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From back-analysis to run-out prediction: a case study in the Western Italian Alps

Abstract Rock avalanches are complex phenomena that occur with a low frequency but which have a high destructive potential. As a consequence, the people who are responsible for the management of a territory are more and more interested in predicting the possible evolutions of well-known potential events. Tackling the above problems from a quantitative point of view, the RASH3D code, based on continuum mechanics concepts, has been here used to predict the evolution of a potential rock avalanche in the Western Italian Alps. A calibration-based approach, in which rheological parameters are constrained by systematic adjustment during trial-and-error back-analysis of past events similar to the landslide under investigation, is proposed to set rheological parameter values to be used for prediction purposes. The back-analysis of a $2{\cdot}10^6$ m^3 rock avalanche located in the Divedro Valley, close to the area of the potential event, has then been analysed using both a frictional and a Voellmy rheology. The characteristics of the slope and the dynamics of the event have made the frictional rheology more suitable to come to the correct simulation of the historical case. The back-analysis results have contributed not only in the selection of the rheological parameter values but also in the choice of the type of rheological law to use in the carried out forward-analyses.

Keywords Continuum mechanics · Landslide prediction · Rheological parameters · Calibration-based approach

Introduction

Rock avalanches are low frequency phenomena, but they have a high impact on the territory. The large size and the high velocity of the moving mass make it possible for the material to cover rapidly long distances and destroy large areas (Hungr et al. 2001).

Due to the abovementioned aspects, it is usually not possible to mitigate this type of event with consolidation and protection works such as rockfall barriers or drapes. A need for methods to predict the extension of areas that can be affected by potential landslide propagation ("run-out analysis") then arises. These methods should fit in the framework of quantitative risk assessment.

A promising way to describe flows on three-dimensional topographies is given by models based on continuum mechanics (i.e. the heterogeneous real mass is treated as a continuum) and that assume the avalanche thickness to be small compared to its length. This hypothesis allows depth-averaged Saint Venant equations to be used, in which a complete three-dimensional description of the flow is avoided (Savage and Hutter 1989).

These landslide dynamic models have gradually improved over the past three decades to the point where, when used in combination with careful engineering and geoscience judgement, first-order run-out prediction appears to be possible (e.g. Chen and Lee 2000; Denlinger and Iverson 2004; McDougall and Hungr 2004). However, there is still considerable room for improvement. In particular, the problem of how to set the rheological parameter values for forward-analysis remains a major challenge that can be dealt with by following either a measurement-based or a calibration-based approach. They both assume that rapid landslide dynamics can be described by constitutive relationships, but the way in which rheological parameter values are determined is different.

The measurement-based approach is representative of the scientific method that is traditionally used for dynamic analysis. It states that rapid landslide behaviour is a function of involved material intrinsic properties, which can be measured using independent controlled experiments before being applied to the analysis of real cases. Instead, in the calibration-based approach, rheological parameters are constrained by systematic adjustment during trial-and-error back-analysis of full-scale prototype events. Simulation is typically achieved by matching the computed travel distance, velocities, and extent and depth of the deposit to those of the prototype (McDougall et al. 2008).

Critics of this last method argue that model calibration can give a successful simulation by arbitrary adjustments of the right type and number of variables, and that model adaptability can therefore be mistaken for model accuracy (Iverson 2003). On the other hand, given the extreme complexity of landslide dynamics, the measurement of rheological parameters could be considered idealistic. Although it is scientifically appealing to be able to measure the input data independently, no standard tests are available to measure, for example the properties of coarse rock avalanche debris travelling at extremely rapid velocities. Such properties, even if measurable, may change significantly during the course of motion, along with the rheology itself, and may be scale-dependent (McDougall 2006).

This is why a calibration-based approach is here proposed to define rheological values to be used for prediction purposes.

First, a database of values for rheological parameters has to be made out back-analysing as much past events as possible. Then, if the potential event to analyse is not in a basin where similar events have already occurred (class A), a range of rheological parameter values can be obtained from the above database as a function of the similarity between potential and past events, even if they concern different geographical areas. As far as this aspect is concerned, it is here stressed that since lithology and morphology widely influence run-out, the parameters calibrated through back-analysis are only transferable when the characteristics of the back-analysis area are as much closer as possible to those of the prediction one. Instead, if the potential event is in the same area where similar well-documented events already occurred (class B), rheological parameters calibrated for past events can be transferred in a more direct way to the forward-analysis. In fact, similarity in lithological and morphological characteristics is almost guaranteed.

Examples of numerical analyses undertaken for cases belonging to class A have been extensively dealt with in Pirulli (2005), Pirulli and Sorbino (2008) and McDougall et al. (2008). A case belonging to class B is here presented and discussed.

The analysed case history pertains to a $2\cdot10^6$ m^3 rock avalanche that occurred in 1951 in the Divedro Valley (Western Italian Alps), close to the village of San Giovanni (Crevoladossola, Verbano-Cusio-Ossola). The event is described and numerically back-analysed using the RASH3D continuum mechanics numerical code.

Since a potentially unstable area was found close to the area of the San Giovanni historical event, through detailed field inspections, the rheological parameters calibrated through the back-analysis of the latter are used for the forward-analysis of the first.

Different scenarios for the potential events are defined and numerically analysed, and the obtained results are discussed.

Description of the study area

The Ossola area, located in the northern Piedmont region (Verbano-Cusio-Ossola province, Italy), belongs to the sector of the Alpine chain that is between the two Swiss Cantons of Ticino and Valais. It is crossed by the Toce river, and is composed of one main valley (the Ossola valley itself) and seven tributary valleys: Anzasca, Antrona, Bognanco, Divedro, Antigorio-Formazza, Isorno and Vigezzo (Fig. 1).

The Divedro Valley, where the Diveria River flows, is particularly important since it is crossed by a railway line and Simplon Road 166 which connect Italy to Switzerland through the Simplon Pass (Fig. 2).

In 1951, this valley was affected by a rock avalanche that damaged the aforementioned infrastructures with heavy economic and social consequences. After this event, the railway line was moved to a tunnel, while Simplon National Road 166 was demoted to a provincial road, as a new Simplon National Road was built in a tunnel.

Geological and geomorphological settings

The Ossola area is a typical glacial environment that has developed in one of the longest fault valleys in the Western Alps. This environment is particularly subject to degradation, is full of alluvial and moraine deposits, and is prone to landslides. In this context, the stretch of the valley in front of the studied area follows a very narrow fluvial incision overimprinted onto the ancient glacial bed.

The whole area is located in the Lower Pennine Nappe, which appears to be greatly reduced in thickness and steeply southeast dipping. In particular, the Divedro Valley belongs to the Monte Leone Unit (Lower Pennine Nappe) constituted by thick-bedded augen gneiss with intercalations of huge till sheets and talus slopes. In the landslide sector, the augen gneiss is linked to thick lenses of strongly fractured limestones and dolomites.

The augen gneiss is normally massive and stable. Only where there is the presence of tectonic disturbance (e.g. faults) do the stability conditions become weak. This is the case of the analysed area, where persistent discontinuity systems, which reflect the regional structural setting, decrease considerably the overall stability of the bedrock and generate relevant predisposing instability conditions due to the possible isolation of multishaped rock wedges sometimes pluridecametric in size that can actually slip or fall towards SE (Fig. 3).

Furthermore, the presence of open cracks allows infiltration of the superficial water which, due to freeze–thaw cycle action, can cause a change in slope stress and strain distribution with consequent destabilisation and failure of rock masses.

All these conditions, together with the high slope gradient (about 60°), increase the probability of gravitational movement occurrence in the area.

Description of the 1951 San Giovanni rock avalanche

In November 1951, following prolonged and intense rainfall in the Alps and in the Northern Appenines, the left bank of the Po River burst at Occhiobello, Malcantone and Paviole (Polesine, Rovigo Province, Italy) causing the largest flooding event in the twentieth century. At the same time, in the Alpine valleys, where the tributaries (e.g. Sesia, Orco, Stura, Dora Baltea, Ticino) of the Po River flow (Fig. 1), floods and landslides were also recorded.

