Assessment of landslide run-out by Monte Carlo simulations

Évaluation de la dynamique des glissements de terrain par des simulations de Monte-Carlo

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ABSTRACT: Landslides run-out models are based on theoretical descriptions of mass motion which attempt to model the complex behaviour of the actual flow phenomenon. To reproduce the general features of the mass motion, these models simplify the problem by using parameters that account for complex aspects, which are not explicitly included. This simplification results in model parameters that cannot be related to a specific physical process, and therefore cannot be directly measured. In order to analyse the effect of uncertainties in the input parameters, a probabilistic procedure based on a Monte Carlo simulation for run-out modelling was considered. The framework is based on a dynamic model (MassMov2D), which is combined with an explicit representation of the different parameter uncertainties. The main goal with the proposed methodology is to present a framework to obtain potentially expected run-out extents and intensities in areas where it is not possible to determine the rheological parameters on the basis of back-analyses. The outlined procedure provides a useful approach for experts to produce hazard or risk maps in cases where historical records are either poorly documented or completely lacking, as well as to derive confidence limits on the proposed zoning.

RÉSUMÉ : Les modèles de la dynamique des glissements de terrain sont basés sur des formulations mathématiques qui tentent de théorétiser les phénomènes d'écoulement réels, par nature très complexes. Afin de simuler les caractéristiques générales du mouvement, ces modèles utilisent des paramètres qui représentent et simplifient les aspects complexes du problème, sans pour autant les prendre en compte explicitement. Il en résulte une simplification des paramètres du modèle: ceux-ci ne sont donc plus liés à un processus physique réel, et ne peuvent par conséquent pas être mesurés directement. Afin d'analyser l'effet des incertitudes entourant ces paramètres, une approche probabiliste, basée sur la méthode de Monte Carlo, a été employée. Celle-ci se base sur un modèle dynamique (MassMov2D) ainsi que sur une représentation explicite des incertitudes des différents paramètres. L'objectif principal de cette méthode est de proposer une approche générale dans le but de prédire la taille et l’amplitude des glissements de terrain dans des zones où il n’est normalement pas possible de déterminer les paramètres rhéologiques par méthode arrière. La méthode décrite ici propose une approche pratique afin d’établir des cartes de risque dans les cas où la documentation est limitée, voire inexistante, ainsi que pour estimer les limites de confiance des zonages proposés.

KEYWORDS: Landslides, run-out, Monte Carlo, Bingham rheology, Voellmy rheology, quantitative risk assessment.

1 INTRODUCTION

Dynamic run-out models for landslides are able to simulate the spatial distribution of depth and velocity of the moving mass, which is essential for a quantitative evaluation of hazard and risk at a specific site. Another advantage of the application of dynamic models is that they can simulate the effect of variations in the release volume as well as in the rheological parameters for different scenarios including ones that have no historical evidences.

In practice, a substantial degree of uncertainty characterizes the definition of the deterministic model parameters. This is due to the lack of experimental data and the poor knowledge of the mechanical behaviour of the moving flows. Consequently all models, either those widely used in practical applications or those more recently developed, are based on simplified theoretical descriptions of mass motion which try to capture the complex rheology of the flow phenomenon. This results in a generalization of all models to attempt to reproduce the general features of the moving mass through the use of parameters (mostly for evaluating base shear) which account for aspects not explicitly described or oversimplified. The outcome is that the model parameters cannot be related to a specific physical process, and therefore directly measured, but need to be calibrated. At the moment, a relatively complete and well-established calibration for most of the run-out models is still lacking or not reliable enough to be applied in practical applications. This is connected with one of the basic limitations with the use of dynamic run-out models, which are significantly sensitive to the parameters controlling the base shear (Revellino et al. 2004, Hurlimann et al. 2007, Hungr & McDougall 2009). Inherent uncertainties in the specification of the input data for models are well acknowledged but usually not explicitly incorporated into the analyses. Such uncertainties are normally addressed through conservative estimate of parameters, or in some cases, by a sensitivity analysis. These approaches do not integrate objectively the estimation of uncertainties, and thus may be impractical and lead to either conservative or underestimated hazard levels.

