Introduction to Hazard Modeling

Jose L. Palma, University at Buffalo
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Volcanic hazards
Why do we need models?

1. Predict flow path, runout, speed- before and during eruptions

2. Understand processes, important effects

3. Help interpret past eruptions
Using models to build hazard maps

Figure 1.2: Left: This is a hazard map generated by Sheridan et al[121] for Pico de Orizaba, Mexico. Middle: This is a map of deposits and flow outlines from Energy Cone, FLOW2D, and FLOW3D simulations used by Sheridan et al[122] to construct the hazard map on the left. Right: This is a probability of flow depth $\geq 1$ [m] that PCQ predicts for an event when all volumes between $5 \times 10^7$ and $4 \times 10^8$ [m$^3$] are considered equally likely; the third sub-figure was generated from an ensemble of Titan2D simulations and also appears in Sheridan et al[124].
Energy balance

\[ E = (U + K) + (C_I - D_I) - F \]

\[ (U + K) = E_M \]

\[ (C_I - D_I) = I \]
$H/L_p$ represents the path-averaged deceleration that causes the loss of mechanical energy of the flow
Figure 2: Schematic diagram of a granular material flowing down a slope, which illustrates the geometrical relationship of the variables used in the thermodynamical (gravity currents) and mechanical approaches. It also illustrates the difference between $L$ (dashed line) and $L_p$ which represent the maximum horizontal displacement and the actual length of travel by the centre of mass, respectively. In addition, there is also a difference in the way $H$ is measured in previous work, indicated by a dashed line, and the way it is defined in this work, indicated by a solid line. The body with a mass $m$ is moving at a velocity $v$ while a frictional force $Fr$ is acting on it in the opposite direction to the movement. The slope has an angle $\theta$ measured from the horizontal.

The term on the left-hand side in equation 4 is very similar to the well known Heim coefficient (mean drop gradient or friction coefficient: $H/L$) (e.g. [17]), but in this case the run out length of the flow is considered instead of its horizontally travelled distance. With the preceding reasoning, the $H/L_p$ coefficient represents the path-averaged acceleration ratio that causes the loss of mechanical energy of the flow.

In the case that erosion or deposition are important processes that occur during the flow of the granular material, extra parameters must be added to the equation of the energy balance in order to incorporate the energy interchange:

$$E = E_i + m \cdot E_e + m \cdot E_d$$

where $m_e$, $E_e$, $m_d$, and $E_d$ are the mass exchange and energy gained or lost by erosion and deposition, respectively.

2.3 The mechanical approach

Figure 2 shows a conceptual force balance of a block with mass $m$ sliding down a rough plane by the influence of gravity. In the case of a rigid body, the frictional force:

$$Fr = \mu N = \mu mg \cos \theta$$

$$\mu = \tan \theta = \frac{H}{L}$$

(Coulomb friction model)
H/L: real data

Figure by Sylvain Charbonnier
Fig. 2. Log(volume) versus log((H/L)), where H is the height descended and L is the runout distance. (a) Volcanic debris avalanches (vda). (b) Nonvolcanic debris avalanches (noda). (c) Pyroclastic flows (pf). (d) Deposit fields for all three types of deposits.

From Hayashi and Self 1992
Energy line

- Convective thrust (billowing ash)
- Gas thrust
- Top of gas-thrust zone
- Energy lines
- Ash collapse
- Cloud
- 12° for largest eruptions (pyroclastic flows reach farther)
- 30° for small eruptions
- Pyroclastic flow
- Topographic barriers (hills)
- L
- H

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H/L and energy line/cone

**Figure 3.** Maps showing Level I (a) and Level II (b) pyroclastic flows simulations. UTM coordinates are UL = 659450E, 2126045N, LR = 710647E, 2076017N. Major communications means are: highways in thick dashed lines, secondary paved road in thin dashed lines, and railways in alternated dotted and dashed lines. For reference the relative population of the major city Orizaba is 250,000 inhabitants, whereas Coscomatepec is around 25,000 inhabitants.

Sheridan et al. (2004). Pyroclastic Flow Hazard at Volcán Citlaltépetl. Natural Hazards
Segmentation of the path

\[ mg \, dH = \frac{1}{2} m \, dv^2 + mA \, dx \]

\[ \frac{1}{2} \frac{dv^2}{dx} = g\sin\theta - A \]
Voellmy–Salm–Gubler model

(A simple model for flowing snow avalanches)

\[
\frac{A}{g} = \mu \cos \theta + \frac{v^2}{\xi h}
\]

\(h\) flow depth

\(\mu\) Coulomb friction coefficient: 0.3 (small avalanches) - 0.155 (large avalanches)

\(\xi\) turbulent friction coefficient [m/s²]: 400 (confined) - 1000 (wide open slope)
Figure 2. Visualization comparison of energy cone (shaded area) and FLOW3D (colored flow threads) simulations of Level I and Level II type events. In the Level I simulation the 4,000-year BP deposits are shown in red. In the Level II simulation the 8,500 y BP deposits are shown in blue. Mapped deposits, digitized as vectors, were color encoded to the topography using a raster bit map.