During this emergency period, on November 12, a rock avalanche, involving a volume of about $2\cdot10^6$ m^3, detached from the left side of the Burra Stream, a tributary of the Diveria River,

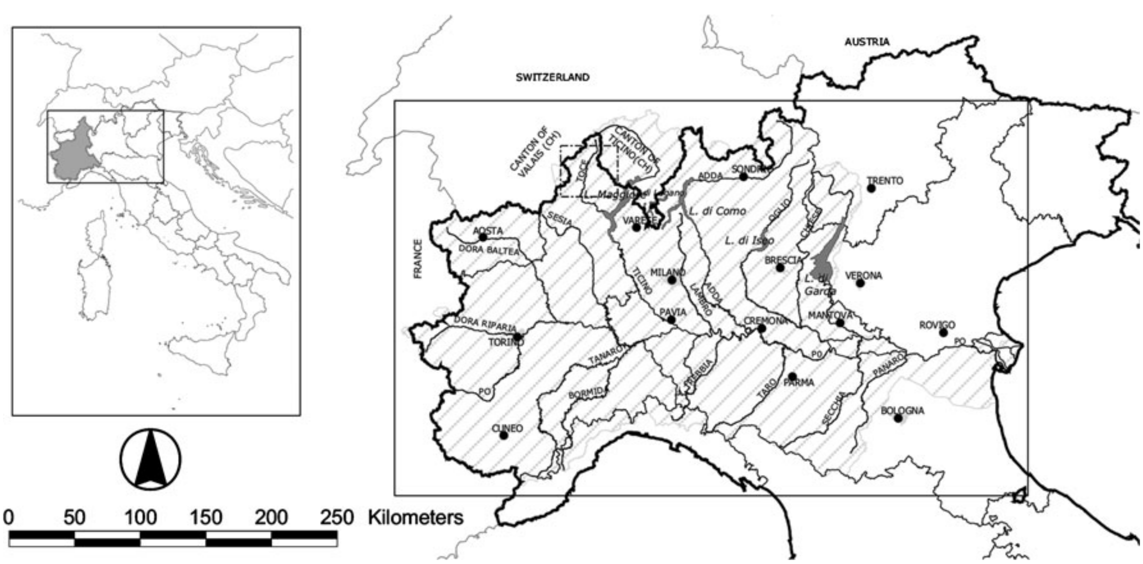

Fig. 1 Geographical setting and hydrographic basin of the Po River (image after http://www.comune.gavello.ro.it/biblioteca/CD_ALLUVIONE/Web/Sit_mete.htm)

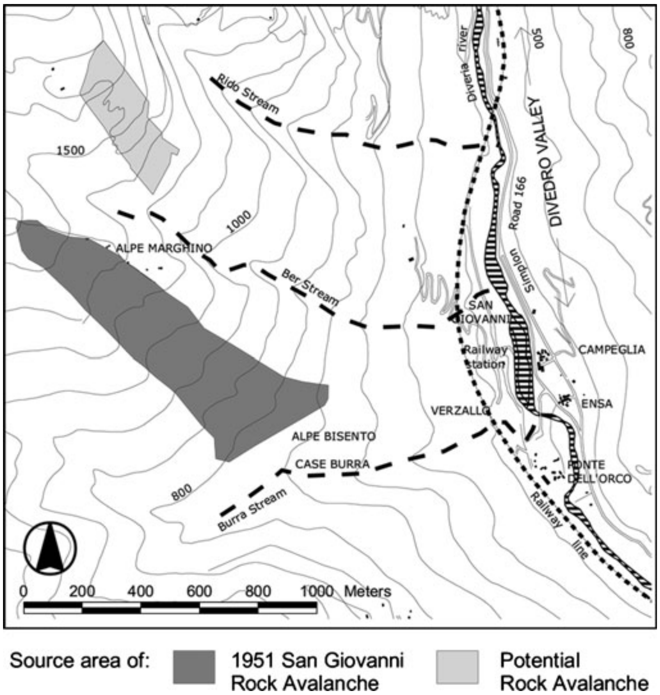

Fig. 2 Description of the study area

near Alpe Marghino, and rapidly moved downslope. This is known as the 1951 San Giovanni rock avalanche (Enso di Crevoladossola, Verbano-Cusio-Ossola, Italy; Fig. 4).

The avalanche source area (Fig. 5) is located at the southeast margin of a pre-existing deep-seated gravitational deformation which affects the slope (Ramasco et al. 2002).

The causes of the event have been put down to a combination of some predisposal ("Geological and geomorphological settings" section) and causal (e.g. rainfall) factors: the presence of a pre-existing and partially exposed schistosity plane at the rock avalanche source area, a slope characterised by the presence of a succession of rock and earth layers, and the decay of the resistance characteristics of some of these layers, due to water chemical action and warm/cool cycles, caused the sudden initiation of a planar sliding phenomenon that successively evolved into the destructive rock avalanche.

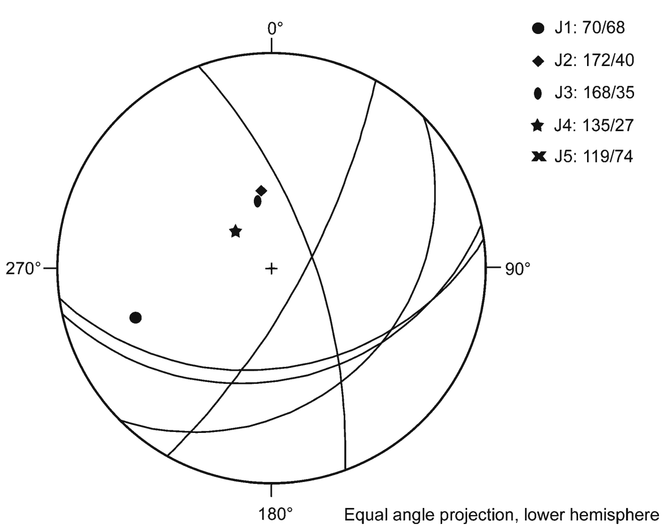

Fig. 3 Stereographic projection of the major discontinuities

According to history chronicles, witness testimonies, aerial photos and site surveys, it has been possible to reconstruct the dynamics of the event as follows.

The mobilised material, mainly rock, mud and trees, travelled a distance of about 1,800 m from its source over a difference in vertical elevation of about 1,100 m.

The mass slid down the steep slope that exists at the base of the southeast exposed detachment zone, at approximately 750 m asl. Due to a watershed divide that runs parallel to the flow run-out direction, the mass splits into two branches in the upper part of the slope (dashed line in Figs. 4 and 6).

The southern branch, made of metric and decametric rock blocks, banged against a northeast exposed slope that caused the formation of the main deposit, where about the 90% of the mass stopped, with an average depth of about 30 m along the Burra stream and the occlusion of the creek bed. The still moving mass turned to the east and continued down towards the Divedro Valley. The deposit mass thickness gradually diminished going towards the bottom of the valley, with the flowing front final stopping at the junction of the Burra stream with the Divedro Valley. Along the path, the destruction of some buildings in the Alpe Bisento and Case Burra villages was caused (Fig. 4).

The northern branch, made of stone and clay, channelled in a softer sloping incision, continued to evolve as far as the Diveria creek bed (increasing its bed by about 3 m) and caused the destruction of some buildings in the Verzallo area and San Giovanni village. A crossing keeper's box, the Simplon railway line and the Simplon National Road 166, located at the bottom of the Divedro Valley, were also affected and damaged by the avalanche. Four people lost their lives.

For both branches, a main run-out and a secondary run-out areas are evidenced in Fig. 5. This distinction is intended to separate the sector of the slope that recorded the main damage since a large quantity of material travelled or deposited on it (main run-out area) from the sector that was interested by a moving mass of only a few decimeter thick (secondary run-out area).

Description of the surveyed potential rock avalanche

A detailed inspection of the slope around the 1951 San Giovanni rock avalanche has revealed that, due to the existing system of tension cracks ("Geological and geomorphological settings" section), important instability features are present on the north side of the 1951 rock avalanche source area. A portion of slope, similar in characteristics to the area of the historical landslide, which could evolve into a destructive event, is in particular highlighted (Fig. 7).

The toe of this potentially unstable area lies at an elevation of about 1,300 m asl on a slope with a local average inclination of about 65°. Since this slope is steeper than that of the 1951 rock avalanche, a landslide with greater speed could be expected. The prediction of its possible evolution therefore plays a key role in the management of the valley below.

