being 2-D, 3-D effects such as channelization or on the contrary lateral spreading are off discussion. The reliability of the contact dynamics to reproduce the behaviour of 2-D simple granular materials was tested against laboratory experiments involving sand, rice or glass beads. In the case of the column collapse experiment for instance, in which a mass of grains was allowed to spread and flow as a response to gravity, the scaling laws obtained experimentally and numerically were identical, as well as the dynamics of the flow; any differences could be attributed to the properties of the material: friction $\mu$, restitution $e$ and to a smaller extent, the shape of the grains (Staron & Hinch 2005).

The initial mass consists of a rounded heap of lateral width $l_w$ and height $h_w$ obtained by deposition of grains under gravity, and counting $N_g$ grains. While the number of grains was varied from 682 to 6251, the shape of the initial mass was kept unchanged, namely $l_w/h_w$ is constant and equal to 3. The topography over which the granular mass is allowed to flow is made of a circular ramp of radius $R_0$ followed by an horizontal plane. The whole length of the topography is made rough by gluing grains of diameter $D$ with the same properties $\mu$ and $e$ as the free grains. Alternatively, further simulations were performed where the circular ramp was left smooth in order to observe qualitatively the influence of roughness on the runout. This setup is in the following referred to as partial roughness. In any case no erosion processes is made possible. The topography is characterized by the height $H_0$ and the lateral extension $L_0$, and the initial slope $\theta_0$ (see scheme in Fig.1), thus obeying the following geometrical relations $L_0 = R_0 \sin \theta_0$ and $H_0 = R_0(1 - \cos \theta_0)$.

The initial height of the mass is denoted $H$, and corresponds to the initial position of the gravity centre. After the mass has flown down the topography and come to a rest, the farthest point of the deposit to the initial position of the front flow defines the lateral extension $L$, referred to as runout distance in the following. The evaluation of $L$ is done practically by excluding the particles rolling ahead independently of the main flow, and takes into account the coherent mass of touching grains only. It should be noted that different definitions are possible for the determination of both $H$ and $L$, depending on if one considers the initial position of the flow front, the initial position of the centre of mass, or the topmost point of the mass. While choosing $H$ from the initial position of the centre of mass seems logical as it scales like the initial potential energy, the definition of $L$ adopted in
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2.2 Comparison with terrestrial and Martian cases

The use of 2-D discrete simulation to study long-runout landslides proceeds from the assumption that in spite of important simplifications, the flow of model granular material under gravity presents essential features which keep a first-order role in real flows. Accordingly, the final deposit left by the flow is expected to share a common geometry in simulations and in nature. In order to check the validity of this assumption, we confront the simulations to real flows data. A set of 40 terrestrial rock-avalanches compiled in (Nicoletti et al. 2004), together with a set of 45 Martian landslides compiled in (Quantin & Sorriso-Valvo 1991), allow us for a systematic comparison with the geometrical characteristics of the numerical flows.

Illustration of a simulation is displayed in Fig. 2, where four successive snapshots of the granular mass flowing over the topography are represented together with the time-evolution of the grains mean velocity.

<table>
<thead>
<tr>
<th>Series</th>
<th>$\mu$</th>
<th>$N_g$</th>
<th>$H_0$ (m)</th>
<th>$\theta_0$ (deg)</th>
<th>Roughness</th>
<th>$g$ (m s$^{-2}$)</th>
<th>Number of runs</th>
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<td>Yes</td>
<td>–</td>
<td>30</td>
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<td>5016</td>
<td>18, 30</td>
<td>$\in [15, 85, 5]$</td>
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<td>–</td>
<td>30</td>
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<td>Partial</td>
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3 Flow runout and effective friction

3.1 Is $H/L$ a relevant characterization?

The main difficulty arising when trying to understand the dynamics of long-runout dry flows is to draw energy balance from the deposit features. Although the surface area $A$ covered by the flow was shown to be a valuable information for stress and thus dissipation evaluation (Dade & Huppert 1998; Iverson et al. 1998), the commonest way of evaluating flow dissipative properties remains the ratio $H/L$, namely the ratio of the initial height of the mass to the runout distance. From a purely geometrical argument, and in the absence of any decisive effect induced by the topography, it can
be argued that the area covered by the flow and the runout distance are somewhat correlated, so that the use of $L$ instead of $A$ is not necessarily a misrepresentation. For instance, Fig. 4 shows a clear correlation between non-dimensional runout and surface area in the case of Martian and terrestrial slides (in spite of the non-negligible dispersion of the data). However, identifying $H/L$ with the effective friction raises the problematic issue of the role of the path followed by the flow. Indeed, writing

