A preliminary compilation of calibrated rheological parameters used in dynamic simulations of landslide run-out

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ABSTRACT: In recent times, a number of dynamic run-out models for landslides have been developed for risk assessment and for the design of potential mitigation measures. Dynamic models allow the effect of a release volume as well as material parameters (e.g. friction coefficient) to be modeled for different types of scenarios. These models are physically-based and solved numerically, simulating the movement of the flow using constitutive laws of fluid mechanics in one or two dimensions. The majority of models used in landslide hazard and risk assessments are based on a "continuum approach" that considers the loose unsorted material and heterogeneous moving mass of a debris flow as a packed one-phased material. The continuum approach enhances the possibility to simulate the dynamics of the debris flows as a homogenous mass whose properties can be approximated to the expected behavior of the real combination of sediments and fluid. The most common rheologies used for base resistance in dynamic models are: the frictional-turbulent "Voellmy" rheology and the visco-plastic "Bingham" rheology. However, the direct measurement of their correspondent resistance parameters is difficult or not possible. The variations in the values of these rheological parameters have a consequence in large uncertainties in model simulations, which must be properly addressed in hazard assessments. This work presents a characterization of the ranges of calibrated parameters that are present in landslide run-out simulations, with the aim of populating a probability density function. The calibrated parameters are obtained from a preliminary database of back-analyses of various past events compiled from several studies. A Gamma function was fitted to the distributions of each one of the parameters used in the Voellmy and Bingham rheologies.

1 INTRODUCTION

Numerical dynamic run-out modelling can play an important role as a tool for forecasting the behaviour and intensity of rapidly moving landslides (Rickenmann et al. 2005). These models can assess the velocity and extent of motion of rapid landslides such as debris flows and avalanches, flow slides and rock avalanches. The correct use of these tools can benefit public authorities when making decisions about communities with potential hazards (van Westen et al. 2006). The goals of computer modelling should be to predict activity with a range of potential scenarios and to inform relevant authorities of these natural hazards in order to plan adequate mitigation and preparedness measures. A variety of models exist for simulating landslide run-out and estimating intensity parameters such as velocity and flow depth (Naef et al. 2006). The run-out behavior of a landslide is controlled by a complex interaction between mechanical and hydraulic properties, and solid and fluid phases; and reflects spatio-temporal trends in the effective strength and rheological properties of the material. Due to these complex interactions, the parameterization of hydrological and geomechanical factors by field and laboratory tests is not sufficient to describe the post-failure movement patterns of landslides and not all the processes can be included in detail inside the models (van Asch et al. 2007).

Several methods have been developed to analyze landslide run-out distance and velocities, ranging from empirical methods to physically-based approaches. Empirical methods are based on field observations and on the analysis of the relationships between parameters characterizing the travel path (local morphology), landslide volume and maximum run-out. Statistical analyses can be used to produce indicators expressing, directly or indirectly, landslide mobility (Corominas 1996). These empirical models require a substantial amount of data about past events and still some difficulty arises when trying to relate the dependence of the released volume with the angle of reach (the angle created between the maximum height at the release area and the end of the deposition zone). These methods are useful to provide preliminary estimates of the spatial extension and travel length of the failed mass; however they are unable to assess velocities and pressures during landslide propagation, which can be important to evaluate the impact on exposed elements.

Most of physically-based models are solved numerically, and use constitutive laws of solid and fluid mechanics. Dynamic run-out models use physical laws to calculate flow velocities. Most 2-D models are based on a "continuum approach" that approximates the dynamics of debris flows using an "equivalent" fluid approach. The rheological properties of the "equivalent fluid" are such that the bulk behavior of the simulated flowing mass is similar to the expected bulk behavior of the real mixture of the solid and fluid phases (Hungr 2009). Continuum models solve the equations of conservation of mass and momentum and are often applied through a depth-averaged approach that integrates the internal stresses in either vertical or bed-normal directions to obtain a form of Saint-Venant equations (shallow water assumption) (van Asch et al. 2007). The depth-averaged shallow water equation approach using different solvers has been often applied for numerical simulations of rapid mass movements over complex topographies (e.g. Cheng & Lee 2000, Iverson & Denlinger 2001, Mangeney-Castelnau et al. 2005, Pitman & Le 2005, Pudasaini & Hutter 2007).