As a function of the sliding surface depth and of the vertical joint setting (Figs. 3 and 7), the potentially unstable area can be

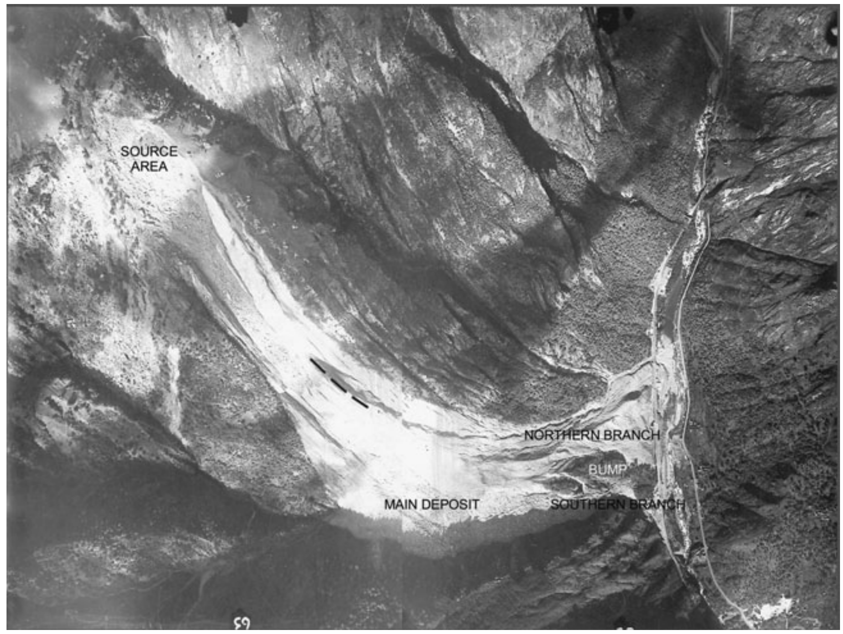

Fig. 4 The 1951 San Giovanni rock avalanche (image courtesy of the Istituto Geografico Militare). *Dashed line* watershed divide

subdivided into subareas which could give rise to the following evolution scenarios (Fig. 8):

- Scenario 1: the mass slides on a shallow sliding surface (de in Fig. 8c, d), having the attitude given for joint J3 in Fig. 3, and involves a volume of about $8.5 \cdot 10^5$ m^3 (1A) or $3.25 \cdot 10^5$ m^3 (1B), as a function of the vertical fractures selected to confine the potentially unstable portions of the slope;
- Scenario 2: the mass slides on a deep sliding surface (fg in Fig. 8c, d), having the attitude given for joint J4 in Fig. 3, and involves a volume of about $3 \cdot 10^6$ m^3.

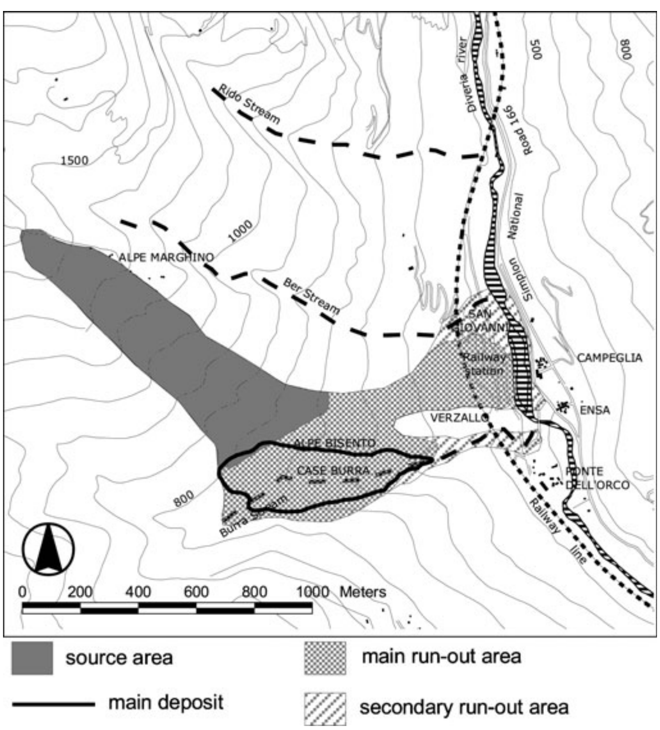

Fig. 5 Scheme of the 1951 San Giovanni rock avalanche

For scenario 1, it has been assumed that some of the open fractures characterising the slope could intersect the shallow sliding surface, which emerges at the toe of the whole instable area. It follows that, as a function of the assumed releasing fractures, the instabilisation of one portion rather than another one can originate (i.e. 1A and 1B).

A different probability of occurrence can furthermore be associated to each scenario. In fact, given the high degree of fracturation of the slope, a one-phase release of the large volume involved in scenario 2 is believed to have less probability of occurrence than the release of some local portions (i.e. scenarios 1A and 1B).

The continuum mechanics approach

The numerical code used in the present paper treats a moving mass as a homogeneous continuum material with constant density (e.g. Savage and Hutter 1989; Iverson and Denlinger 2001).

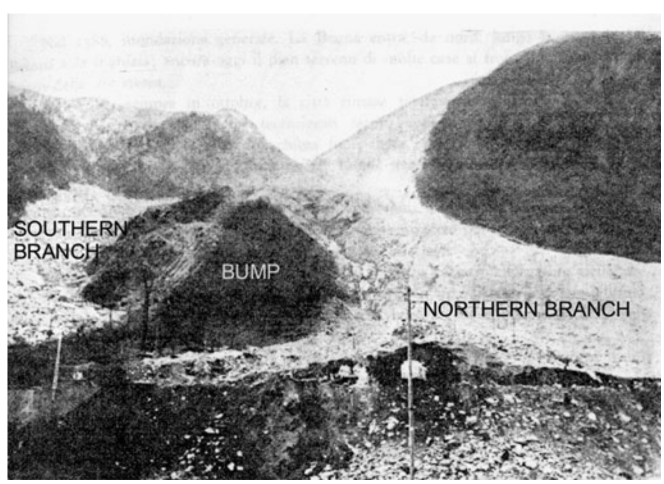

Fig. 6 The splitting in two branches of the 1951 San Giovanni rock avalanche at the bottom of the valley (vintage photo)

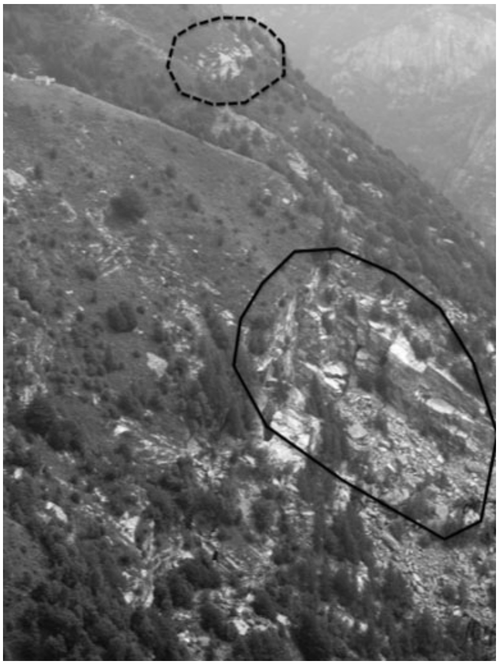

Fig. 7 Sketch of the unstable slope. *Dashed line* source area of the potential event; *continuous line* detail of the source area of the 1951 rock avalanche

This assumption is supported by the observation that the depth and length of a flowing mass are usually large compared to the characteristic dimension of the particles involved in the movement.

Within these limits, it becomes then possible to find an "equivalent" fluid whose rheological properties are such that the bulk behaviour of the flowing body can simulate the expected bulk behaviour of the real landslide.

It follows that the evolution of the avalanching mass is governed by mass and momentum conservation laws, namely

$$\nabla \cdot \mathbf{v} = 0 \tag{1}$$

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v}\right) = -\nabla \cdot \boldsymbol{\sigma} + \rho \mathbf{g} \tag{2}$$

in which $\mathbf{v}=(\mathbf{v}_x, \mathbf{v}_y, \mathbf{v}_z)$ denotes the three-dimensional velocity vector of the avalanche in a (x, y, z) coordinate system, $\boldsymbol{\sigma}$ is the Cauchy stress tensor, ρ is the mass density, and $\mathbf{g}$ is the gravitational acceleration vector.