In order to analyze the effect of the uncertainty of input parameters, a probabilistic framework based on a Monte Carlo simulation for run-out modelling is considered as an alternative approach. Monte Carlo analysis is a method that uses statistical sampling techniques of input parameters to derive the probability distributions of solutions for mathematical equations or models. The Monte Carlo analysis was initially developed in the 1940’s and it has been applied to a wide variety of problems for addressing the uncertainty of data and models (Metropolis 1987).

2 METHODOLOGY

The dynamic model used in this study was MassMov2D (Beguería et al. 2009), which solves the equations of conservation of mass and momentum averaged over the depth of the landslide mass using an Eulerian scheme scripted in PCRaster, a GIS modelling environment (Karssenberg et al. 2001). In the equation of conservation of momentum, the shear stress at the bed contact (base of the analysed differential column) is calculated using a rheological model (a relation coupling stresses and strain rates) that should be physically consistent with the overall behaviour of the landslide. In this particular case, two models are used for describing frictional and cohesive-like dominated behaviours, namely the Voellmy and the Bingham models. Simplified formulations of these models are presented in Equations (1) and (2), respectively:

$$\tau = \sigma \tan \phi_{app} + \frac{\rho g\, v^2}{\xi} \tag{1}$$

$$\tau = \tau_y + \mu \dot{\gamma} \tag{2}$$

where, τ is the shear stress at the base of a differential column of landslide mass, σ is the normal stress at the base, ϕ_{app} is an apparent friction angle, ρ is the bulk density of the landslide mass, g is the acceleration of gravity, v is the velocity, ξ is the turbulent coefficient, τ_y is the yield strength, μ is the viscosity, and $\dot{\gamma}$ is the shear strain rate. The apparent friction angle and the turbulent coefficient are material parameters of the Voellmy rheology. The yield strength and the viscosity are the corresponding parameters for the Bingham model.

The main objective of the present application of the Monte Carlo analysis is to examine the effect of uncertainty associated to the variability of the rheological parameters of the Voellmy and Bingham models on the estimation of debris flow run-out. This method allows evaluating the probability distribution of the relevant output parameters (intensity parameters) for a hazard assessment once the proper probability distributions for the parameters of both rheologies have been defined. In other words, it is possible to account explicitly and objectively for the effect of uncertainties in the model. For the application of the Monte Carlo analysis, each of the input parameters was assigned a distribution. The output from the model is calculated several times for a set of randomly selected input parameters. This produces a probability distribution for the output values, such that the uncertainty for the exceedance of any particular value can be estimated. Figure 1 presents a simplified flowchart of this procedure.

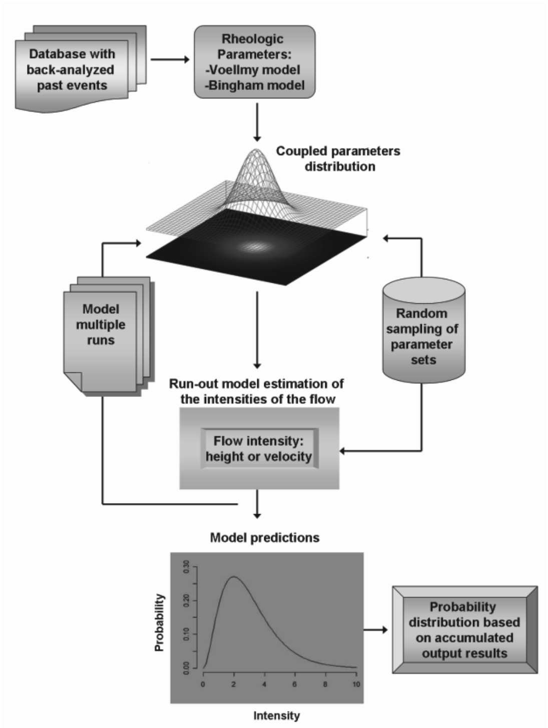

Figure 1. Flow chart of the application of a Monte Carlo method for a probabilistic assessment of landslide run-out.

