Mobility and topographic effects for large Valles Marineris landslides on Mars

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[1] Recent experiments on dry granular flows over horizontal plane bare some similarities with large Martian landslides observed in Valles Marineris (VM). However, Martian normalized runout are twice as large as those that observed in dry granular flow experiments. Numerical simulations on theoretical 2D and real 3D topographies reconstructed from remote sensing data show that slope effects significantly reduce the shift between experimental results and Martian observation. However, topography effects are not strong enough to explain the high mobility of Martian landslides. As a result, other physical and/or geological processes should play a key role into the dynamics of Martian landslides. A new mobility is defined that makes it possible to characterize the dynamics of the flow regardless of the geometry of the released mass and of the underlying topography.
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1. Introduction

[2] Thanks to orbital imagery, morphologies related to granular flows (landslides, debris flows, gullies...) were identified on Mars [*Lucchitta*, 1979]. Martian granular flows may be still active today [*Malin et al.*, 2006]. Former work highlights a very great mobility of large Martian landslides compared with terrestrial cases [*Lucchitta*, 1979; *McEwen*, 1989].

[3] Indeed, the behavior of these catastrophic events on Earth as well as on Mars is still poorly understood in spite of many experimental and numerical studies. In addition, water often takes part in the dynamics of these events on Earth [*Cruden and Varnes*, 1996; *Legros*, 2002]. On Mars, Valles Marineris (VM) provides a good paradigm to study different landslides in a similar geological context. Due to the basalt-like lithology at VM scale [*Bibring and Erard*, 2001], the rheological properties of landslides are thought to be homogeneous within VM. Studying these landslides contribute to an understanding of the dynamics of the landscapes and is expected to provide insight into the climatic conditions during emplacement at Amazonian Time [*Quantin et al.*, 2004b] as the potential presence of groundwater in liquid or solid phases.

[4] Former laboratory experiments have shown that the normalized runout ($\Delta L/L_i$) of a dry granular mass spreading on a horizontal plane is controlled by a, the initial aspect ratio of the mass, where $\Delta L = L_f - L_i$ and $a = H_i/L_i$ with H_i the initial height and L_i and L_f the initial and final length, respectively [*Lajeunesse et al.*, 2004; *Lube et al.*, 2004] (see insert in Figure 1). A similar correlation for Martian landslides has been observed by *Lajeunesse et al.* [2006]. However, the Martian normalized runout distance is twice as high as that obtained experimentally. As experimental and numerical models represent a huge simplification of natural processes, several parameters are expected to affect the modeled runouts as grain size and shape effects (M. Frank and P. W. Cleary, Three-dimensional non-spherical particle discrete element simulation of axi-symmetric collapses of granular columns, preprint, 2006), the presence of a fluid phase, the fragmentation of the grains [*Davis et al.*, 2006] or topography effects.

[5] Currently, very few studies focus on the simulation of gravitational flows on Mars [*Harrison and Grimm*, 2003; *Barnouin-Jha et al.*, 2005]. To the authors' knowledge, no simulations of Martian landslides were performed on a real 3D topography. We investigate here the effect of the topography by using a numerical model based on the Thin Layer Approximation (TLA) that takes into account the complex 3D curvature effects [*Mangeney et al.*, 2007]. A series of numerical simulations has been performed on theoretical 2D and real 3D topographies reconstructed from remote sensing data. Our results show that a very small change of the slope significantly increases the mobility of the granular flow but is not strong enough to explain the high mobility of VM landslides. A new mobility is defined to reflect the dynamics of the flow regardless of the geometry of the initial mass and of the underlying topography that can be useful for further investigation of long-runout landslides.

2. Experimental and Numerical Results

[6] Numerical simulations are performed here using a depth-averaged continuum model based on the TLA (i.e. Saint-Venant equations) and on a Coulomb-type friction law with a constant friction coefficient $\mu = \tan\delta$, where δ is an empirical friction angle. This model made it possible to reproduce the basic behavior of the collapse of granular columns over an horizontal plane [*Mangeney-Castelnau et al.*, 2005]. Indeed, numerical results using a friction coefficient $\delta = 32°$ are in very good agreement with 2D as with antisymmetric experiments on the spreading of granular columns over an horizontal plane for small aspect ratio of the initial column ($a < 1$) as it is the case for large Martian landslides observed in VM (Figure 1).When $a > 1$, the TLA is not ascertained. *Mangeney-Castelnau et al.* [2005] show