Assuming that the vertical structure of the flow is much smaller than the characteristic length, the balance equations can be integrated in depth, obtaining the so-called depth-averaged Saint Venant equations (Savage and Hutter 1989). This depth-averaged approach, together with the assumption that most of the collisions and deformations are concentrated in the boundary layer near the bed surface (Kilburn and Sorensen 1998), allows us to ignore changes in the mechanical behaviour inside the flow. The complex rheology of the moving material is therefore incorporated in a single term which describes the frictional stress that develops at the interface between the flowing material and the rough surface. Neglecting transverse shear stress (i.e. τ_{xy}), the equations that have to be solved are therefore:

$$\begin{cases} \dfrac{\partial h}{\partial t} + \dfrac{\partial(\overline{v_x} h)}{\partial x} + \dfrac{\partial(\overline{v_y} h)}{\partial y} = 0 \\ \rho\left(\dfrac{\partial(\overline{v_x} h)}{\partial t} + \dfrac{\partial(\overline{v_x^2} h)}{\partial x} + \dfrac{\partial(\overline{v_x v_y} h)}{\partial y}\right) = -\dfrac{\partial(\overline{\sigma_{xx}} h)}{\partial x} - \tau_{zx_{(z=b)}} + \rho g_x h \\ \rho\left(\dfrac{\partial(\overline{v_y} h)}{\partial t} + \dfrac{\partial(\overline{v_y v_x} h)}{\partial x} + \dfrac{\partial\left(\overline{v_y^2} h\right)}{\partial y}\right) = -\dfrac{\partial(\overline{\sigma_{yy}} h)}{\partial y} - \tau_{zy_{(z=b)}} + \rho g_y h \end{cases} \tag{3}$$

Where $\overline{v_x}, \overline{v_y}$ denote the depth-averaged flow velocity in the x and y directions, h is the fluid depth, τ_{zx}, τ_{zy} are the shear stress in the x and y directions, $\overline{\sigma_{xx}}, \overline{\sigma_{yy}}$ denote the depth-averaged stress in the x and y directions, and g_x, g_y are the projections of the gravity vector along the x and y directions.

The RASH3D code

The RASH3D code, which is based on the continuum mechanics approach and which is able to run propagation analyses on a complex topography, is applied in the present work.

RASH3D originates from a pre-existing code (SHWCIN) that is based on the classical finite volume approach to solve hyperbolic systems using the concept of cell-centred conservative quantities, developed by Audusse et al. (2000) and Bristeau and Coussin (2001) to compute Saint Venant equations in hydraulic problems.

An extension of SHWCIN to simulate dry granular flows using a kinetic scheme was initially introduced by Mangeney et al. (2003).

Pirulli (2005) proposed further modifications of SHWCIN to prevent observed mesh-dependency problems, permit simulation of motion across irregular three-dimensional terrain, incorporate the influence of internal strength and allow the selection of more than one possible basal resistance relationship. The new upgraded code (RASH3D) has been validated both in laboratory tests and through back-analysis of real events.

Rheological models and parameters

As for the rheological characteristics of the flowing mass, four different rheologies are implemented in RASH3D at the present time: frictional, Voellmy, quadratic and Pouliquen. Among these, the following two rheologies were selected for the numerical analysis of the 1951 San Giovanni rock avalanche and of the potential rock avalanche:

- Frictional rheology, based on a constant friction angle δ, which implies a constant ratio of the shear stress to the normal stress. The shear resistance stresses, τ_{zi} (i=x,y), are independent of the velocity:

$$\tau_{zi} = (\rho g_z h \tan\delta)\,\mathrm{sgn}(\overline{v}) \tag{4}$$

where ρ is the material bulk density, g_z is the acceleration due to gravity, h is the flow depth and $\overline{v}$ is the depth averaged flow velocity.

- Voellmy rheology, which consist of a turbulent term, $\overline{v}^2/\xi$, accounts for velocity-dependent energy losses, and a

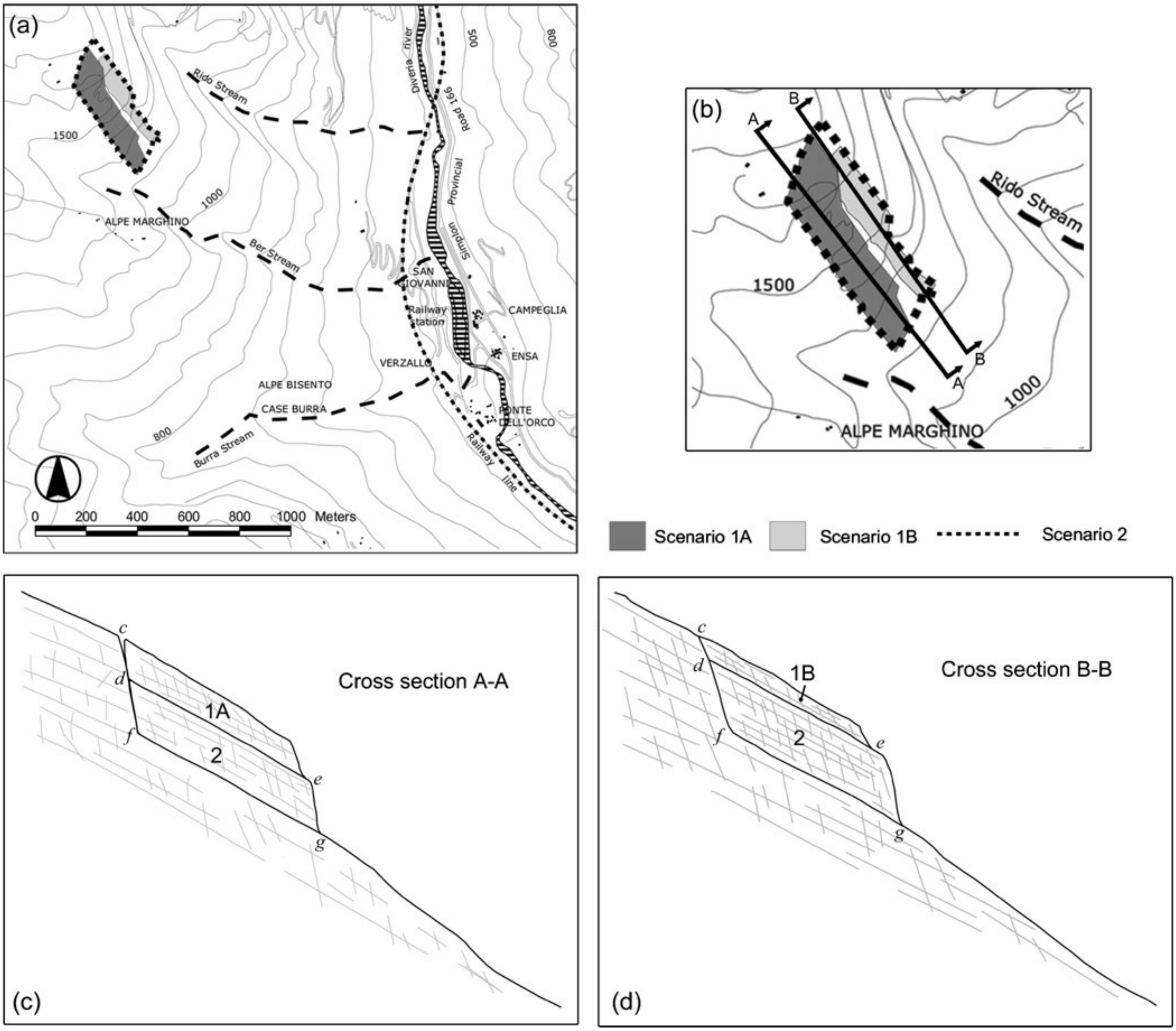

Fig. 8 Scheme of the potential event source area. **a** Indication of the possible evolution scenarios. **b** Detail of **a** with indication of **c** and **d** representative cross-section position. *Lines de* have the attitude given for joint J3, *fg* for joint J4, and *cd* and *df* for joint J5 in Fig. 3

Coulomb or basal friction term to describe the stopping mechanism. The resulting basal shear stress is given by the following equation:

$$\tau_{zi} = \left(\rho g_z h\mu + \frac{\rho g\overline{v}^2}{\xi}\right)\mathrm{sgn}(\overline{v}) \quad (5)$$

where ξ is the turbulence coefficient, and μ is the friction coefficient, with $\mu = \tan\delta$.

Numerical model settings and input parameter selection

Three steps are necessary to carry out numerical analyses with RASH3D: (1) uploading the topography of the study area as a digital elevation model (DEM), (2) determining the landslide initial volume and (3) defining guidelines for the rheological parameter calibration.