$$mgH = \mu_e mgL,$$

$$\frac{H}{L} = \mu_e,$$

where $m$ is the mass of the flowing material and $\mu_e$ the associated coefficient of friction, proceeds from the assumption that the whole initial potential energy is left available for the horizontal flow, regardless of the topography, namely regardless of the details of the work actually performed by the flowing material. It seems however likely that these details are part of the mechanisms where by potential energy is converted efficiently into lateral motion. Accordingly, one would expect the measure of the effective friction to be sensitive to the conditions of the flow. Eventually, the key question is whether the ratio $H/L$ is a relevant characterization of the flow mobility.

In the following, we discuss the sensitivity of $H/L$ to the volume of the flow and to the topography.

3.2 Volume control

An aspect much discussed but poorly established is the sensitivity of the ratio $H/L$ to the volume $V$ of the flowing mass, known as the Heim dependence (Heim 1932). Although the subject of a lively debate, this correlation has however found so far no physical ground. Using numerical run from series D of the simulations (see Table 1), we form the ratio $H/L$ for avalanches involving from few hundredths to few thousands of grains $N_g$. The resulting dependence is plotted in Fig. 5 for different initial heights $H_0$, and for a fixed initial slope $\theta_0$. We observe a clear diminution of $H/L$ with the number of grains, namely the volume of the avalanche, in agreement with the Heim law. The range of values over which both $H/L$ and $N_g$ vary is too
Figure 5. Ratio $H/L$ as a function of the number of grains $N_g$ involved in the avalanches for $H_0=12$, 18 and 24, and $\theta_0=60^\circ$ (series D of simulations).

Figure 6. Ratio $H/L$ as a function of the normalized volume $V^{1/4}/H$, with $d=2$ for numerics and $d=3$ for terrestrial (Nicoletti & Sorriso-Valvo 1991) and Martian (Quantin et al. 2004) data. Numerical points represent all the simulations listed in Table 1.

Figure 7. Variations of the ratio $H/L$ for numerical simulations (series A in Table 1): (a) as a function of the initial slope $\theta_0$, (b) as a function of the initial height $H$, (c) as a function of $H$ compared with terrestrial (Nicoletti & Sorriso-Valvo 1991) and Martian (Quantin et al. 2004) data.

4 THE RUNOUT SCALING LAW

The fact that the ratio $H/L$ is ‘blind’ to the topography implies that it does not reflect at all the dynamics of the flow, that is, the process through which the initial potential energy is converted into spreading. Yet, the collapse experiments (Balmforth & Kerswell 2004; Lajeunesse et al. 2004; Lube et al. 2004) suggest that this energy transfer plays an important role in the control of the runout distance. In these experiments, the scaling obeyed by the runout was shown to be only dependent on the column initial aspect ratio, and to coincide with the way the vertical acceleration of the falling grains was re-injected in lateral spreading (Staron & Hinch 2005). Although the flow conditions are quite different from those presented in the present contribution, the collapse experiment still suggests that the runout distance is correlated with the way initial potential energy is made available to lateral spreading.

Transposed to our case, the aspect ratio of the initial mass $l_m/h_m$ seems no longer a relevant parameter. However, an aspect ratio can be defined for the topography, as the ratio of the initial height over the horizontal distance travelled by the flowing material before it reaches flat ground. Denoting $a$ this aspect ratio related to the topography, we have

$$a = \frac{H}{L_0}. \quad (3)$$

In other words, $a$ is only a function of the initial slope. Moreover, we define the normalized runout as $L/L_0$ which can be seen as a kind of ‘horizontal travel index’ measuring the relative distance travelled by the flow over flat ground. (As a remark, this quantity can be compared to the ‘excessive travel distance’ defined by (Hsü 1975), save that we do not presume of the properties of the incline over which the mass flows). It thus now seems possible to generalize the scaling law observed in (Balmforth & Kerswell 2004; Lajeunesse et al. 2004; Lube et al. 2004) and successfully applied to Martian slides (Lajeunesse et al. 2006). The variations of $L/L_0$ as a function of $a$ is reported in Fig. 8 for the series A, B and C of the simulations, for which the number of grains involved is constant (see Table 1). We observe the collapse of the data following a linear dependence:

$$\frac{L}{L_0} = \lambda(\mu)a, \quad (4)$$

3.3 Topographic control

To check the effect of the topography on the value of $H/L$, we focus on the series A of the simulations (see Table 1), namely we do consider variations of $H$ and $\theta_0$ only without introducing variations of material properties, volume, topography roughness or gravity. From Fig. 7(a), we observe that the initial slope $\theta_0$ of the topography plays a negligible role in the values taken by $H/L$. In the same way, Fig. 7(b) shows the poor influence of the initial height of the flowing material. For comparison, the influence of $H$ on $H/L$ for Martian and terrestrial flows is displayed in Fig. 7(c): no obvious correlation can be seen. It thus seems that the topography only poorly affects the values of $H/L$. As implicitly presumed in eq. (2) and established by (Heim 1932), $H/L$ is mostly independent on the path followed by the flowing material.
where the pre-factor of the linear dependence is a function of the frictional properties of the material, namely function of the value of the intergrain friction $\mu$. We obtain $\lambda(0,1) = 1.76$ in series A, $\lambda(0.01) = 3.2$ in series B and $\lambda(0.5) = 5.3$ in series C. We thus recover the scaling law observed in the collapse experiment (Balmforth & Kerswell 2004; Lajeunesse et al. 2004; Lube et al. 2004). Note that the scaling (4) can be simply rewritten

$$\frac{L}{L_0} = \frac{H}{H_0} = \frac{L}{H} \times a,$$

which leads directly to

$$\frac{L}{H} = \lambda(\mu).$$

In other words $L/H$ is independent on the topography as observed in previous section, and varies only with the grains properties.

For comparison, the data related to Martian slides and processed by (Lajeunesse et al. 2006) are reported in Fig. 8. We observe a very similar behaviour. At this point, one may question the origin of this similarity considering that the Martian scaling account for the initial aspect ratio $a$ of the flowing mass while the numerical scaling (4) accounts merely for the aspect ratio $a$ of the topography. We explain it simply by the fact that in the case of the Martian data, the flow results from cliff collapses, so that the initial aspect ratio of the flowing mass and the topography over which the material flow are intricately related. This is illustrated in Fig. 9. Hence, the aspect ratio defined in (Lajeunesse et al. 2006) can easily be interpreted in terms of topography. Inversely, trying to define an aspect ratio for the numerical systems leads us to compare the vertical projection of the sample dimension to its horizontal projection, which is only dependent of the initial slope of the topography, namely of $a$. It thus appears that the aspect ratio defined in (Lajeunesse et al. 2006) and in this work are not essentially different.

Another important difference between the Martian data and the numerical series A, B and C, is that in the latter cases, the volume of the flow is constant, while Martian landslides involve volumes varying between 60 and 9000 km$^3$. To clarify the influence of volume variations on scaling (4), we report the data points from the numerical series D on Fig. 8. We observe that volume variations induce deviations from the linear approximation, but that the latter remains relevant. Moreover, the relative deviations from the linear trend are comparable in the Martian and the numerical case. Certainly a detailed analysis of the influence of volume variation would be interesting at this point; it is however beyond the scope of this paper. At any rate, the concordance of behaviour between Martian and numerical data is in favour of the generalization of the runout scaling shown in (Lajeunesse et al. 2006) to any flow configuration.

Transposed to real flows, this result implies that the description of landslides in terms of runout and initial height is a reflection of the properties of the material only, irrespective of the flow conditions. By opposition, another important information is the proportion of the runout covered on flat ground, which we expect to be related to the flow dynamics. It implies the evaluation of the lateral extension of the relief whom the flowing mass was initially belonging to, which would give an equivalent of the length $L_0$ defined in our ideal numerical topography. Although no such measurements are available yet nor such scaling is evidenced in nature, our simulations suggest that the runout scaling is likely to be observed in the case of real geological flows.

Relating the runout scaling to the dynamics of the flow is the subject of the following section.

