Numerical analysis of the rheological behaviour of the Socompa debris avalanche, Chile

Vagnon Federico*
Ph.D., Department of Earth Science, University of Turin, Via Valperga Caluso 35, 10125 Turin, +39 0116705325, fvagnon@unito.it (*corresponding author)
Marina Pirulli
Ph.D., Associate Professor, Department of Structural, Geotechnical and Building Engineering, Politecnico of Turin, Corso Duca degli Abruzzi 24, 10129 Turin, +39 0110904865, marina.pirulli@polito.it
Irene Manzella
Ph.D., Lecturer (Assistant Professor), School of Geography, Earth and Environmental Sciences, Plymouth University, PL4 8AA Plymouth, UK, +44 1752 585958, irene.manzella@plymouth.ac.uk
Karim Kelfoun
Ph.D., Maître de Conférence (Associate Professor), Laboratoire Magmas et Volcans, OPGC, UMR Clermontn Université-CNRS-IRD, 5 rue Kessler, 63038 Clermont-Ferrand, France, +33 0473346741, K.Kelfoun@opgc.univ-bpclermont.fr
Anna Maria Ferrero
Ph.D., Full Professor, Department of Earth Science, University of Turin, Via Valperga Caluso 35, 10125 Turin, +39 0116705114, anna.ferrero@unito.it

Abstract

Socompa Volcano provides one of the world's best-exposed example of a sector collapse that generated debris avalanche deposit. The debris avalanche, occurred about 7000 years ago, involved 25 km^3 of fragmented rock that formed a thin but widespread (500 km^2) deposit.
Numerical model of this event was already performed using a shock-capturing method based on double upwind Eulerian scheme in order to provide information for investigating, within realistic geological context, its dynamic and run-out (Kelfoun and Druitt 2005).
This paper analyses an important aspect of the continuum numerical modeling of rapid landslides as debris avalanche: the interchangeability of rheological parameter values. The main question is: by using the same rheological parameter values, are the results, obtained with codes that implement the same constitutive equations but different numerical solvers, equal? Answering this question has required to compare the previous back analysis results with new numerical analyses performed using RASH3D code.
Different rheological laws were selected and calibrated in order to identify the law that better fits the characteristics of the final debris deposit of the Socompa landslide.

Key words: Volcanic debris avalanche, Numerical modelling, Runout simulation, Depth-averaged equations, rheological laws

1. Introduction

The collapse of a giant sector of the Socompa Volcano caused a long runout debris avalanche, which represents one of the most critical and hazardous types of geological instability phenomena (Melosh, 1990). The potential for destruction of this type of flow-like landslides, due to the extremely rapid propagation velocity, requires reliable forecasting methods to predict their motion characteristics.

Continuum mechanics based numerical models (e.g. Savage and Hutter, 1989, O'Brien et al., 1993, Hungr, 1995, Iverson and Delinger, 2001, Mc-Dougall and Hungr, 2004, Pirulli, 2005, Pastor et al., 2009, Manzella et al., 2016) are useful tools for investigating, within realistic geological contexts, the dynamics of these phenomena.

The back analysis of real events is indispensable for the correct selection of the rheological laws and the calibration of the rheological parameters. Moreover, in order to perform robust numerical analyses, two aspects shall be considered: firstly, the use of more than one code and the comparison of results are recommended (Pirulli and Sorbino, 2010). Secondly, the interchangeability of rheological parameters should be evaluated. This aspect is particularly important because it helps users in the decisional process for assessing potential risks and evaluating/designing possible countermeasures (Vagnon, 2017).

The aim of this paper is to evaluate the interchangeability between calibrated values of rheological parameters comparing the simulation results of two different continuum-based numerical codes: VolcFlow (Kelfoun and Druitt, 2005) and RASH3D (Pirulli, 2005). In the next Sections, the codes are briefly described and used to back-analyse the Socompa debris avalanche. The obtained results are compared and discussed. Moreover, new simulations are carried out using Bingham rheology.