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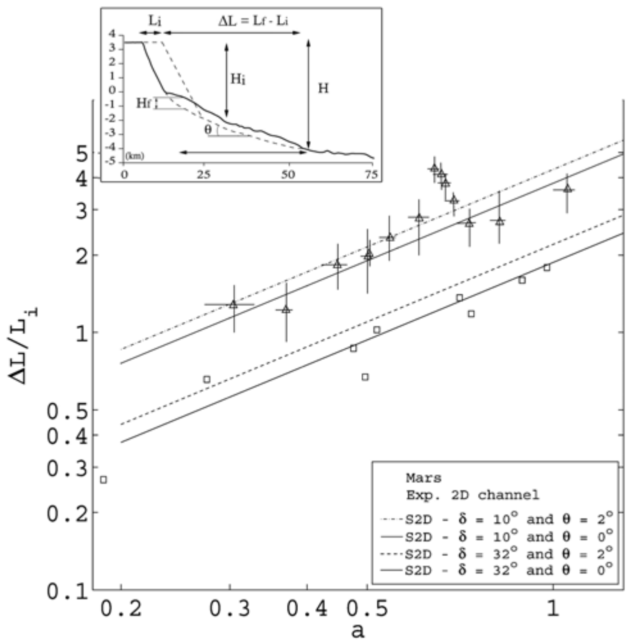

Figure 1. Normalized runout ($\Delta L/L_i$) as a function of a. Squares are experimental results in 2D channel geometry. Triangles are Martian data from MOLA. Courtesy of *Lajeunesse et al.* [2006]. Solid, dashed and dotted lines are numerical simulation using a 2D channel geometry (S2D). (Insert) Topographic profile of a Martian landslide defining H_i initial height, L_i initial length, ΔL runout length and θ the local slope.

that the scaling laws observed experimentally are intrinsically contained in the Saint-Venant equations. Furthermore, dimensional analysis of these equations demonstrates that the normalized runout distance does not depend on the gravity: only the time of emplacement is gravity-dependent.

[7] Martian normalized runouts appear to be a function of the initial aspect ratio a [*Lajeunesse et al.*, 2006] but with values twice as high as that observed experimentally (Figure 1). Analytical solutions provide insights into the scaling laws observed experimentally and numerically [*Mangeney et al.*, 2000; *Kerswell*, 2005]. Analytically, the normalized runout distance depends on the aspect ratio a, on the friction angle δ and on the angle θ of the sloping plane on which the material is flowing:

$$\frac{\Delta L}{L_i} = \frac{\alpha a}{\tan\delta - \tan\theta}, \qquad (1)$$

with α = 2. Experimental data of antisymmetric granular collapse however suggest $\Delta\ L/L_i$ = 1.24 a [*Lube et al.*, 2004]. Assuming that δ = 32°, the coefficient α is equal to 0.77. In order to fit the Martian long-runout according to equation (1), the slope inclination θ should be increased or the friction angle δ should be decreased.

3. Slope and Friction Effects on a Simple 2D Topography

[8] Comparison of numerical results based on the TLA with experiments and discrete element simulation show that the granular deposit is well reproduced by the TLA but with a slightly higher friction angle (δ = 32°) than that expected for the involved granular material (i. e. glass beads). The need of such a high friction coefficient is probably due to the neglected vertical acceleration [*Mangeney et al.*, 2006]. The friction coefficient used in TLA models should therefore be considered as an empirical coefficient making it possible to reproduce granular flows in a given range of variation of morphological parameters as for example here when varying the aspect ratio of the column. It reflects the effective mobility of the flow.

[9] Previous laboratory and numerical experiments on granular collapse were carried out on an horizontal plane. We perform here a series of numerical simulation to study the behavior of the flow on a simple sloping plane before taking into account the real topography observed on Mars, which is very complex and thus involves high numerical cost. The 2D topography consists in a channel configuration where the slope on which settles the granular flow (initially as a vertical column) $\theta \in [0°, 2°]$ and the initial aspect ratio $a \in [0.3, 1.2]$ are controlled (see inset in Figure 1). This range of parameters correspond to the natural values observed on Mars.