The uncertainty resulting from the physical process (variability inherent to the phenomenon) is expressed inside the probability density functions of the parameters characterizing the base shear. An extensive literature study was carried out for collecting a database of past back-analyzed landslides, including the calibrated rheological parameters for each event. The relationships between the parameters of the Voellmy and Bingham rheologies were modelled as a "Gaussian Copula" to define the probability density function for both rheological models (Fig. 2)

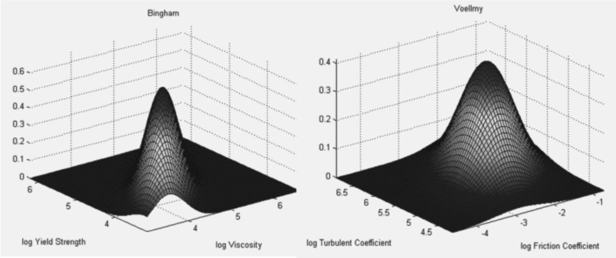

Figure 2. Fitted "Gaussian copula" distribution function to the Bingham rheology (left) and Voellmy rhoelogy (right).

Each distribution was randomly sampled to obtain a set of 5000 pairs of rheological parameters. In the next step, a routine was coded to repeatedly run the simulations for each pair of parameters. At the end of each simulation, the output values of peak intensity parameters (maximum depth and velocity) were saved for selected points on the area of interest. Finally, the output values were fitted to a theoretical probability density function. The parameters for each probability distribution were reported. In addition, the probability that the output exceeds a particular value or will fall within a certain range was calculated.

The dynamic run-out model MassMov2D (Begueria et al. 2009) was selected because it allows the use of scripts which can be modified to include output reports in the form of maps or text files. A batch file was built-in and incorporated inside MassMov2D which selects the randomly generated sets of parameters to produce multiple simulations. The results of each simulation regarding the maximum flow depth and maximum velocity at each control point were reported in a text file form for being fitted to a theoretical probability density function.

3 STUDY CASES

3.1 The Faucon catchment in the Barcelonnette Basin

Inside the Barcelonnette Basin, the Faucon torrent was selected as a test site. The Faucon catchment is a steep forested watershed with an area of approximately 10.5 km^2 which rises to 2984 m a.s.l. Most slopes are steeper than 25°, reaching 80° at the highest elevations. Many of the slopes in the Faucon catchment are covered by various types of Quaternary deposits: thick taluses of poorly sorted debris; moraine deposits; screes and landslide debris. These deposits have a sandy-silty matrix, may include boulders up to 1–2 m in size and are between 3 and 15 m thick (Remaître 2006). The main incised channel has an average slope of about 20°, ranging from 80° in the headwater basin to 4° on the alluvial fan, and is approximately 5500 m in length. Channel morphology is characterized by a V-shaped profile with a steep channel in the upper part, and a flat-floored cross-profile between steep slopes. The Faucon torrent has formed a 2 km^2 debris-fan that spreads across the Ubaye valley floor. It has a slope gradient ranging from 4 to 9°. The fan consists mostly of cohesionless and highly permeable debris (debris-flows strata and/or torrent deposits) (Remaître et al 2005). Two points within the area of interest (in terms of exposed elements) were selected on the accumulation area to calculate the maximum flow height and the maximum velocity (Fig. 3).

3.2 Tresenda village in the Valtellina Valley

Valtellina is an important Italian alpine valley located in Central Italian Alps (Northern Italy, Sondrio Province). The valley starts near Bormio (1,225 m a.s.l.) and it runs for about 100 km to Colico (218 m a.s.l.) near Como Lake. The axis of the valley is formed by the Adda River, originating from small lakes in the Rhaetian Alps at 2,335 m a.s.l. The Adda River flows through the entire valley in a flat alluvial plain up to 3 km wide and it joins the Po River in the Lombardy Plain. Valtellina has a U-shaped valley profile derived from Quaternary glacial activity. The lower part of the valley flanks are covered with glacial, fluvio-glacial, and colluvial deposits of variable thickness (Crosta et al. 2003) The Tresenda village is located in the Valtellina area and is located in the municipality of Teglio in the Valtellina Valley. Spatial information of past damage derived from historical records, local chronicles, and interviews with local people confirmed that the village of Tresenda was affected by debris flows events which caused significant losses in 1983, 2000 and 2002. Soil slips, resulting in debris flows were triggered on the steep slopes above Tresenda, where the soil thickness varies from 0.7 to 2.5 m.