2. Description of the Socompa avalanche

Socompa Volcano is a stratovolcano located at the border between Chile and Argentina, in the Andes Mountains (Figure 1a). About 7000 years ago, the Chilean sector collapsed, generating a 40 km long debris avalanche that flowed into the flat and arid plan below before being deflected to northeast by a range of hills, forming a frontal lobe (Francis et al., 1985, Wadge et al., 1995, Van Wyk de Vries et al., 2001, Kelfoun and Druitt, 2005). The debris deposit covered an area of 500 km^2, forming a sheet of 50m average thickness. The deposit has an estimated volume of about 36 km^3 and it results from the sum of two subsequent events. The first of 25 km^3 is analysed in the paper, while the second of 11 km^3 that gave origin to the Toreva blocks deposit (Figure 1b) is not analysed due to its negligible runout distance.

The avalanche deposit is characterized by a mixture of brecciated lavas and volcanoclastic deposit (Socompa Breccia Facies; SB) directly originated by the Socompa edifice itself and ignimbrites, gravels, sands and minor lacustrine evaporates from the Saline Formation (Reconstruited Ignimbrite Facies; RIF) of the volcano basement). Mostly of the deposit volume is constituted of RIF and only the 20% of SB.

The first avalanche was generated by a series of retrogressive failures that merged to form a single flowing mass (Wadge et al., 1995) that spread on a basal layer of RIF, characterized by very weak mechanical resistance (Van Wike de Vries et al., 2001). The deposit can be morphologically divided into two main zones by a median escarpment (ME), oriented NE-SW (Figure 1b), generated by secondary flow off the western and north-western basin margins.

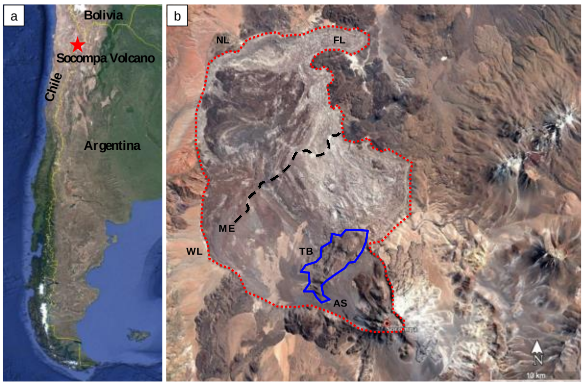

Figure 1. Location of Socompa Volcano (a) and aerial image of the avalanche deposit showing the avalanche scar (AS), the Toreva blocks (TB), the median escarpment (ME), the frontal lobe (FL) and northern and western levees (NL and WL) (b). In detail: the red dotted line surrounds the deposit limits; the blue continuous line draws the margins of Toreva deposit; the black dotted line highlights the medial escarpment.

3. Numerical modeling

Kelfoun and Druitt (2005), starting from geological investigations and morphological observations, reconstructed the original topography of the area before the collapse. Then, they performed several numerical simulations using VolcFlow code, testing different rheological laws in order to find the best model for obtaining the actual avalanche deposit configuration.

In this work, the Authors want to compare VolcFlow numerical results with those obtained with RASH3D code (Pirulli, 2005) for evaluating the interchangeability between codes of calibrated rheological values and providing new run-out simulations with a Bingham rheology.

3.1. Basic equations

The numerical simulation of rapid landslides is a common practice since in 1989, when Savage and Hutter firstly introduced the depth-averaged equations for the dynamic analysis of flowing mass. The hypotheses for applying depth-averaged equations to rapid landslides are:

- both thickness and length of flowing mass are assumed to exceed the size of single moving particles of several times;
- the flow thickness is considerably smaller than its length;
- the real moving mixture is replaced by an “equivalent fluid” whose properties approximate the bulk behaviour of the real mixture;
- the flowing mass is described as a single-phase, incompressible and homogeneous material;
- a kinematic boundary condition is imposed on free and bed surfaces;
- the rheological characteristics are all included in a single term acting at the interface between flow and terrain surface.