Sheridan et al. (2004). Natural Hazards

\[ \tau = a_0 + v^* a_1 + v^{2*} a_2 \]

- basal friction
- viscosity
- turbulence
Flow spreading and deposition

\[ L_p \approx (H^2 + L_{cm}^2)^{1/2} \]

\[ H_{cm} = H - \frac{1}{2} \frac{V}{S} = H - \frac{1}{2} \bar{h} \]

\[ V \quad \text{volume} \]
\[ S \quad \text{planimetric area} \]
\[ \bar{h} \quad \text{average depth} \]

\[ L_s = \left( \frac{S}{k_s} \right)^{1/2} \]

\( k_s \) is a shape factor: 4\( c \) for a rectangle, \( \pi c \) for an ellipse (\( c \) is the ratio between axes)

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Figure 4: Sketch showing the geometrical relationship of the flow spreading and deposition.
Flow spreading and deposition

Flow spreading and deposition

Flow spreading and deposition

\[ L_s = \left( \frac{S}{k_s} \right)^{1/2} \]

\( k_s \) is a shape factor: 4\( c \) for a rectangle, \( \pi c \) for an ellipse (\( c \) is the ratio between axes)

\[ L_s = \left( \frac{V}{k_v} \right)^{1/3} \]

\( k_v \) is a shape factor related to the volume of the flow

\[ S = \frac{k_s}{k_v^{2/3}} V^{2/3} \]
Flow spreading and deposition

Calder et al. (1999). GRL
A lahar may gain or lose sediment and/or water and thereby alter its volume shapes. Because equation 6 neglects downstream attenuation, it provides a conservatively large estimate of the maximum cross section inundated during a lahar.

The relationship between lahar volume and planimetric area of inundation is expressed by the equation:

\[ A = c_1 V^{2/3} \]

where \( A \) is the planimetric area, \( V \) is the volume, and \( c_1 \) is a constant. This equation applies to the distal lahar path and is based on the Iverson and others (1998) method, which assumes the volume of a distal lahar equals the volume of distal lahar deposits. Therefore, the volume can be written as a function of the planimetric area.

Dimensionless peak discharge is defined as:

\[ Q^* = \frac{Q_{\text{max}}}{A_{\text{max}} \sqrt{gR}} \]

Dimensionless lahar duration at cross section is given by:

\[ T^* = \frac{T}{\sqrt{A_{\text{max}}/gR}} \]

The constant \( c_1 \) is defined in terms of dimensionless peak discharge and dimensionless lahar duration:

\[ c_1 = (KQ^*_{\text{max}} T^*)^{-2/3} \]

where \( K \) is a dimensionless parameter related to the lahar hydrograph.

Cross section area, \( A \), calculated at each stream cell:

\[ B = c_2 V^{2/3} \]

\[ c_2 = \varepsilon^{-2/3} \]

\[ \varepsilon = \frac{\bar{h}}{\sqrt{B}} \ll 1 \]
LAHARZ

\[ A = 0.05V^{2/3} \]

\[ B = 200V^{2/3} \]

Iverson et al. (1998). GSA Bulletin
Lahar-inundation hazard map constructed by applying LAHARZ to the Mount Rainier region in western Washington. Topography is depicted by shaded relief. The proximal hazard zone enclosed by the dark line surrounding Mount Rainier is subject to diverse hazards, including lahars.

Iverson et al. (1998). GSA Bulletin
Objectives

The overall objective of this study is to extend the hazard-zone delineation methodology of Iverson and others (1998) to nonvolcanic debris flows and rock avalanches. To attain this objective, several steps are taken and are enumerated here.

1. Assemble a database consisting of flow volumes ($V$) paired with maximum inundated valley cross-sectional areas ($A$) and (or) total inundated planimetric areas ($B$) for a large number of nonvolcanic debris flows and rock avalanches (fig. 2). This database parallels that assembled for lahars by Iverson and others (1998) and partly reproduces the rock-avalanche databases assembled by Li Tianchi (1983), Legros (2002), and others.