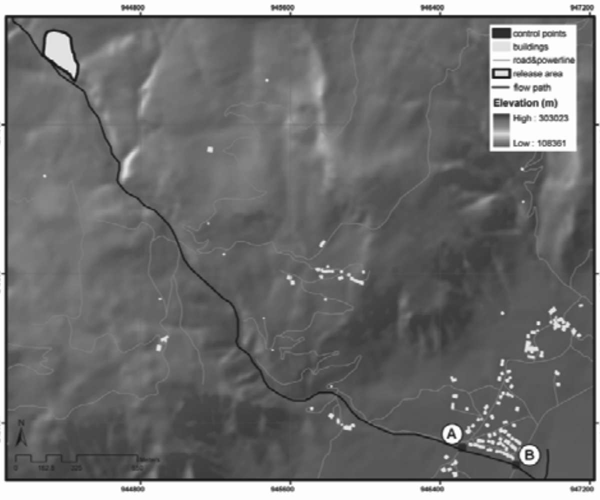

Figure 3. Digital elevation model of the Faucon catchment with the location of the two points used for reporting the results (A and B).

The documented past events crossed minor roads and impacted buildings in the Tresenda village, while running along main drainage lines (Cancelli & Nova 1985, Guzzetti et al. 1992). Major events in future may produce casualties and serious property damages as well as the obstruction of a main road. In the Tresenda case study two location points were also located within the area having the highest concentration of exposed elements.

4 RESULTS

4.1 Application of the methodology to the Faucon catchemnt

The release volume chosen in the Faucon study was 50,000 m^3 and was set as constant in the simulations. Past events in the Faucon area have had final volumes between 55,000 m^3 – 80,000 m^3. The unit weight of the debris flow was set to a constant value of 19 kN/m^3. The time step was set at 1 s and the total duration of each simulation was 500 s. The Monte Carlo method applied in the Faucon catchment was modelled with the Bingham model. This model was selected because of the geo-environmental setting of the area where past events are described to have viscoplastic behaviour (Remaître et al. 2005). In total, 5,000 runs were completed corresponding to the input parameters obtained from randomly sampling the fitted Gaussian copula. For each of the 5,000 runs, the maximum flow heights and maximum velocities were reported for each of the two points. The results of each point were used to populate a probability density function of each intensity parameter. A Gamma distribution was the distribution that best fitted the maximum flow height and velocities measured in points A and B (Fig. 5 & 6).

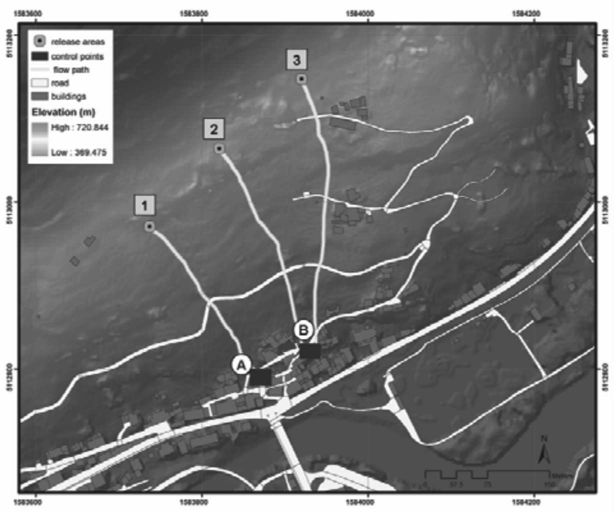

Figure 4. Digital elevation model of the Tresenda village with the location of the two points used for reporting the results (A and B) and three different release areas (1, 2 and 3).