Since no pre-event DEM was available for the back-analysis of the 1951 San Giovanni rock avalanche, analyses were first carried out using the post-event DEM with a 5-m grid spacing. As will be shown in "Numerical back-analysis of the 1951 San Giovanni rock avalanche" section, the drawing of a pre-event DEM was successively necessary to improve the quality of the back-analysis results. To this aim, aerial photographs taken before and just after the event, existing descriptions of the avalanche and on-site surveys were used to define the border and the average distribution of material thickness of the past-event deposition area. In particular, the monoclinal trend of the triggering slope allowed to define the slope average dip to use as upper surface for calculating the triggering volume in the source area and lower surface for the computation of the main deposit depths. Since about the 90% of the mobilised material deposited in the main deposit (Fig. 5), the pre-event DEM was obtained from the post-event DEM by subtracting the thickness of the avalanche deposit from the altitudes of the post-event DEM only in this area. The total volume removed from the post-event DEM equals the sum of the 1951 San Giovanni rock avalanche initial failure mass and an estimate bulking due to fragmentation of the rock during propagation (e.g. Sherard et al. 1963; Hungr and Evans 2004).

The main uncertainties for modelling the potential event concerned:

- the estimation of the initial volume. This problem was faced by defining the three scenarios described in the "Description of the surveyed potential rock avalanche" section;
- the setting of rheological parameter values. Since the potential and the past events belong to the same basin, this problem was faced by resorting to a calibration-based approach, and rheological parameters for prediction purposes were obtained through the back-analysis of the past event.

Numerical back-analysis of the 1951 San Giovanni rock avalanche

The dynamics of the 1951 San Giovanni rock avalanche has been investigated with RASH3D using two rheological laws ("Rheological models and parameters" section): frictional rheology, with one unknown parameter (i.e. friction angle), and Voellmy rheology with two unknown parameters (i.e. friction coefficient and turbulence coefficient). The numerical results have been judged in terms of their ability to reproduce the rock avalanche main run-out area (Fig. 5), taking into account that (1) a part of the moving mass deposits in the upper part of the slope, (2) most material stops in the area-defined main deposit, (3) a progressive thinning of mass deposit is observed outside the main deposit going towards the bottom of the valley and (4) the deposit in the valley bottom is mainly due to the northern branch of the flow. A trial-and-error selection of rheologies and rheological parameter values has then been necessary.

The first set of analyses has been carried out using the post-event topography as supplied by the existing DEM. According to Hungr and Evans (1996), who back-analysed 23 cases of rock avalanche with three different rheologies (frictional, Voellmy and Bingham) and observed that about 70% of the cases were reasonably simulated with the Voellmy model with the friction coefficient set to 0.1 and the turbulence coefficient of 500 m/s^2, this combination of parameters was at first assumed for the Voellmy rheology. Unsatisfactory results caused that new simulations were carried out testing the following range of rheological parameters: $0.05 \leq \mu \leq 0.5$ and 100 m/s$^2 \leq \xi \leq$1,000 m/s^2. Similarly, the following range $20 \leq \delta \leq 35$ was examined for the frictional rheology. The best-fit data for both frictional (δ=31°) and Voellmy (μ=0.4; ξ=100 m/s^2) results have showed that the two rheologies can satisfactorily simulate the splitting of the mass in the upper part of the slope (Fig. 9) and approximate the maximum travel distance of the mass, but probably due to the use of a post-event DEM, the main deposit is shifted with respect to its on-site position (Fig. 10). Nevertheless, the frictional rheology, according to reality, allows for partial deposition in the upper part of the slope and defines a valley deposit that is mainly due to the northern branch of the flow (Fig. 10a). Regardless of what rheological values were, the Voellmy rheology has not been able to simulate neither the partial deposition in the

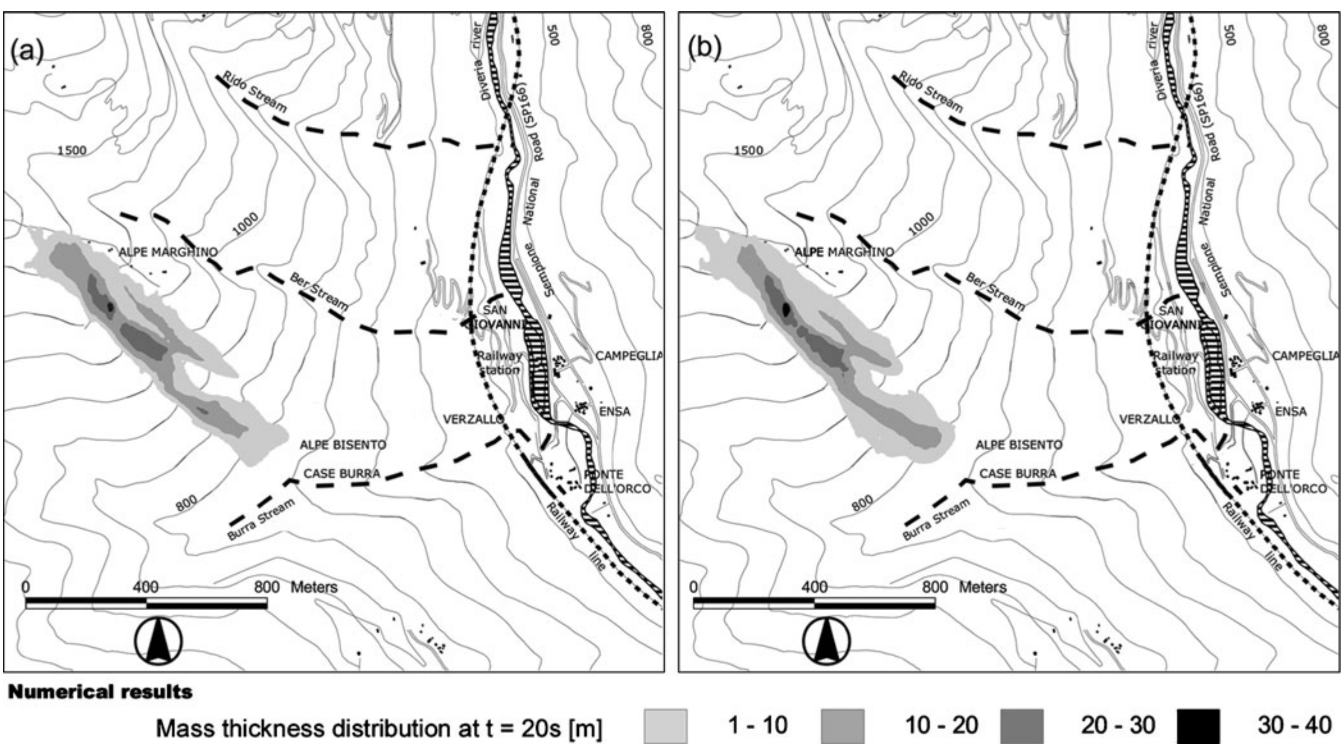

Fig. 9 1951 San Giovanni rock avalanche—post-event DEM: detail of numerical simulation of mass splitting in the upper part of the slope as observed at t=20 s. **a** Frictional rheology δ=31°. **b** Voellmy rheology μ=0.4 and ξ=100 m/s^2