Under the above listed conditions, the motion is described by the equations of mass and momentum conservation:

$$\begin{cases} \dfrac{\partial h}{\partial t} + \dfrac{\partial(\overline{v_x}h)}{\partial x} + \dfrac{\partial(\overline{v_y}h)}{\partial y} = 0 \\ \rho\left(\dfrac{\partial(\overline{v_x}h)}{\partial t} + \dfrac{\partial\left(\overline{v_x^2}h\right)}{\partial x} + \dfrac{\partial(\overline{v_x v_y}h)}{\partial y}\right) = -\dfrac{\partial(\overline{\sigma_{xx}}h)}{\partial x} + \tau_{zx_{(z=b)}} + \rho g_x h \\ \rho\left(\dfrac{\partial(\overline{v_y}h)}{\partial t} + \dfrac{\partial(\overline{v_y v_x}h)}{\partial x} + \dfrac{\partial\left(\overline{v_y^2}h\right)}{\partial y}\right) = -\dfrac{\partial(\overline{\sigma_{yy}}h)}{\partial y} + \tau_{zy_{(z=b)}} + \rho g_y h \end{cases} \qquad (1)$$

where $\bar{v} = (\overline{v_x}, \overline{v_y})$ denotes the depth-averaged flow velocity in a reference frame (x, y, z) linked to the topography, ρ is the bulk material density, h is the flow depth, τ is the shear stress in the x and y direction, $\bar{\sigma} = (\overline{\sigma_{xx}}, \overline{\sigma_{yy}})$ is the depth-averaged stress and g_x, g_y are the projections of the gravity vector along the x and y direction.

The here applied VolcFlow and RASH3D codes differ in the numerical scheme adopted for solving the above equations. VolcFlow code uses a Eulerian explicit upwind scheme for solving the system of equations (1) where scalar quantities (thickness and terrain elevation) are evaluated at the centres of cells and vectors (velocity and fluxes) at the edges (Figure 2a). For a complete description of this method, see Kelfoun and Druitt 2005.

The RASH3D Eulerian code, developed by Pirulli (2005) uses a finite volume scheme for modelling rapid landslide run out problems. The system of equations (1) is discretized on an unstructured triangular mesh with a finite element data structure using a particular control volume, which is the median dual cell (Pirulli, 2005). Dual cells C_i are obtained by joining the centres of mass of the triangles surrounding each vertex P_i of the mesh (Figure 2b).

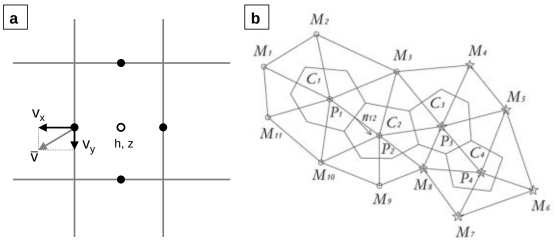

Figure 2. Definition of scalars and vector (a) in the numerical scheme of VolcFlow code (modified after Kelfoun and Druitt 2005) and triangular finite-element mesh and dual cells (C1, C2, C3, C4) in RASH3D code (b) (modified after Pirulli 2005).

3.2. Rheological laws

As stated above, the complex rheology of the flowing mass is incorporated in a single term (τ) that describes the frictional stress generated between terrain surface and flowing body.

In this paper, three rheologies were selected for the numerical back-analysis of Socompa avalanche:

1. Frictional rheology in which the resisting shear stress depends only on normal stress and it is independent of velocity.

   $$\tau_{zi} = -(\rho \cdot g_z \cdot h \cdot tan\varphi_{bed})\frac{v_i}{\|\bar{v}\|} \quad i = (x, y) \qquad (2)$$

   where φ_{bed} is the bulk friction angle.

2. Constant retarding stress in which the basal shear stress is constant and consequently independent by velocity, normal stress and frictional parameters.

   $$\tau_{zi} = -const\frac{v_i}{\|\bar{v}\|} \quad i = (x, y) \qquad (3)$$

These two rheological laws are implemented in both the presented codes and they were used to compare the RASH3D analyses with the already published VolcFlow simulations (Kelfoun and Druitt, 2005).