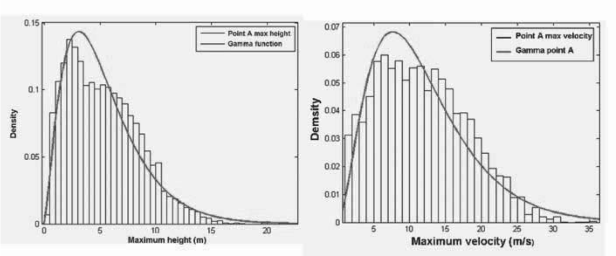

Figure 5. Gamma distribution fitted to the maximum height (left) and velocities (right) values obtained in point A.

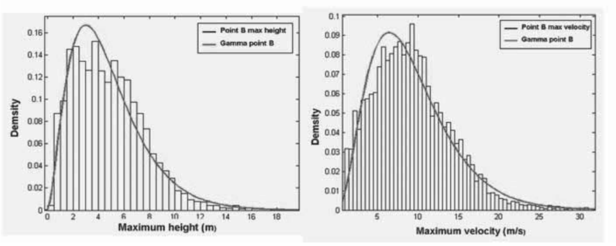

Figure 6. Gamma distribution fitted to the maximum height (left) and velocities (right) values obtained in point B

The obtained results of the mean values of height and velocity computed with the Monte Carlo method were compared with the events that took place in 1996 and 2003 (Remaître et al. 2008, Remaître et al. 2009). In both cases, the mean value of the distribution overestimates the flow height and the flow velocities. In the results, point A which is located higher up in the catchment than point B (apex of the fan) reports higher values for both intensity parameters (height and velocity).

4.2 Application of the methodology to the Tresenda village

In the Tresenda case, the main purpose of the study was to observe the response of the model when using more than one release area. In the Tresenda case, three simultaneous release areas with different volumes were considered (Table 1). The initiation of the debris flow is assumed to be caused by soil slips and the flows are unchanneled along most of the path. The unit weight of debris flow was set to the same value as in the case of Faucon. The total duration for each simulation was 500 s. The Voellmy model was used in the run-out analysis.

In total, 5,000 simulations were carried out associated to the corresponding set of input parameters sampled from the Gaussian copula. For each simulation the maximum flow heights and maximum velocities were reported for each point. Also in the Tresenda case, a Gamma distribution had the best fit to the output parameters. Figures 7 and .8 show the results for the maximum flow height and velocities calculated in points A and B.

Table 1 Release volume used for the Monte Carlo simulation for the three different release areas in the Tresenda village

	Release Volume (m^3)
Release area 1	1424
Release area 2	1410
Release area 3	1518
Total released volume	4352

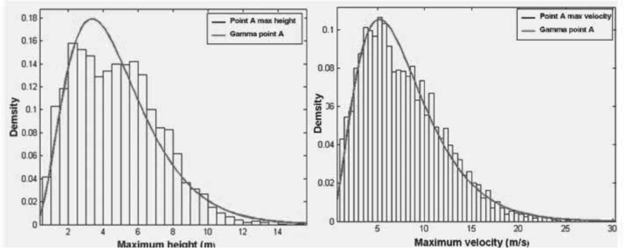

Figure 7. Gamma distribution fitted to the maximum height (left) and velocities (right) values obtained in point A.

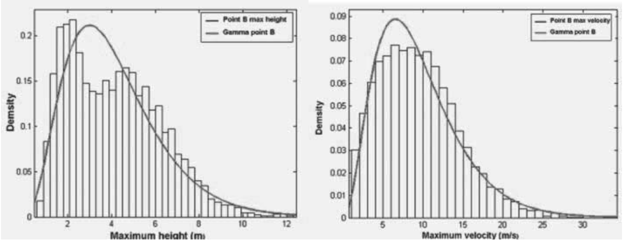

Figure 8. Gamma distribution fitted to the maximum height (left) and velocities (right) values obtained in point B.