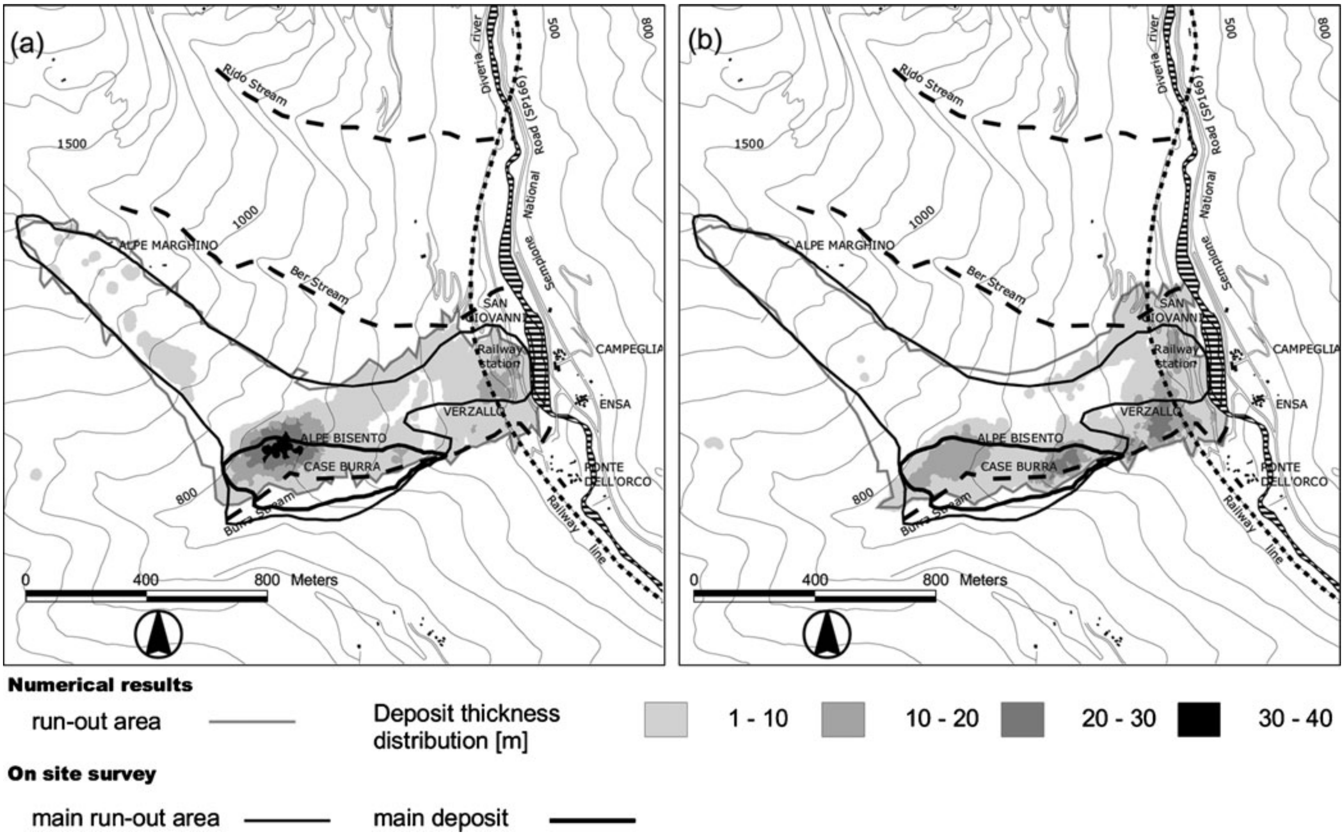

Fig. 10 1951 San Giovanni rock avalanche—post-event DEM: comparison between RASH3D best-fit results and on-site survey. **a** Frictional rheology δ=31°. **b** Voellmy rheology μ=0.4 and ξ=100 m/s^2

upper part of the slope nor the deposition in the valley bottom due to the northern branch (Fig. 10b).

In order to test the influence of the post-event DEM on the above results, the pre-event DEM, obtained as described in "Numerical model settings and input parameter selection" section, has then been used for a new calibration of the above rheological parameters. But the aforementioned δ=31°, for the frictional rheology, and μ=0.4, ξ=100 m/s^2, for the Voellmy rheology, have still remained valid to reproduce the run-out of the real mass (Fig. 11).

Actually, the analyses carried out with the pre-event DEM have improved the quality of the results obtained with the frictional rheology: the simulated main deposit is now shifted and better fits the position of the real one (comparison between Figs. 10a and 11a). On the contrary, the Voellmy rheology is still unable to simulate the main deposit mass distribution: the simulated deposit unrealistically localises major depths in the southern part of the main deposit. As a consequence, the Voellmy rheology has been abandoned.

An in-depth study has been finally undertaken for the frictional rheology. This has led to the identification of a set of values for the friction angle, ranging between 31° and 33°, that can reproduce in an acceptable way the real run-out.

The simulations obtained with δ=32° and δ=33° (Fig. 12) have underestimated the travel distance, but have reproduced the deposition of material in the upper part of the slope more precisely than with δ=31° (Fig. 11). The maximum velocity reached by the simulated mass has been $v\approx39$ m/s for the case of δ=31°, while a lower value $v\approx33$ m/s has been observed using δ=33°.

Numerical analysis of the potential rock avalanche evolution

Given the vicinity of the 1951 San Giovanni rock avalanche to the potential landslide area, the rheological parameters calibrated for the historical event have been used for prediction purposes. In this regard, it is here suggested that it is more reliable and safer to select a range of values for the rheological parameters than using a single rheological value. Therefore, two different numerical analyses have been carried out for each of the three scenarios described in "Description of the surveyed potential rock avalanche" section, using the frictional rheology and a friction angle of 31° and 33°, respectively (i.e. the minimum and maximum best-fit values obtained for the above back-analysis).

In the case of scenario 1A, the higher friction angle value (δ=33°) has determined a larger deposition of material on the slope and lower depths in the distal deposit compared to the results obtained using δ=31°. The lateral spread of the deposit is rather unchanged, while the run-out distance is shorter when δ=33° has been adopted (Fig. 13).

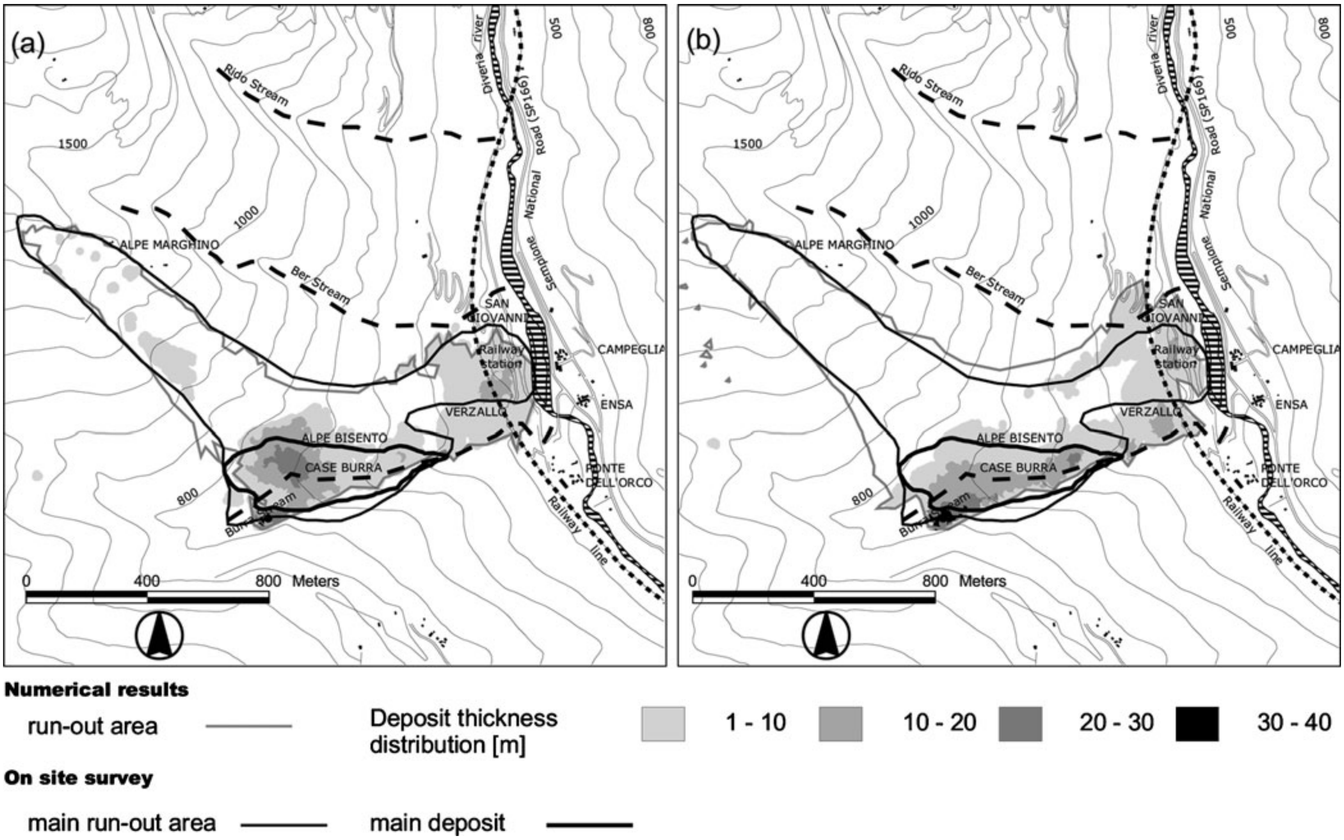

Fig. 11 1951 San Giovanni rock avalanche—pre-event DEM: comparison between RASH3D best-fit results and on-site survey. **a** Frictional rheology δ=31°. **b** Voellmy rheology μ=0.4 and ξ=100 m/s^2

As far as scenario 1B is concerned, it has been observed that there is a larger lateral spread of the deposit compared to scenario 1A. This is caused by the position of the initial volume which has determined the channelling of a part of the mass along another tributary of the Diveria River, called the Rido stream (Fig. 14).