3. Bingham rheology combines plastic ad viscous behaviour, so that the flowing mass moves as a rigid body below a given threshold yield strength and then have a viscous behaviour above this threshold. The basal stress is determined solving the following equation:

   $$\tau_{zi}^3 + \left(\frac{\tau_y}{2} + \frac{\mu_B \bar{v}_i}{h}\right)\tau_{zi}^2 - \frac{\tau_y^3}{2} = 0 \qquad (4)$$

   where τ_y is the Bingham yield stress and μ_B is the Bingham viscosity.

In RASH3D equation (4) is solved using polynomial economization technique proposed by Pastor et al. (2004). Bingham rheological law was selected to back-analyse Socompa avalanche since the type of material that characterized the deposit had a ductile behaviour (RIF) and behaved as a lubricant for the SB facies.

4. Results

Numerical analyses were carried out following two different steps. Firstly, the VolcFlow numerical simulations (Kelfoun and Druitt, 2005) were replicated using RASH3D code for evaluating the interchangeability of rheological values. Then, once that RASH3D results were commented, a back-analysis using Bingham rheology was performed.

The goodness of numerical simulations is evaluated if the following conditions are satisfied:

1. best fit to the north-western margin
2. best fit to overall outline of the deposit
3. reproduction of the main structures, especially the median escarpment (cfr. Figure 1).

4.1. Evaluation of the two codes interchangeability of rheological values

Figure 3 compares VolcFlow (a and c) and RASH3D (b and d) simulations of the final avalanche deposit considering a frictional behaviour (model 1, Figures 3a and 3b) and a constant retarding stress rheological law (model 2, Figures 3c and 3d). The rheological values used for model 1 are $\varphi_{bed} = 2.5°$, in an isotropy condition of stresses, and a constant retarding stress equal to 52 kPa for model 2.

For each time step of the simulations, the thickness and the areal distribution of the deposit simulated by the two codes are satisfyingly comparable. In general, RASH3D simulations show a marked lateral spreading: however, the calculated thickness values at the margin of the simulated deposit are less than 10 cm. For what it concerns model 2, the conditions previously imposed for evaluating the goodness of the model (point 1 to 3, Section 4) were satisfied: the overall outline of the deposit was respected and the median escarpment, characteristic of this deposit, was well reproduced.