The results for the Tresenda case study were compared with events in 1983 and 2002. In these incidents, only information regarding the flow heights was available (no velocities were estimated for these events). In the Tresenda case, the mean value of the flow height in point A is overestimated compared to the actual event while point B has a lower mean value than the observed event. In the Tresenda case the simulated values are closer to the actual events than in the Faucon case. This can be possibly attributed to the potential of the Voellmy rheology to model consistently these types of events.

5 CONCLUSIONS

The Monte Carlo method offers the advantage of modelling the probability distributions of the intensity parameters from run-out simulations. Of course, the reliability of the fitted probability density functions for the input parameters strongly depends on the completeness and accuracy of the original back-analyses included in the collected database. Another limitation of this study is that the estimated probabilities do not explicitly account for the temporality of the phenomena. For future assessments it is recommended that run-out simulations using a stochastic approach become a routine practice in order to produce adequate future hazard scenarios and quantify the uncertainty due to the input parameters. This will result in intensity maps that are easier to interpret for end users, especially within a probabilistic framework for landslide mitigation.

6 ACKNOWLEDGEMNETS

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7 REFERENCES

Begueria S., van Asch Th.W.J., Malet J.-P., Grondahl S. 2009. A GIS-based numerical model for simulating the kinematics of mud and debris flows over complex terrain. *Nat. Hazards and Earth Syst. Sci.*, 9, pp. 1897-1909.

Cancelli A. and Nova R.. 1985. Landslides in soil debris cover triggered by rainstorms in Valtellina (Central Alps – Italy). In: Proceedings of 4th International Conference and Field Workshop on Landslides. The Japan Geological Society, Tokyo, pp. 267–272.

Crosta G.B., Dal Negro P., Frattini P. 2003. Soil slips and debris flows on terraced slopes. *Nat. Hazards and Earth Syst. Sci.*, 3, 31- 42.

Guzzetti F., Crosta G., Marchetti M., Reichenbach P. 1992. Debris flows triggered by the July, 17–19, 1987 storm in the Valtellina area (Northern Italy). International Symposium Interpraevent 1992, Bern, Switzerland, pp. 193-203

Hungr O. and McDougall S. 2009. Two numerical models for landslide dynamic analysis. *Computers & Geosciences* 35, pp. 978–992.

Hürlimann M., Medina V., Bateman A., Copons R., Altimir J. 2007. Comparison of different techniques to analyse the mobility of debris flows during hazard assessment-Case study in La Comella catchment, Andorra. In Chen & Majors (eds.) Debris-Flow Hazard Mitigation :Mechanics, Prediction and Assessment. Millpress, Netherlands, pp. 411-422.

Karssenberg, D., Burrough, P. A., Sluiter, R., De Jong, K. 2001. The PCRaster software and course materials for teaching numerical modelling in the environmental sciences. *Transactions in GIS*, 5(2), pp. 99-110.

Metropolis N. 1987. "The beginning of the Monte Carlo method". Los Alamos Science (1987 Special Issue dedicated to Stanisław Ulam): 125–130.

Remaître A., Malet J.-P., Maquaire O. 2005. Morphology and sedimentology of a complex debris flow in a clay-shale basin. *Earth Surf. Process. Landforms* 30 pp.339-348.

Remaître A. 2006. Morphologie et dynamique des laves torrentielles: Applications aux torrents des Terres Noires du bassin de Barcelonnette (Alpes du Sud). Ph.D. thesis.

Remaître A., van Asch Th.W.J., Malet J.-P., Maquaire O. 2008. Influence of check dams on debris flow run-out intensity. *Nat. Hazards Earth Syst. Sci.* 8, pp. 1403-1416.

Remaître A., Malet J.-P., Maquaire O. 2009. Sediment budget and morphology of the 2003 Faucon debris flow (South French Alps): scouring and channel-shaping processes.Proc. Landslide Processes: from geomorphological mapping to dynamic modelling, pp. 75-80.