2. Use the database to test whether power-law equations with specified $2/3$-exponents satisfactorily predict inundated-planimetric and cross-sectional areas as functions of flow volume for nonvolcanic debris flows and rock avalanches. This test involves determining the goodness of fit of the $2/3$ power-law equations, as well as statistical comparison of these equations to alternative statistical models. If the $2/3$ power-law equations are validated, it would imply that the flows behave in a similar way to the many lahars and rock avalanches used to calibrate these equations.

Flow Volume, $V$ ($m^3$)

Cross-sectional Area, $A$ ($m^2$)

Planimetric Area, $B$ ($m^2$)

Figure 2. Diagram showing the maximum inundated cross-sectional area, $A$, and total inundated planimetric area, $B$, of a lahar runout path downstream from a source area on a volcano. The downstream edge of the source area is delineated by using an H/L cone in this instance. Figure modified from Iverson and others (1998).

Griswold & Iverson. USGS Scientific Investigations Report 2007-5276
For all data: $A = 0.05 \ V^{2/3}, \ B = 35 \ V^{2/3}$

For Montserrat data: $A = 0.1 \ V^{2/3}, \ B = 40 \ V^{2/3}$
LAHARZ for block-and-ash PFs


![Image of map showing block-and-ash PF deposits on Montserrat with volume ranges and surge limits indicated.](image-url)
Shallow water models

- Valid when the horizontal length scale is much greater than the vertical length scale.

- Derived from depth-integrating the Navier-Stokes equations.

- Vertical velocity gradient is very small and it is discarded (only one vertical level); vertical pressure gradients are nearly hydrostatic.
Shallow water models - TITAN2D

\[
\frac{\partial h}{\partial t} + \frac{\partial}{\partial x} (hu) + \frac{\partial}{\partial y} (hv) = 0 \tag{3}
\]

\[
\frac{\partial}{\partial t} (hu) + \frac{\partial}{\partial x} (hu^2) + \frac{\partial}{\partial y} (huv) = gh \sin \alpha_x - \frac{1}{2} k_{actpass} \frac{\partial}{\partial x} (gh^2 \cos \alpha) + \tau_x \tag{4}
\]

\[
\frac{\partial}{\partial t} (hv) + \frac{\partial}{\partial x} (hv^2) + \frac{\partial}{\partial y} (hv^2) = gh \sin \alpha_y - \frac{1}{2} k_{actpass} \frac{\partial}{\partial y} (gh^2 \cos \alpha) + \tau_y \tag{5}
\]

- **TITAN 2D simulation code → geophysical mass-flow model** developed at the University of Buffalo, USA (Pitman et al., 2003; Patra et al., 2005)

  - **depth-averaged granular-flow model** on 3D terrain (Iverson and Denlinger, 2001)

  - **conservation equations** for mass (3) and momentum (4 and 5) → **Coulomb-type friction** term at the basal interface

  - incorporation of **topographical data + grid structure** (DEM) → **visualization platform** for displaying the flows
Shallow water models- VolcFlow

- VolcFlow, developed at the Laboratoire Magmas et Volcans, Clermont-Ferrand, by Karim Kelfoun, allows the simulation of dense isothermal volcanic flows

  ▶ VolcFlow is written in Matlab and runs on Windows

  ▶ VolcFlow can take into account frictional (with one or two friction angles), viscous, Bingham, Voellmy, etc... as well as more complex, user-defined flow behaviors

The default equation defining the stress in VolcFlow is:

\[ T = \rho h \tan(\text{delta}_\text{basal}) \times (u^2 \text{curb} + g \cos \alpha) + \text{cohesion} + \frac{du}{dh} \text{viscosity} + \rho u^2 \text{coef}_\text{u2} \]
Shallow water models

Pyroclastic flow simulations with TITAN2D showing flow thickness on main ravines.

Capra et al. (2008). Volcanic hazard zonation of the Nevado de Toluca volcano, México. JVGR
Shallow water models

Simulation of the Arroyo Grande debris avalanche with (A) FLOW3D and (B) TITAN2D model

Capra et al. (2008). Volcanic hazard zonation of the Nevado de Toluca volcano, México. JVGR
Multiphase flow modeling

- PDAC2D, axisymmetric, transient

- Solves for one gas phase coupled to a few solid components (different grain size)

Clarke et al. (2002). Nature
3D multiphase flow modeling

Esposti Ongaro et al. (2008). JVGR
3D multiphase flow modeling

Spatial distribution of pyroclastic particles in the atmosphere 1000s after the start of a sub-Plinian eruption (mass flow = 5.0e07 Kg/s) of Vesuvius. (Image: Menconi et. al. 2005).
End