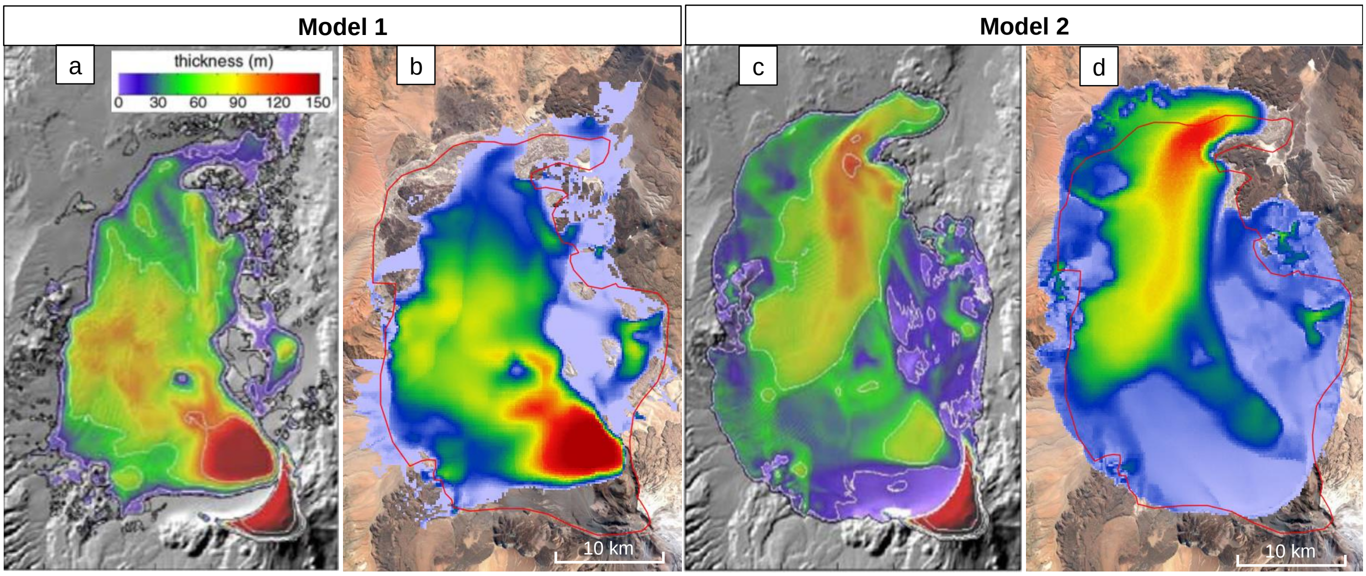

Figure 3. Final deposit thickness of the Socompa avalanche considering frictional rheological law with φ_{bed} = 2.5° and in an isotropy condition of stresses in VolcFlow code (a) and RASH3D code (b). Figures c and d show the obtained final deposit considering a constant retarding stress rheological law with $\tau = 52$ kPa in VolcFlow code (c) and RASH3D code (d).

4.2. Bingham rheology

The Bingham rheology was never used before for simulating Socompa avalanche but, on the basis of previously discussed geological and geomorphological evidences, this rheology was adopted to evaluate thickness and velocity of the Socompa emplacement with the RASH3D code.

A large number of analyses was performed to obtain the combination of rheological values that best simulate the deposit in terms of extension, thickness and escarpments. These conditions were satisfied considering the Bingham yield stress and the viscous coefficient respectively equal to 52 kPa and 10 kPa*s. Figure 4 shows the depositional height (a) and the flow velocity (b) of the simulated emplacement. The simulated final deposit (Figure 4a) remarkably well reproduces the real event. In particular, analysing Figures 4c and 4d that represent the shaded relief map of the simulated deposit and the satellite image, a topographic discontinuity is evident (red dotted line in Figure 4c) and it represents the median escarpment. Moreover, the presence of a frontal lobe can be clearly identified.

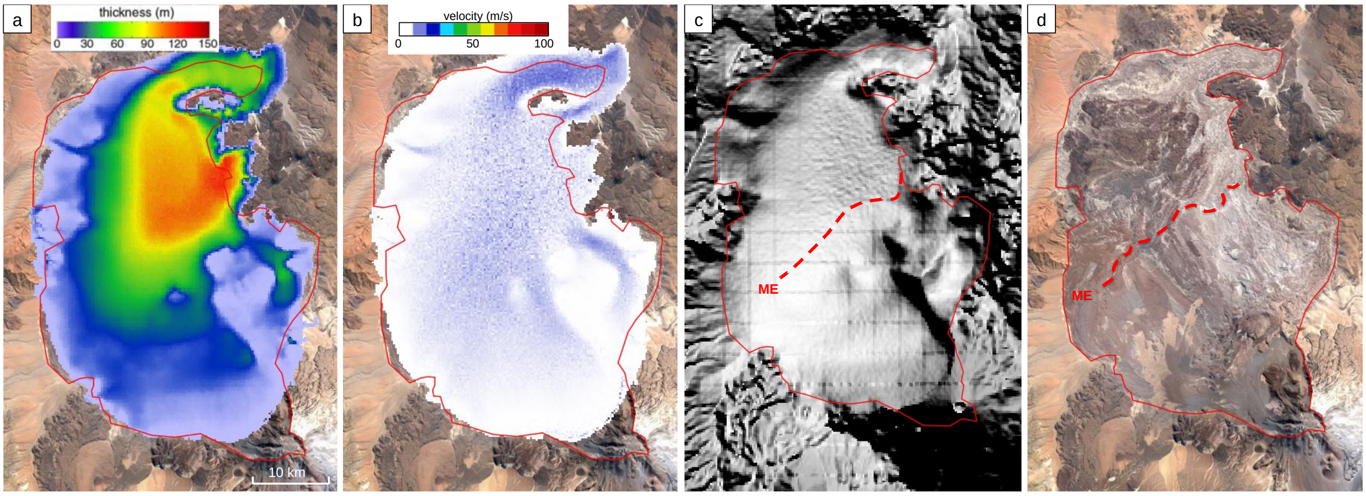

Figure 4. Deposit thickness (a), flow velocity (b) and shaded relief map of the Socompa avalanche, simulated considering Bingham rheological law with $\tau = 52$ kPa and $\mu = 10$ kPa*s using RASH3D code and satellite image of the actual Socompa emplacement (d).