## 5 DYNAMICS OF THE FLOW

### 5.1 The front velocity

In order to filter out the fluctuations induced by the agitation of individual grains, we compute the front velocity $v_f$ as the mean velocity of the grains situated between the front position $x_f$ and the immediately following interval $x_f - 10D$. A example of the evolution of $v_f$ (normalized by the maximum value $v_{f,\text{max}}$ of $v_f$) as a function of the front position $x_f$ (normalized by $L_0$) is displayed in Fig. 10, for different values of $H_0$ and $\theta_0$. In each case, we observe a period of quick acceleration followed by a slower deceleration. While the influence of the initial angle $\theta_0$ on the final runout is obvious, the curves remains similar one to the other as long as $x/L_0 \lesssim 1$. We thus assume that the maximum velocity reached by the front $v_{f,\text{max}}$ gives a reasonable estimate of the kinetic energy available for the horizontal runout $L - L_0$ (namely the part of the runout covered on flat ground only) irrespective of the topography. To relate the runout to the flow energy, we plot the normalized horizontal runout $(L - L_0)/L_0$ as a function of $v_{f,\text{max}}^2/(gh)$ for all the simulations (Fig. 11). We observe the collapse of the data following a power
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5.2 The centrifugal acceleration

Considering the radius of curvature $R_0$ of the topography, one can expect non-negligible effect due to centrifugal acceleration, denoted $g'$ in the following. If we assume the mean velocity $v$ of the flowing mass to scale like $(gH)^{1/2}$, then $g'/g = v^2/(gR_0)$ scales like $(1 - \cos \theta_0)H/H_0$, that is, like $\simeq (1 - \cos \theta_0)$. In other words, the role of centrifugal acceleration becomes non-negligible compared to the role of gravity when the initial slope of the topography is steep enough. One question raised by the possibility of centrifugal acceleration playing a role, is the dependence of rock flows mobility on the absolute value of the gravity $g$. Indeed, is we stick to the simple friction model as written in eq. (2), we have to include an additional term standing for the centrifugal force which increases the apparent weight of the flowing mass. In other words, we should write, as a crude energy balance:

$$mgH = \mu_e (mg + mv^2/R_0)L,$$

where $g'$ is no longer simplified out. Since however the simple analysis above predicts that $g'/g$ depends only on the initial slope, the runout should remain independent of $g$. To check this, we performed a set of simulations with $g = 3.7 \text{ m s}^{-2}$, namely equal to the gravity of Mars (series E of simulations). As can be seen in Fig. 12, all parameters beside $g$ being equal, the value of $g$ does not affect the value of the runout beyond the amplitude of error bars, as could be expected. A similar behaviour is expected to hold for real flows.

5.3 Evaluating the effective coefficient of friction

For all simulations, we have access to the position and velocity of each grain in the course of time. Hence, keeping friction as the most likely dissipation process, we can compute an estimation of the effective friction properties of the flow from the details of the work performed by the weight of each grain and the centrifugal force they are subjected to. If we assume that the overall dissipation can be summarized in an effective friction coefficient $\mu_e$, than a possible approximation of the global energy balance is:

$$E_{p0} - E_{p\infty} = \mu_e \sum_i \left( \int_{x_{i0}}^{x_{i\infty}} m_i g dx_i + \int_{x_{i0}}^{x_{i0}} m_i v_i^2 dx_i \right)$$

where $E_{p0}$ and $E_{p\infty}$ are, respectively, the initial and final potential energy of the flowing material, $m_i$ is the mass of the grain $i$, $v_i$ its velocity, $x_{i0}$ and $x_{i\infty}$ its initial and final position, and where $dx_i$ and $ds_i$ are, respectively, its horizontal and curvilinear incremental displacement (i.e. displacement during a computational time step). Using relation 8, we estimate precisely the value of $\mu_e$ for all simulations listed in Table 1 (Note that $\mu_e$ is different in meaning and in value from the interparticle friction $\mu$, although dependent on it). We can then relate the runout distance to the actual effective friction properties of the flow.
here the sensitivity of properties of the grains, but also on the topography namely on the series show that the effective friction is not only dependent on the order equality $\mu$ for larger values of $\mu$ friction $(a)$ shows the approximation $H/L$ is indeed a reflection of the friction properties of the material, in agreement with the conclusion drawn in Section 4. However, in each series of simulations, namely for a fixed value of intergrain friction $\mu$ but for varying topography, $H/L$ shows no or little variations: as previously established, $H/L$ is essentially ‘blind’ to topography. Moreover, the variations of $\mu_e$ in each simulation series show that the effective friction is not only dependent on the properties of the grains, but also on the topography namely on the dynamics of the flow.

The variation of the ratio $L/L_0$ with $\mu_e$, reported in Fig. 13(b), show no obvious correlation. In the mean, $L/L_0$ takes smaller values for larger values of $\mu_e$. However, the most apparent feature is the range of values taken by $L/L_0$ for one given value of $\mu_e$: we observe here the sensitivity of $L/L_0$ to the variations of the topography.