Depth averaging allows representing the rheology of the flow as a single term that expresses the frictional forces that interact at the interface between the flow and the bed path. The most common rheologies used in the dynamic models are: the frictional-turbulent "Voellmy" resistance proposed initially for snow avalanches (Voellmy 1955) and used for granular cohesionless material with or without the presence of a pore fluid; the visco-plastic "Bingham" resistance relationship applicable for plastic clay-rich material (Imran et al. 2001). The aim of this study is to present and characterize a dataset compiled from reported calibrated rheological parameters from published studies. The calibrations have been made by back-analyses of previous landslide incidents. The characterization of the parameters in the present study includes the derivation of probability density functions.

2 RHEOLOGICAL MODELS

As mentioned in Section 1, the most common rheology models used for simulating landslide run-out are the Voellmy and Bingham models. The resistance parameters of these two rheologies are described in this section.

2.1 The Voellmy rheology

This model features a velocity-squared resistance term (turbulent coefficient ξ) similar to the Chezy resistance for turbulent water flow in open channels and a Coulomb-like friction (apparent friction coefficient μ). The model assumptions are incompressibility of the flow along the whole path; constant discharge and small variations of flow height along the track; and non-steady quasi-rigid body movement both in the starting and the run-out zone. Voellmy (1955) established this model using a fundamental hydraulic theory with two resistive force contributions, one in which the shear force is proportional to the normal force and the other of viscous type, in which the drag is assumed proportional to the velocity squared. The unit base resistance for a Voellmy fluid is (Eq.1):

$$Sf = \mu\cos\varphi + \frac{U^2}{\xi h} \tag{1}$$

where, Sf is the unit base resistance, μ is the friction coefficient, φ the slope angle, U is the flow velocity and ξ is the turbulent coefficient. The parameters μ and ξ are constants whose magnitudes depend, respectively, on the flow properties and the roughness of the flow surface (Christen et al. 2010).

Various authors have used the run-out from granular avalanches to estimate the friction coefficients of the Voellmy model (Hungr et al. 2009, McKinnon et al. 2008, McDougall et al. 2005). The sliding friction μ has the greatest effect on run-out distance, whereas ξ has greater influence on the velocity.

2.2 The Bingham rheology

The Bingham model is a function of flow depth, velocity, constant yield strength (τ_c) and dynamic viscosity (μ) (Eq. 2). A linear stress-strain rate relationship is assumed once the yield strength is exceeded. The mean flow velocity is derived from the linear increase of shear stress with depth (Coussot 1994). Debris flows have often been modelled as viscoplastic materials with the Bingham model (Remaître et al. 2005, Malet et al. 2004). This model can be used for materials where the fine fraction is large enough to lubricate contacts between grains. According to Rickenmann (2005), a clay fraction (particle size less than 40 μm) greater than 10% is necessary so that a flow material may be assumed to behave like a Bingham fluid.

$$\tau(z) = \tau_c + \eta\left(\frac{\partial v}{\partial z}\right) \tag{2}$$

where, $\tau(z)$ is the resisting shear stress at a given depth z, τ_c is a constant yield strength due to cohesion, $\partial v/\partial z$ is the shear rate, and η is the viscosity parameter (Begueria et al. 2009). The yield stress and the viscosity of the flow are closely related to the concentration of solids.