5. Conclusions

In this paper, the two codes VolcFlow and RASH3D, based on a continuum mechanics approach, were compared.

The results obtained from the carried out analyses have highlighted the good interchangeability of the rheological values between the presented codes. Moreover, the Bingham rheological law was applied to further simulate the avalanche emplacement: the results were satisfying both in terms of areal extension, depositional heights and topographical evidences (frontal lobe, median escarpment and well-defined lateral margins) compared to the actual morphological situation.

Further developments of this research will include the use of others numerical codes with different numerical scheme for solving mass and momentum conservation equations (e.g. Lagrangian code) for again evaluating and comparing these approach.

6. References

Francis, P. W., Gardeweg, M., Ramirez, C. F., and Rothery, D. A. 1985. Catastrophic debris avalanche deposit of Socompa volcano, northern Chile, Geology, 13, 600–603.

Hungr, O. 1995. A model for the runout analysis of rapid flow slides, debris flows, and avalanches. Canadian Geotechnical Journal, 32(4), 610–623.

Iverson, R. M., and Denlinger, R. P. 2001. “Flow of variably fluidized granular masses across three-dimensional terrain: 1. Coulomb mixture theory.” Journal of Geophysical Research: Solid Earth, 106(B1), 537–552.

Kelfoun, K., and Druitt, T.H. 2005. Numerical modeling of the emplacement of Socompa rock avalanche, Chile, J. of Geophysi. Res., 110, B12202, doi:10.1029/2005JB003758.

Manzella, I., Penna, I., Kelfoun, K., and Jaboyedoff, M. 2016. High-mobility of unconstrained rock avalanches: Numerical simulations of a laboratory experiment and an Argentinian event, in Landslides and Engineered Slopes. Experience, Theory and Practice, 1345-1352.

Mcdougall, S., and Hungr, O. 2005. Dynamic modelling of entrainment in rapid landslides. Canadian Geotechnical Journal, 42(5), 1437–1448.

Melosh, H. J. 1990. Giant rock avalanches, Nature, 348, 483–484.

O'brien, J. S., Julien, P. Y., and Fullerton, W. T. 1993. Two Dimensional Water Flood and Mudflow Simulation. Journal of Hydraulic Engineering, 119(2), 244–261.

Pastor, M., M. Quecedo, E. Gonzalez, M.I. Herreros, J.A. Fernandez Merodo, and P. Mira. 2004. Simple approximation to bottom friction for Bingham fluid depth integrated models. Journal of Hydraulic Engineering 130(2): 149–155.

Pastor, M., Haddad, B., Sorbino, G., Cuomo, S., and Drempetic, V. 2009. A depth-integrated, coupled SPH model for flow-like landslides and related phenomena. International Journal for Numerical and Analytical Methods in Geomechanics, 33(2), 143–172.

Pirulli, M. 2005. Numerical modelling of landslide runout, a continuum mechanics approach. Ph.D dissertation, Politecnico of Turin, Turin, Italy.

Pirulli, M., and Sorbino, G. 2008. Assessing potential debris flow runout: a comparison of two simulation models. Natural Hazards and Earth System Science, 8(4), 961–971.

Savage, S. B., and Hutter, K. 1989. The motion of a finite mass of granular material down a rough incline. Journal of Fluid Mechanics, 199(1), 177.

Vagnon, F. 2017. Theoretical and experimental study on the barrier optimization against debris flow risk. Ph.D dissertation, University of Turin, Turin, Italy.

Van Wyk de Vries, B., Self S., Francis, P. W., and Keszthelyi, L. 2001. A gravitational spreading origin for the Socompa debris avalanche, J. Volcanol. Geotherm. Res., 105, 225–247.

Wadge, G., P. W. Francis, and C. F. Ramirez (1995), The Socompa collapse and avalanche event, J. Volcanol. Geotherm. Res., 66, 309–336.