[10] In the first series of simulation, the friction angle δ = 32° calibrated to reproduce the experimental results is used. Figure 1 shows that the rescaled runout is strongly dependent on the slope angle θ: very small change of this slope significantly increases the runout distance. However, numerical results demonstrate that topography effect can only partly explain the discrepancy between experimental results and observed runout on Mars when a friction angle δ = 32° is considered (Figure 1). In the range of the inclination angles observed in VM, numerical simulation on schematic 2D topographies requires a very small friction angle ($\delta \sim 10°$) to reproduce the high mobility of Martian landslides. Small friction angle is also generally required when simulating terrestrial landslide [see, e.g., *Pirulli et al.*, 2007] although its value is larger than for VM landslides ($\delta \sim 15°$). *Lajeunesse et al.* [2006] propose that the presence of surface flows (progressive flow localization in a surface layer which gets thinner and thinner) should be responsible for this high mobility. On the contrary, numerical modeling of granular collapse involving surface flows requires the use of higher friction angles as was discussed previously.

4. Simulation on Real 3D Topography

4.1. Topographic Reconstitution

[11] Using 1D parameter as the runout distance in order to study a 3D complex process is obviously questionable. As the runout distance can always be reproduced by fitting the friction coefficient, the area of deposit provides a stronger constraint on numerical models. Let us look at the calculated area of the deposit obtained by simulating a real landslide on 3D topography.

[12] A major problem when simulating real flows is the reconstruction of the pre-event DTM (Digital Topographic Model). The identification of deposits in the DTM grid needs a geological analysis. Images from HRSC, THEMIS and MOC are used in order to find out the signal characterizing the deposits in the DTM grid. The thickness is estimated by combining all data set in a GIS software. A

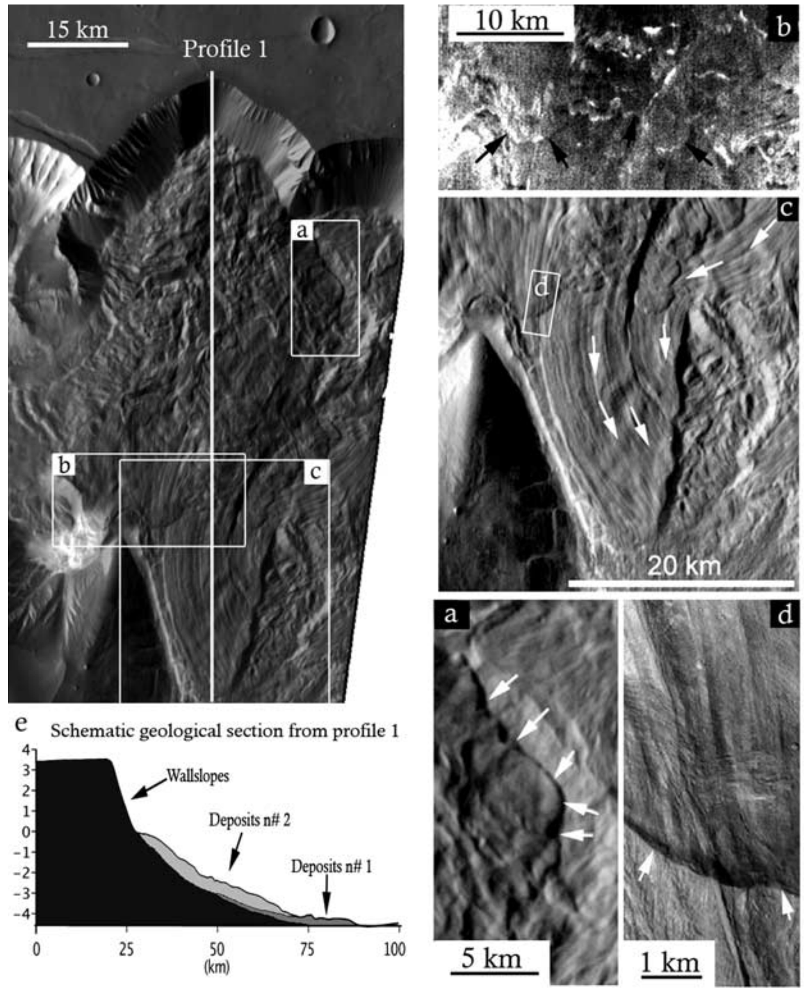

Figure 2. Geological analysis of Ophir Chasma landslide. (top left) Context image from IR THEMIS mosaic. Several scarps indicating that different flows occurred. (a) White narrows showing boundaries of deposits at THEMIS scale. (b) The variation of thermics inertia signal, from IR THEMIS at night time, makes it possible to discern deposits from different landslides. (c) Curved grooves features indicating clearly that very distal aprons come from eastern scarp. (d) Deposits boundaries identified at MOC scale. (e) Geological interpretation using MOLA profile. Our study focused on deposits 2.

