Numerical modeling of gravitational flows on Earth and on Mars

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Numerical modeling of avalanches and landslides

Motivation

- Understanding erosion processes at the earth surface and on telluric planets
- Risk assessment
- Precursors of volcanic activity?

Wide variety of geophysical granular flows: avalanches, landslides, debris flows…

Several sources (earthquakes, precipitation, volcanism…), various scale, composition
Avalanche dynamics: Field scale to laboratory scale

- Physics and mechanics of granular flows in laboratory

- Physics and mechanics of natural flows?
  Very complex flows
  Few data: essentially on the deposit

Simplified systems
Velocity and thickness measurements

Same physical processes?
Numerical simulation

Emplacement conditions
Numerical simulation, Lucas, Mangeney, Bouchut

Nathalie Thomas, IUSTI
From morphometric observations to emplacement dynamics

- The levee/channel morphology of self-channelling flows on the Earth, on Mars …

Lascar volcano, Chili, Scanner Laser Labazuy et al. [2008]
How does it form?

Numerical modelling of dry granular flows over complex topography?

Lascar volcano, A. Mangeney
Thin Layer Approximation

- Flow on complex natural topography
  \[ a = \frac{H}{L} \ll 1 \]

  small Aspect ratio

  high computational cost \[ \Rightarrow \]

- Depth-averaged thin layer model

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial X} = \gamma_X g - K \frac{\partial}{\partial X} (g \gamma_Z h) - \mu \left( g \gamma_Z + \frac{u^2}{R_x} \right) \frac{u}{|u|}
\]

inertia \quad gravity \quad pressure gradient \quad Coulomb friction: \[ \mu = \tan \delta \]

\[ \gamma_X = \sin \theta, \quad \gamma_Z = \cos \theta \]

[Savage and Hutter, 1989]
Friction force: from grain to averaged media behavior

Constitutive relation at the local scale: existence and formulation?

Continuum equations for granular flows are not well established
Empirical relation deduced from experiments

Scaling law from experiments of **steady uniform flows over inclined plane**

*Pouliquen* [1999]

\[
\frac{\delta_2}{\delta_1} + h = \tan \delta_1 + (\tan \delta_2 - \tan \delta_1) \exp \left(-\frac{\beta}{Fr d} \frac{h}{h_{stop}}\right)
\]

Friction \(f_f\) as the thickness

\[
Fr = \frac{u}{\sqrt{gh}}
\]
Simulation of laboratory experiments

Mangeney et al. [2005]

Pirulli, Bristeau, Mangeney, Scavia [2006]

Mangeney, Vilotte, Bristeau, Perthame et al. [2003]
Simulation of self-channeling flows

Qualitative agreement between experimental and numerical results

Experimental deposit

Numerical simulation

Mangeney et al. [2007]

Polydispersity and mixture concepts are not needed to explain self-channeling flows and levee formation

Labazuy, Kelfoun, Mangeney et al. [2008]
**Relation between dynamics and deposits**

**Scaling laws** for mean velocity $u_f$ and thickness $h_f$

$$\frac{w_f}{w_s} = \left( \frac{h_f}{h_{stop}} \right)^{-5/2}, \quad u_f = \gamma h_f^{3/2}$$

**Measurement of** $w_c$ and $h_c$ — first order estimation of the dynamics ($h_f, u_f$)
Limits of the thin layer approximation

Initial aspect ratio: \( a = \frac{H_i}{R_i} \)

\( a = 0.8 \)

Shaltop-2d well match dry granular collapse in the laboratory if \( a < 1 \)

which is generally the case for natural landslides!
Simulations with \textit{friction angle $\sim$ typical friction angle for the granular material} roughly reproduce:

- mean behavior of the flow
- mean shape of the deposit
- some morphological structures

What about \textit{natural avalanches}?
Simulation of natural gravitational flows

- **Operational codes**: Six des Eaux Froides landslide, Switzerland, 1946 [Pirulli and Mangeney, 2006]

  \( t = 70 \, \text{s} \)
  
  Friction angle \( \delta = 17^\circ \)

**Good news**: The calculated deposit area well match the observations

- Ophir Chasma, Valles Marineris, Mars [Lucas and Mangeney, 2007]

Simulation using \( \delta = 10^\circ \).