Finally, scenario 2 has determined the most catastrophic results in terms of run-out distance, deposit thickness and lateral spread of the mass (Fig. 15).

For the three scenarios, it is furthermore observed that:

- more compact deposits have been obtain for δ=31° than those simulated with δ=33°;
- the maximum distance reached by the simulated mass has been influenced to a great extent by the characteristics of the Divedro Valley, which is narrow in the mass of propagation direction (i.e. west to east);
- the maximum velocity reached by the simulated mass has ranged from between 50 and 60 m/s, which is higher than that obtained for the back-analysis. It can in fact be observed that the slope just below the source area of the historical event is more gentle than that below the source area of the potential event.

Conclusions

The RASH3D code, based on a continuum mechanics approach, has been used in the present paper to predict the run-out of a potential rock avalanche located in the Divedro Valley, Western Italian Alps.

The main faced problem has concerned the procedure of setting the rheological parameter values to be use for prediction purposes. A calibration-based approach, in which rheological parameters are constrained by systematic adjustment during trial-and-error back-analysis of past events, has been proposed to solve this tricky point.

The back-analysis of a $2{\cdot}10^6$ m^3 rock avalanche located in the Divedro Valley, close to the area of the potential event, has been then analysed using both a frictional and a Voellmy rheology. The characteristics of the run-out area and the composition of the moving mass originated a phenomenon whose dynamics cannot be simulated with a Voellmy rheology. In particular, this rheology has not been able to reproduce the large deposition of material that can be observed on-site in the proximal part of the flow path. On the contrary, the best simulations have been obtained with a frictional rheology and a friction angle ranging from between 31° and 33°.

Three possible evolution scenarios of the potential instability have been then investigated with the above calibrated frictional parameters. The use of a range of values for the rheological parameters

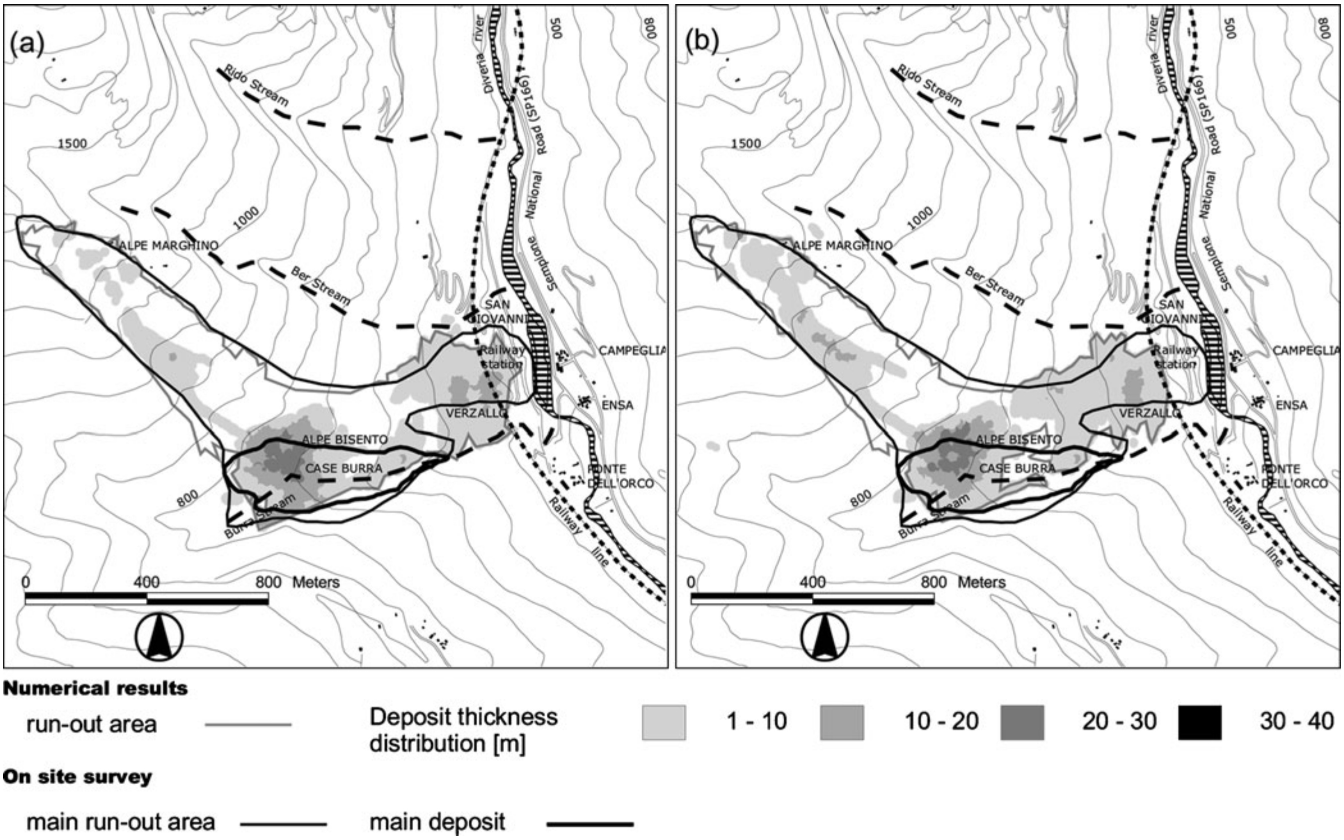

Fig. 12 1951 San Giovanni rock avalanche—pre-event DEM: comparison between RASH3D best-fit results and on-site survey. **a** Frictional rheology $\delta=32°$. **b** Frictional rheology $\delta=33°$

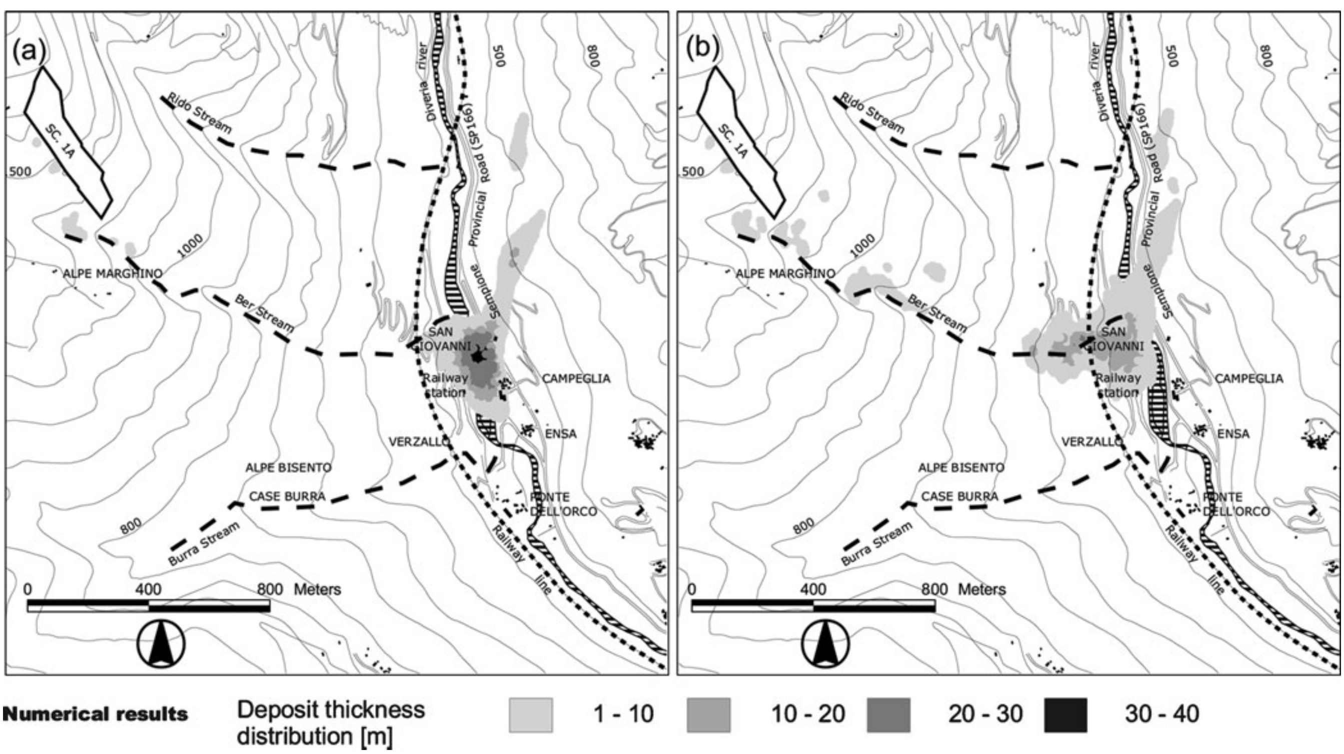

Fig. 13 Scenario 1A: comparison between numerical results obtained with the frictional rheology. **a** $\delta=31°$. **b** $\delta=33°$