geomorphological mapping of landslides deposits is thus performed (Figure 2). According to their thickness, the removal of the deposits is done using a vectorial mapping software. This withdrawal generates the dispersion of altimetrics information in the initial grid. The altimetric grid is thus rebuilt thanks to a geostatistic kriging method [*Stein et al.*, 2002]. This method makes it possible to take into account the spacial position and the spacial variability of the information. As a result, it minimizes the errors and make it possible to bring the spacial resolution up to 115 m/pixel, i.e., four times better than MOLA (e.g., 463 m/pixel). Subsequently, reconstruction of the original shape of the collapsed volume is obtained by the same method described previously so as to be very similar to spur-and-gully featured wallslope.

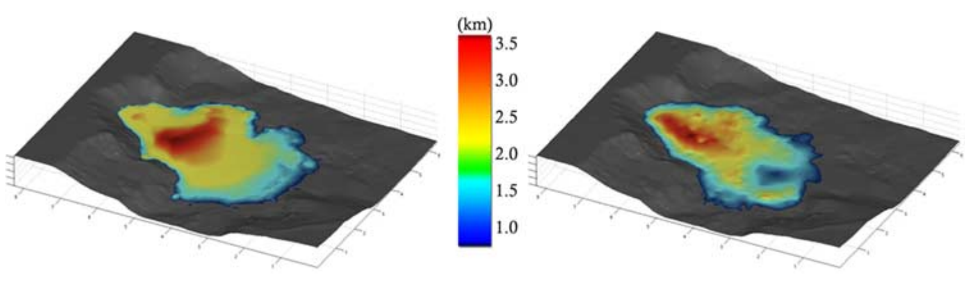

Figure 3. (left) Numerical simulations (left) using $\delta = 10°$ compared to (right) the MOLA DTM. Runout and area of deposits are similar in both cases.

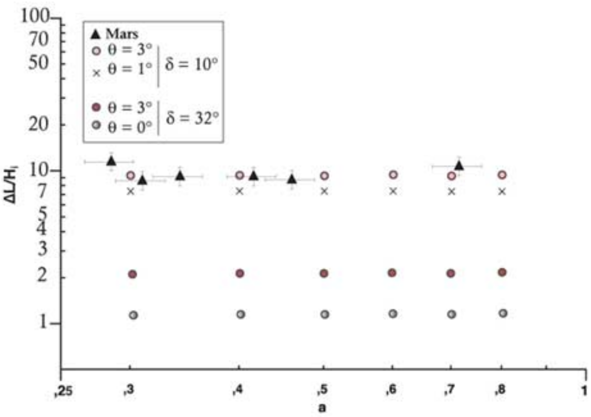

Figure 4. Mobility ($\Delta L/H_i$) as a function of initial aspect ratio a. Black triangles are Martian data. Circles are dry granular flows simulation. Mobility of Martian landslides is one order of magnitude larger.

4.2. Simulated Deposit and MOLA DTM

[13] The Ophir Chasma landslide is simulated here because in that particular case, the material spread in a wide and open valley avoiding reflection of the flow on the opposite cliff. Using the empirical friction coefficient $\delta \simeq 10°$ determined in section 3 to fit Martian data in the simple 2D configuration makes it possible to recover the extent of the deposit (Figure 3). The calculated and observed deposit's area are similar, respectively 1 395 km^2 and 1 380 km^2. The larger calculated area could be partly due to the reconstruction of the initial wallslope. Indeed, local fluctuations of the topography as the weathering morphologies such as spur-and-gully are not taken into account. Furthermore, the numerical model describes the behavior of an incompressible fluid. *Quantin et al.* [2004a] actually noticed a deficient volume balance between scarp hole and aprons volume close to 20%. In the case of Ophir Chasma, we calculate a total volume of deposits $V_{deposits} \simeq 7.5\ 10^{11}$ m^3 with a deficient volume balance close to 9%. Considering spur-and-gully features present before the spreading, this value is consistent. But without a clear knowledge of the substratum lying below deposits, this volume estimation is quite rough. Consequently, the value of the initial volume is very sensitive to the reconstruction method as will be discussed in a following paper.