Martian observation MOLA DTM.
**Prediction?**

- **Small friction angles** $\delta$ compared to typical of natural materials! $\theta_r \sim 35^\circ$

  $\mu = \tan \delta$ : empirical description of the mean dissipation

- **Quite bad news** : High variability of **adjusted friction angle** for natural flows

<table>
<thead>
<tr>
<th>Landslide</th>
<th>Volume</th>
<th>Basal friction angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fei Tsui landslide, Hong-Kong, 1995</td>
<td>$V = 1.4 \times 10^4$ m$^3$</td>
<td>$\delta = 26^\circ$</td>
</tr>
<tr>
<td>Shum Wan landslide, Hong-Kong, 1995</td>
<td>$V = 2.6 \times 10^4$ m$^3$</td>
<td>$\delta = 18^\circ$</td>
</tr>
<tr>
<td>Six des Eaux Froides, Switzerland, 1946</td>
<td>$V = 5 \times 10^6$ m$^3$</td>
<td>$\delta = 17^\circ$</td>
</tr>
<tr>
<td>Frank, Canada, 1903</td>
<td>$V = 3 \times 10^7$ m$^3$</td>
<td>$\delta = 14^\circ$</td>
</tr>
<tr>
<td>Boxing Day, Montserrat, 1997</td>
<td>$V = 5 \times 10^7$ m$^3$</td>
<td>$\delta = 15^\circ$</td>
</tr>
<tr>
<td>Ophir Chasma, Valles Marineris, Mars</td>
<td>$V = 5 \times 10^{12}$ m$^3$</td>
<td>$\delta = 9.8^\circ$</td>
</tr>
<tr>
<td>Candor Chasma, Valles Marineris, Mars</td>
<td>$V = 2.3 \times 10^{11}$ m$^3$</td>
<td>$\delta = 9.9^\circ$</td>
</tr>
<tr>
<td>Ganges Chasma, Valles Marineris, Mars</td>
<td>$V = 1 \times 10^{12}$ m$^3$</td>
<td>$\delta = 9.4^\circ$</td>
</tr>
</tbody>
</table>

**Useful tool for risk assessment** using calibration on past events in the same context!
Mobility of experimental and natural flows

Very low friction $\Rightarrow$ mechanical behavior of Martian landslides $\neq$ Experimental dry granular flows

Lube et al. [2004]
Lajeunesse et al. [2006]
Lucas and Mangeney [2007]
How to define the mobility of gravitational flows?

Lab areatory Experiments

Lucas and Mangeney [2007]

Mobility vs. Aspect ratio $a$ : OK
But still $a$-dependent !!!

Initial aspect ratio: $a = H_i / L_i$
New mobility vs. initial aspect ratio is relevant!

ΔL/H_i ≈ 10

But still topography-dependent

ΔL/H_i = f(δ, θ)

Lucas and Mangeney, [2007]
An “intrinsic” Mobility

\[ m'_e = f'(\delta, \theta) = \frac{1}{\text{mean dissipation}} \]

New mobility calculated from analytical solution [Mangeney et al., 2000]

Friction coefficient, i.e. the effective dissipation

\[ m'_e = \frac{1}{\tan \delta} = \frac{1}{\tan \theta + \frac{H_i}{\Delta L}} \]

Field measurements give the friction coefficient, i.e. the effective dissipation

Lucas and Mangeney [2007]
New mobility: survey at the field scale

A few landslides in Valles Marineris

Geomorphic survey using Imagery (THEMIS, HRSC, MOC, HiRISE) and Topography (MOLA, HRSC)