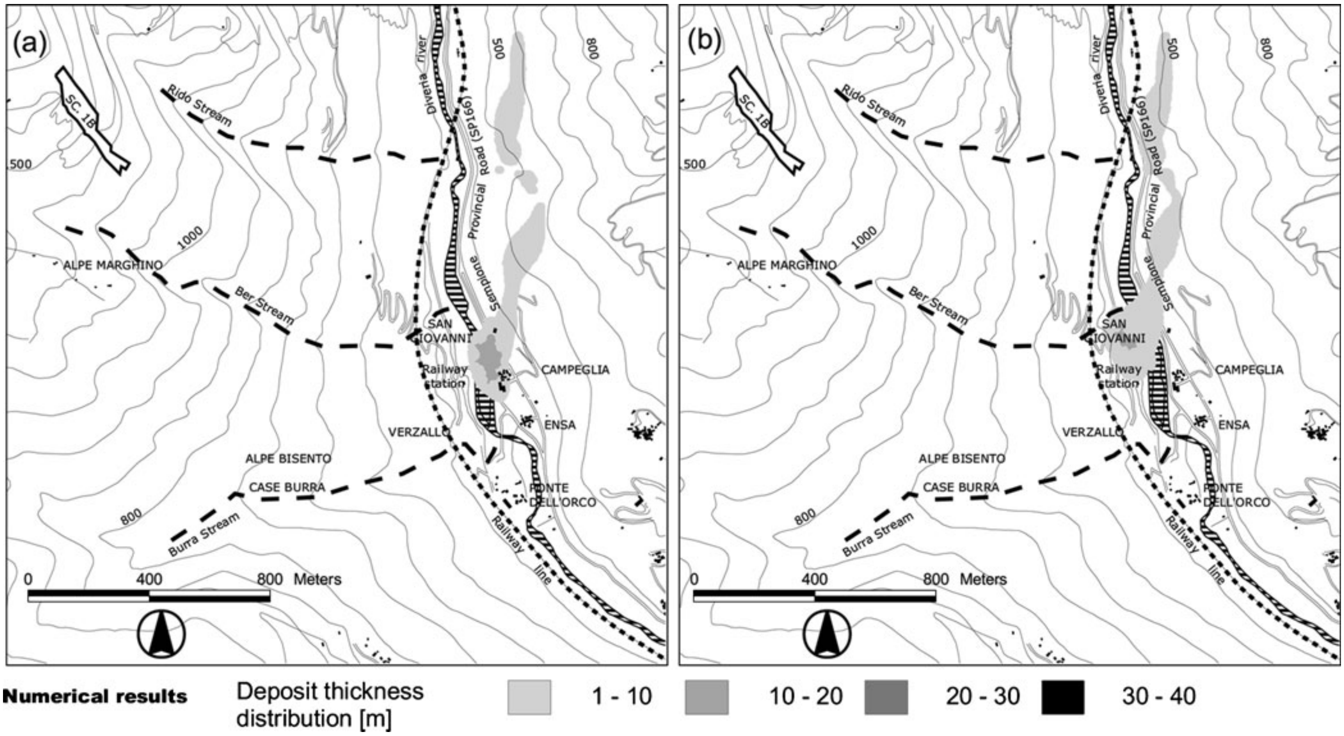

Fig. 14 Scenario 1B: comparison between numerical results obtained with the frictional rheology. **a** $\delta=31°$. **b** $\delta=33°$

has been considered to be more reliable and safer than using a single rheological value, given the high number of unknowns of a potential event.

As a result of the carried out analyses, it can be stated that the consequences of the three analysed potential scenarios could be damage to Simplon Provincial Road 166, occlusion of the Diveria River and burial of the San Giovanni area. Furthermore, all the simulations carried out with $\delta=31°$ have suggested the destruction of the Campeglia village, while scenario 2 has also indicated the possibility of the moving mass touching the Ensa village.

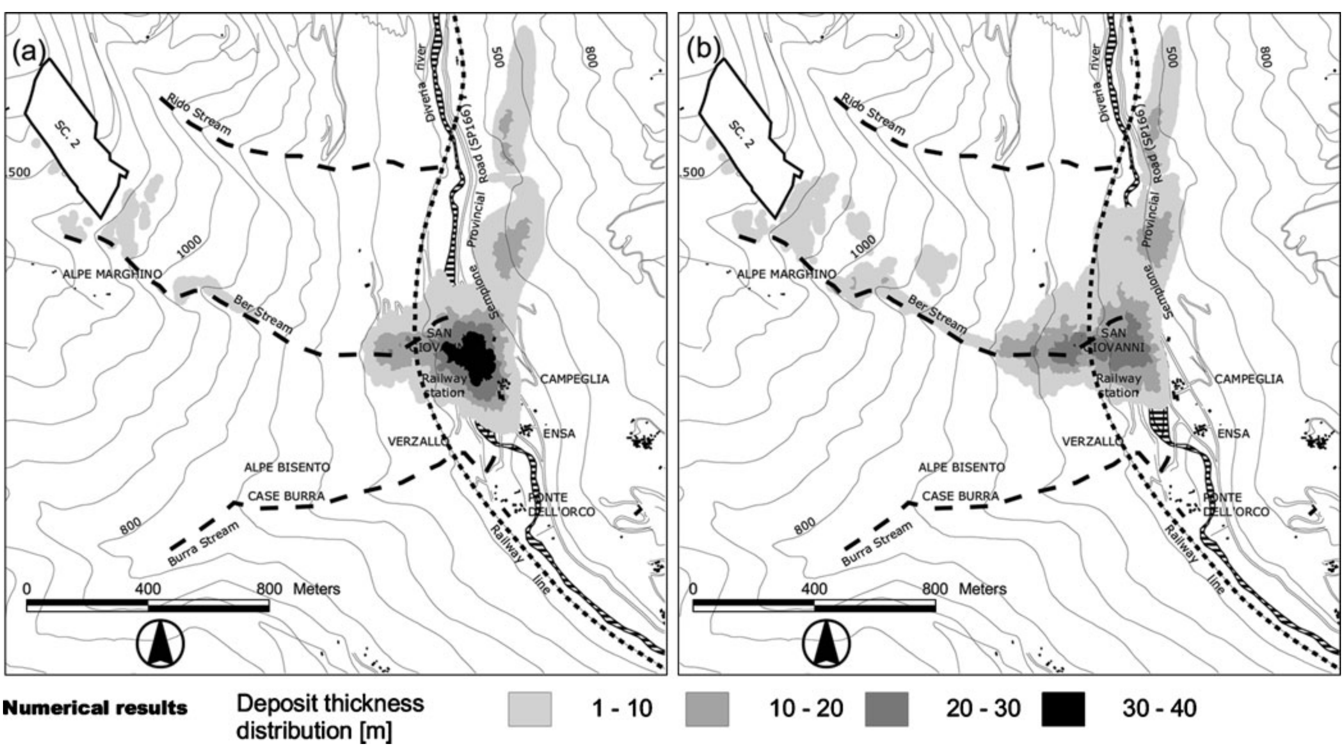

Fig. 15 Scenario 2: comparison between numerical results obtained with the frictional rheology. **a** $\delta=31°$. **b** $\delta=33°$

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