3 PARAMETRIC ANALYSIS

The flow behavior, sediment concentration and velocity during the occurrence of an event may vary in space and in time. The complexity of the flow processes and its activity are characterized by a rheological model and a numerical model of the equations of conservation of mass and momentum. A usual assumption is that the flow behaves as a single phase mixture with representative bulk parameters. The following three different approaches are used for estimating the rheological parameters of a solid-fluid mixture:

1) Samples are collected in the field after a recent event and the rheological parameters are derived directly through laboratory tests and/or empirical laws (e.g. Remaître et al. 2005). Such direct derivation of the rheological parameters might be the most desirable option. However, measuring for instance pore-pressure and viscosity remains extremely difficult for full-scale events and point wise determined parameters may not be representative of the actual scale.
2) The model parameters are back-calibrated so that the model outcome fits with observations of a past-event. Observations may thereby include run-out estimated from historical records, vegetation damage and/or statistical models having as results useful estimates of velocity and impact pressures along the path and run-out zone (e.g. Pirulli and Sorbino 2008);
3) The rheological parameters and release volumes are adopted from other previously back-calibrated events (in the same area or other areas) or published values (e.g. Medina et al. 2008); and

As a result of relative high expenses for field collection and laboratory analyses of numerous samples, the latter two indirect approaches, based on back analyses of past-events, are more common in practice. Thereby the parameters are iteratively altered until the results of the model simulations show an acceptable agreement with field observations of past events. Major variations of the back-calibration results are associated with the fitted observations, whereas especially volume estimations have to be treated with caution (Kerle 2002) and established probability-density functions may provide a starting point to better estimate ranges where the data situation is poor (Brunetti et al. 2009).

A further source of uncertainties arises from the back-analyses itself, whereas existing models use different numerical schemes to approximate a solution of the governing equations. This leads to differences in the derived parameters and makes their transference into other modelling frameworks difficult. Run-out modeling can be rather complicated because the flow behavior during its course suffers alterations depending on the initial composition, the morphology of the path and the material incorporated during the flow (Iverson et al. 2004, Hungr et al. 2005). In many cases, there is no information on velocities or flow type making difficult to define and select a correct rheological resistance model.

4 DATABASE COMPILATION

As a first step towards a stochastic analysis of ranges and uncertainties of model parameters and their effects on run-out modeling, we began with the compilation of a database from past-analyzed events. At present it includes a number of 253 past events, characterised by type of landslide, volume, run-out behaviour and rheological parameters derived from model back-calibration (Figure 1). The database was compiled from peer-reviewed literature and unpublished material of all collaborators.

It is planned to further extend the number of collected cases, whereas this paper provides a preliminary description of the rheological parameters, observed volumes and their relationships.

At present 61% of the cases in the database are debris flows, 25% are rock avalanches and14% cover other landslide types. The compiled cases for the Voellmy rheology are 152 events and for the Bingham rheology 101 events.

-Case	Panabaj
-Movement type	Debris flow
-Volume (m^3)	65000
-Height release area (m)	1440
-Length run-out (m)	4900
-Angle of reach (°)	16.3
-Velocity (m/s)	15
-Rheology	Voellmy
-Apparent Friction coefficient	0.04
-Turbulent coefficient (m/s^2)	450
-Viscosity (Pa.s)	--
-Yield stress (Pa)	--
-Author and year	Quan Luna, 2007
-Method	Back-calibration
-Post-failure behaviour	Channeled
-Environment	Volcanic
-Source sediment	Pyroclastic material
-Volume entrained (m^3)	570000
-Unit weight (kg/m^3)	2250

Figure 1. Example of a case analyzed inside the database created showing the different fields of classification.

It can be observed that the rheological parameters of the Voellmy (Fig. 2) and Bingham models (Fig. 3) are not fully independent and a quantification of this should be targeted as the database expands. Furthermore the collected cases comprise a large range of displaced volumes (Fig. 4) which can be an additional parameter in the analysis of the distributions.