Using this "measured" friction angle, what about 3D deposit??!

\[ m'_e = \frac{1}{\tan \theta + \alpha \frac{H_i}{\Delta L}} \]

<table>
<thead>
<tr>
<th>Landslides</th>
<th>Mobility ($m'_e$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ophir</td>
<td>5.8</td>
</tr>
<tr>
<td>Candor</td>
<td>5.6</td>
</tr>
<tr>
<td>Ophir</td>
<td>6</td>
</tr>
<tr>
<td>Meres</td>
<td>7.7</td>
</tr>
<tr>
<td>Melas</td>
<td>6.9</td>
</tr>
</tbody>
</table>

Tab 1 – Mobility $m'_e$ and angle of friction $\delta$ calculated for a few landslides on Mars.
3D Numerical simulation of Martian Landslides

Numerical simulation

Ophir Chasma

Observation

Predictive power of actual empirical models

Coprates Chasma

Lucas and Mangeney, [2008]
High mobility of natural gravitational flows can not be explained by dry granular flows over a rigid bed.

Significant physical processes are missing in the laboratory.

Fluid phase, Fluidization, Erosion ...

fresh granular flow
past deposits
Laboratory experiments on granular flows

Glass beads $d = 0.5 \text{ mm}$  
Initial thickness $h_0 = 42d$

Inclination angle $\phi = 23^\circ$ [Pouliquen and Forterre, 2002]

$h_i \ll h_0$

Simulation using thin-layer model

$h_i = 0$

Decelerating avalanche with deposit

$h_i = h_s$ : thickness of the deposit for granular flow over a rigid bed

Surge wave
The partial fluidization theory

- Main fundamental problem:
  \[ \sigma_{ij} = \sigma_{ij}^f + \sigma_{ij}^s \]
  constitutive relation valid for flowing and static grains

- The partial fluidization model faces the challenge: [Aranson and Tsimring, 2002]
  \[ \begin{align*}
  \sigma_{ij}^f & \quad \text{- flowing part: rheology of flowing grains} \\
  \sigma_{ij}^s & \quad \text{- static part}
  \end{align*} \]

- The order parameter
  \[ \rho = \frac{\Sigma \text{ static contacts}}{\Sigma \text{ contacts}} \]
  \( \rho \) characterizes the state of the granular matter

- Well known theory of phase transition (Ginzburg-Landau equation)
Numerical modeling: from decelerating avalanches to surge waves

- 2D numerical simulation

[Mangeney et al., 2007]
Impact of erosion on avalanche mobility

- The erodible bed is a source of potential energy $E_p$ → flowing mass $E_k$

No signature of the erosion process on the deposit!

Data on the dynamics??!
Dynamic properties of natural gravitational flows?

Landslide in Taiwan

Seismology...
An extreme case...

Simulation of the landslide
Friction angle $\delta = 30^\circ$

Simulation of the generated seismic waves

Pascal Favreau

• Discharge and tangential stress

• Discharge and normal stress

Favreau, Mangeney, Lucas, ...

Released mass $V = 5000 \text{ km}^3$
5 km
56 km

Coprates Chasma, Valles Marineris, Mars
**Synthetic waveforms from normal (red) and tangential (blue) forces**

- $\tau_{xz} \Rightarrow$ Short periods
- $\sigma_{zz} \Rightarrow$ Low frequencies

Comparable static displacement

Mass front arrival
**Conclusion**

Numerical models: *empirical tool to study the mobility* of natural flows

*once calibrated on past events*

**prediction** in the same geological context

Numerical modeling helps « reading » the deposit’s morphology

insight into **emplacement dynamics**

water on Mars?...

Operational software for risk assessment *(mangeney@ipgp.jussieu.fr)*

- More **physics** in the models: fluid/solid mixture model, erosion/deposition …
- More data on the dynamics: **seismology**
- Detailed analysis of the **deposit morphology** in various contexts