5. A New Mobility

[14] The mobility of geological flows is classically defined as

$$m_e = \frac{\Delta L}{H}, \tag{2}$$

where H is the total height of the granular mass (see inset in Figure 1). Several attempts have been made to define the mobility of a granular mass. In work by *Mangeney-Castelnau et al.* [2005], the mobility was defined as $m_e = \frac{L_f}{H_i}$ but the a-dependence of this mobility does not make it a good parameter to reflect the dynamics of landslides. *Lajeunesse et al.* [2006] refer to $\Delta L/\Delta H$, where $\Delta H = H_i - H_f$, a mobility which actually depends on the volume of the granular mass.

[15] We propose here a new mobility that is shown to be independent of the aspect ratio and of the volume of the granular mass. The idea is to separate the effect of the initial thickness of the released mass and that of the topography. Instead of the total height H in equation (2) [*Quantin et al.*, 2004a], the mobility is defined using the thickness H_i of the granular mass on top of the topography. Owing to equation (1), the new mobility reads

$$m_e = \frac{\Delta L}{H_i} = \frac{\alpha}{\tan\delta - \tan\theta}, \tag{3}$$

where $\alpha \simeq 1.24$. This mobility is shown to be independent of the aspect ratio both for the numerical results and for the Martian data (Figure 4). Martian landslides show a very high mobility ($m_e \simeq 10$) compared to that observed experimentally ($m_e = 1.24$).

[16] In equation (3), the role of the topography ($\tan\theta$) has been clearly separated from the role of the effective friction ($\tan\delta$). As a result, an "intrinsic" mobility only controlled by the effective friction can be defined

$$m_e' = \frac{1}{\tan\delta} = \frac{1}{\tan\theta + \alpha\frac{H_i}{\Delta L}}, \tag{4}$$

Using equation (4), the numerical simulation obtained with $\delta \simeq 10°$ and the Martian data represented on Figure 4 almost collapse to the value $m_e' = 5.6 - 6.3$. As a result m_e' really reflects the mobility of the flow independently of its initial volume, aspect ratio and of the underlying topography. It is obviously difficult to calculate θ for the flow on a complex topography. However, if we assume a mean slope $\theta \simeq 2 \pm 1°$ for VM landslides, equation (4) together with the measurements of $H_i/\Delta L$ on the field make it possible to estimate the mobility m_e' of VM landslides. Furthermore, equation (4) provides a useful way to fit the friction coefficient in TLA models ($\tan\delta = 1/m_e'$) in the field measurements.

[17] Note that using equation (3) and geometrical considerations, the inverse of the classically used mobility m_e reads

$$\frac{1}{m_e} = \tan\delta + \frac{1}{2\cos^2\theta\left(A + \frac{V}{2H_i^2}\right)}, \tag{5}$$

where $A = \frac{\alpha}{\tan\delta - \tan\theta} - \frac{\tan\delta}{2}$. When substituting the volume $V = 2\ L_i H_i$, equation (5) shows that m_e only depends on the aspect ratio. Equation (5) could partly explain the artificial decrease of the mobility when the volume increases which is generally observed on geological data. Furthermore, equation (5) show that for high volumes (and small aspect ratio) the mobility is simply $m_e = 1/\tan\theta$ which is observed at leading order on geological data.

6. Conclusions

[18] Numerical results show that the topography effects could only explain part of the high mobility observed for Martian landslides compared to simple granular flows in laboratory. As a result, fundamental processes, not active in

laboratory experiments dealing with dry granular flows, occur in real landslides. The presence of water could be a possible factor although the morphology of landslides in VM is very similar. It is thus difficult to call upon liquid water which would not be distributed in a homogeneous way in the sub-surface at VM scale. Other processes as degassing by sublimation of ice lenses in the ground [*McKenzie et al.*, 2002] implying air cushioning are possible candidates.

[19] The TLA model was able not only to extrapolate the laboratory experiments on simple sloping topography but also to take into account the 3D topography in a geophysical context. Despite the very small, and accordingly nonphysical, but nevertheless in agreement with [*Quantin et al.*, 2004a], empirical friction coefficient used in the numerical model, the area of the deposit is quite well reproduced.

[20] Based on analytical solution, a new "intrinsic" mobility is defined to reflect the dynamics of the flow but provided the initial aspect ratio $a < 1$. Contrary to the effective mobility proposed previously, this parameter depends neither on the initial geometry of the released mass nor on the underlying topography, The new mobility can be calculated from field measurements and provides a first estimation of the effective friction required in TLA model to reproduce the extent of the deposits.

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