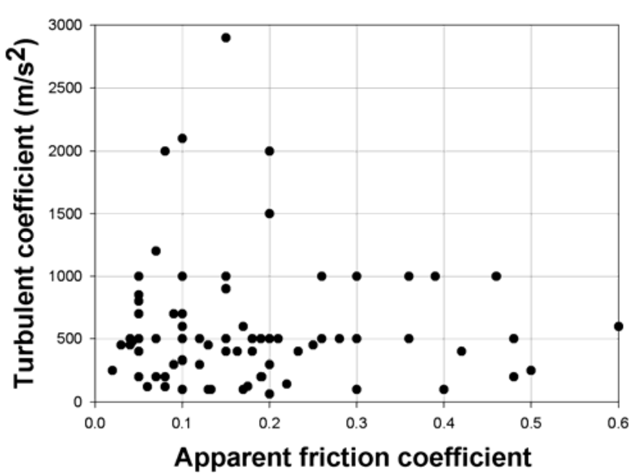

Figure 2. Relation between the Voellmy model parameters: turbulent coefficient (ξ) and friction coefficient (μ).

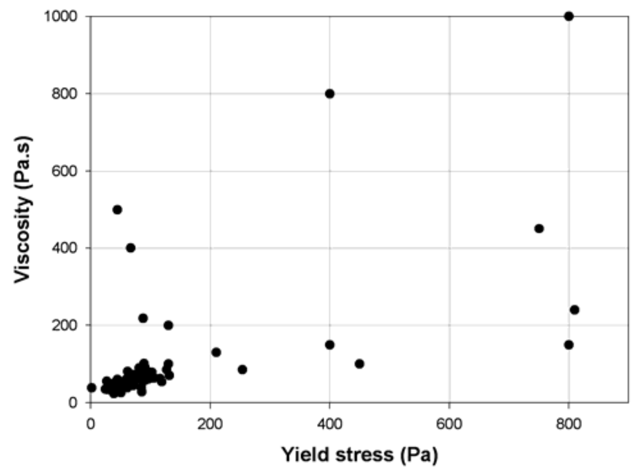

Figure 3. Relation between the Bingham model parameters: viscosity (η) and yield stress (τ).

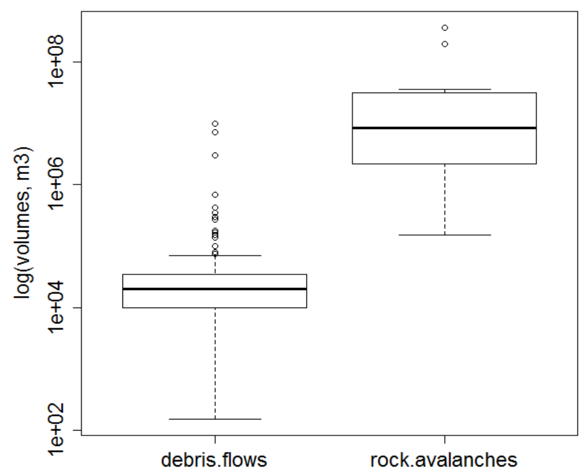

Figure 4. Boxplot representation of the volumes of debris flows and rock avalanches in the database.

5 PROBABILITY DENSITY FUNCTIONS

The variability for a parameter can be represented as a probability density function (PDF), for a continuous variable (a variable that can assume any value within some defined range) the probability density function expresses the likelihood that the value for a random sample will fall within a particular very small interval (Fig. 5, 6, 7 & 8). Probability density functions are used as the basis of stochastic analysis and the proper selection of the PDF's is essential for a good assessment of the uncertainties associated with the choice of rheological parameters. A Gamma curve was found as the one that best fitted the data.