6 SHAPE OF THE FINAL DEPOSIT

We finally characterize the shape of the deposit through its depth $h$ and its lateral extension $l$ (see Fig. 1). Relating $h$ or $l$ to the dynamics of the flow or to its dissipative properties is very uneasy, and no clear dependence can be evidenced. However, a purely geometrical tendency can be shown between the depth of the deposit and its extension depending on the volume involved in the flow and the initial height of the flowing mass (see Fig. 14). Although rather loose, this correlation nevertheless reflects the role that initial height and flow volume play in the spreading dynamics, even though this role still has to be clarified.

To check whether the correlation observed in Fig. 14 is relevant to real flows, a similar scaling is reported in Fig. 15 for Martian and terrestrial data. In these cases, the extension $l$ of the flow was identified with the runout distance $L$. The depth $h$ is simply taken as the total volume divided by the surface area of the slide. We observe a similar correlation with a relative collapse of the data compatible with a power law. The numerical points, also reported in Fig. 15, show a behaviour similar to the Martian and terrestrial data (although with a slope slightly smaller).

The conclusion that can be drawn from Fig. 15 is twofold. It first shows that in spite of the differences in context, material and topography, the spreading dynamics seems to obey a common organization, depending on the initial height and volume of the flow. This suggests the first order role of the geometry in the flowing behaviour. Then, the agreement between numerical and data point assert the fact that simple 2-D simulations can be relevant to the study of 3-D real cases in spite of the many simplifications.

7 DISCUSSION

In this contribution, we present the results of a discrete numerical study of granular avalanches and their mobility. Different series of simulations were carried out in order to include the influence on the runout of a large number of parameters: grains frictional properties, volume, substrate roughness, gravity and topography, the focus being set on the latter. Meanwhile, systematic comparison between simulations on one hand, and terrestrial and Martian data on the other hand (Nicoletti & Sorriso-Valvo 1991; Quantin et al. 2004) allows us to discuss the reliability of our numerical approach, and brings forwards new hypothesis for the behaviour of real flows.

We first analysed the behaviour of the ratio $H/L$ depending on the different factors varied in the simulations. We show its poor sensitivity to the topographic parameters, namely the initial height of the flowing mass and the slope. As well, $H/L$ proves to be independent of the gravity. On the contrary, a correlation between $H/L$ and the frictional properties of the material is established. These three results are in favour of an identification of $H/L$ with the effective friction associated to the flow. However, computing an effective coefficient of friction $\mu_e$ from the work actually done by the grains,
we show that this coefficient is sensitive to the topography, namely to the dynamics of the flow. The fact that $H/L$ is independent of the topography implies that it cannot reflect these variations of the effective friction induced by the dynamics.

As an alternative to the $H/L$ description of the flow behaviour, we propose a new scaling for the runout distance taking into account the lateral extension $L_0$ of the relief, and forming the normalized runout $L/L_0$. Considering the aspect ratio $a$ of the topography, we show the dependence of $L/L_0$ on $a$, thus generalizing previous analysis of Martian data (Lajeunesse et al. 2006). Analysing the correlation between the normalized runout and the front velocity for the numerical simulations, we show how $L/L_0$ depends both on the frictional properties of the material and on the dynamics of the flow. Accordingly, for one given material, or for materials of similar properties, the ratio $L/L_0$ only would allow to distinguish and discriminate between various flow occurrences. This result suggests that evaluating the lateral extension of the relief $L_0$ in the case of natural flows, in order to define a ‘horizontal travel index’ and include the topography in the description of the flow mobility, could help better understanding the flow dynamics. By contrast, the value of $H/L$ should be related to other parameters: volume, static friction, etc.

Finally, analysing the deposit for both simulations and real flow data, we show that relating them to the flow dynamics or frictional properties is not straightforward. Nevertheless we evidence a common behaviour suggesting the existence of a single mechanism prevailing in the spreading dynamics irrespective of the details of the flow context and conditions. This suggests the first order role of geometric factors in flow behaviour. We moreover assert the relevance of discrete simulations to the discussion of real cases.

Although the conclusions drawn in this contribution should be eventually confronted to real flow data, our numerical simulations bring a new insight in the problem of flow mobility by allowing to address quantitatively the role played by the relief, and allowing to investigate the existence of new relevant scaling to flow mobility. One key issue in the problem of long runout flows is the influence of more complex topographic features, as obstacles or abrupt slope transition, as well as fragmentation and erosion of the bed. Each of these aspects should be tackled in relation with the results presented here. One other important aspect is the influence of the volume of the flowing mass, and will be the subject of further work.

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