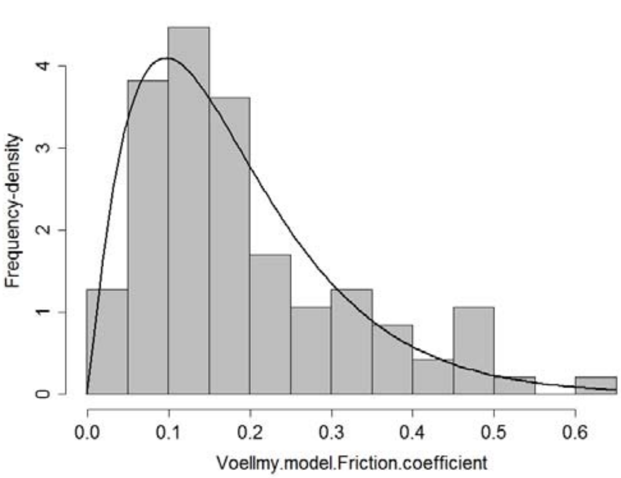

Figure 5. Probability density function of the apparent friction coefficient (μ) inside the Voellmy model.

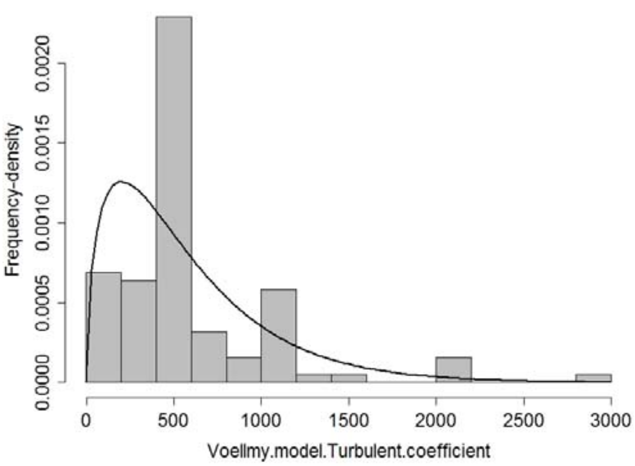

Figure 6. Probability density function of the turbulent coefficient (ξ) (m/s^2) inside the Voellmy model.

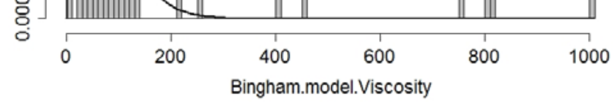

Figure 7. Probability density function of the viscosity (η) (Pa.s) inside Bingham model.

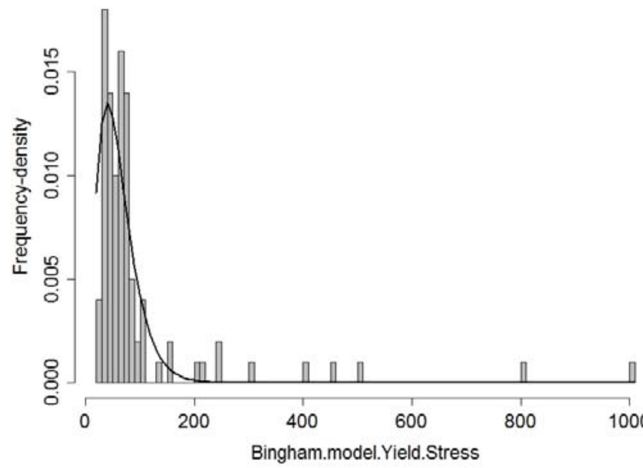

Figure 8. Probability density function of the Yield stress (τ) (Pa) inside the Bingham model.

6 DISCUSSION AND FUTURE WORK

Run-out estimates from dynamic models involve substantial uncertainty due to simplifications and uncertainty involving the release volume, equations of flow including depth averaging, terrain topography, entrained material, run-out and friction coefficients. The uncertainty in the inputs parameters inside the rheological models can be assessed based on analyses of the compiled dataset. This will allow the effect of the release volume as well as unit base resistances to be modeled for different scenarios.

The resulting probability density functions obtained can be used as an input for a probabilistic methodology where the uncertainties in the release volume and unit base resistances (rheological parameters) inside the dynamic models can be addressed. This may help in assessing the confidence of the dynamic run-out model outputs such as the distribution of deposits in the run-out area, velocities and impact pressures.

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