An integrated procedure to evaluate rheological parameters to model debris flows

Corresponding author: ANNA MARIA PELLEGRINO

Department of Engineering

University of Ferrara

Via Saragat 1, 44122, Ferrara

ITALY

Phone: +39 0532 974932

E-mail: annamaria.pellegrino@unife.it

ANNA SCOTTO DI SANTOLO

Pegaso University

Piazza Trieste e Trento, Napoli

ITALY

anna.scottodisantolo@unipegaso.it

LEONARDO SCHIPPA

Department of Engineering

University of Ferrara

Via Saragat 1, 44122, Ferrara

ITALY

leonardo.schippa@unife.it

Abstract: In the present paper, the problem of modeling the propagation of debris flow using suitable rheological parameters is considered. A procedure is proposed based on field observations, laboratory investigations and numerical analysis. The back analysis of a debris flow event that occurred in the Campania region (southern Italy) has been used to investigate the reliability of the rheological parameters assumed. The well-known Bingham constitutive equation has been used to model the behavior of the flow mixture. Numerical analysis has been conducted using DAN-W, a code based on a single-phase, depth-averaged continuum mechanics approach. The results show that extrapolating model parameters from laboratory experiments alone may lead to inaccurate predictions. Instead, when the rheological parameters are assumed according to stress field observations and experimental data, the model replicates the cases study well. This finding suggests that the calibration of model parameters using a combined approach may be applicable for field-scale debris flow simulations and can yield useful information about the dynamics of flows being investigated. The accuracy of this approach was demonstrated by the numerical prediction of other fifty events that occurred in the same area.

Keywords: debris flow; run-out; numerical modeling; Bingham model; pyroclastic soil mixtures; hazards

1 Introduction

Periodically, debris flows involving volcanoclastic deposits mantling very steep slopes of carbonate bedrock affect the north-western Campania region in southern Italy. During these catastrophic events, debris flows move suddenly down-valley with high velocity, invading the plains at the mountain foothills and affecting towns, roads and factories (Cruden & Varnes, 1996). Rapid, long-runout landslides pose a risk to areas situated at a considerable distance from the source and represent a difficult challenge in hazard studies. The prediction of runout distance, flow velocity and depth (i.e., dynamic parameters) is necessary for planning and designing protective measures and is a key requirement for delineating hazard zones.

Models used to predict flows at field scale may be classified either as empirical or analytical (Scotto di Santolo & Evangelista, 2009). Empirical models are based on limiting criteria

(Fannin & Rollerson, 1993) or statistical relations (Sheidegger, 1973; Cannon, 1993; Corominas, 1996; Fannin & Wise, 2001; Rickenmann, 2005; Zang & Yin, 2013). Although empirical models are easy to use, their application is limited to conditions matching those of the original model.

Recently, several analytical runout models were developed and applied to hazard evaluation (Van Westen et al., 2006). These models are based on physical data and solved numerically, simulating the motion of flow using constitutive equations of fluid mechanics in one or two dimensions (Luna et al., 2011). Most models are based on a “continuum approach” that considers the multiphase moving mass of a debris flow as a continuum. In this way, the dynamics of debris flow are modeled using an equivalent fluid, whose rheological properties can approximate the expected bulk behavior of the real mixture. In the continuum mechanical approach, the flow is modeled by a Saint Venant-type system (e.g., shallow water equations) derived in a reference frame linked to an inclined plane. This allows numerical simulation of rapid mass movements over complex topographies (Savege & Hutter, 1989; Chen & Lee, 2000; McDougall & Hungr, 2004; Mangeney et al., 2003; Pudasaini & Hutter, 2007; Hungr & McDougall, 2009; Christen et al., 2010).

Many of the analytical models are based on single-phase solutions of depth-averaged equations of motion and relatively simple one-phase rheological relationships, which define the frictional force acting at the interface between the flow and the bed path. However, the choice of a rheological law and the calibration of its peculiar parameters still remain open problems (Pirulli, 2010). The most common rheologies used in the dynamic models are the Coulomb model, the Voellmy model, the Bingham (or Herschel & Bulkley) model and the Quadratic model (Naef et al., 2006). Currently, the rheological parameters of constitutive equations can be estimated following either a measurements-based approach or a calibration-based approach (Pirulli, 2010). Using a measurements-based approach, the input parameters can be obtained through controlled laboratory experiments on reconstructed samples of the material involved. However, laboratory analysis alone may not be adequate for reproducing the properties of a complex debris flow because such properties, even if measurable, may be scale-dependent (Blanco et al., 2009;

Medina & Bateman, 2014; Pellegrino et al., 2014). Using a calibration-based approach, the rheological parameters are evaluated with systematic adjustment during trial-and-error back analysis of full-scale events. Although this approach makes the study of past debris flow phenomena simpler, the effectiveness of the calculated parameters is strictly related to the degree of similarity between the characteristics of historical and potential events. This limitation restricts the use of rheological parameters measured with a calibration-based approach to the study of a particular area of interest (Scotto di Santolo & Evangelista, 2009).

Currently, methods for determining the dynamic characteristics of a debris flow may be based on experimental data as well as on data generated by physical models. By combing these two sources of data, a promising approach could emerge for refining the methods for assessing the dynamics of a flowing mass (Luna et al., 2011).

The present paper contributes to the assessments of runout distance, flow velocity and depth by integrating field measurements, laboratory investigations and back analysis of well-documented case histories. To this aim, two real debris flow events that occurred in the Campania region have been back-calculated with the 2-D numerical code DAN-W (Hungr, 1995) based on the continuum mechanics approach. The classic, one-phase Bingham model was selected. To calibrate the rheological model parameters, the Pozzano landslide (Naples) was chosen as the case study. The constitutive parameters of the Bingham model were obtained using three different procedures: one based on field observations on-site (Coussot, 1997), another based on laboratory experiments (Scotto di Santolo et al., 2011) and a hybrid procedure combining elements of both. The resulting calibrated model parameters were used for the prediction of the second case study (Vena San Marco Est, Corbara, Salerno). In this case, a parametric study of the geometric characteristics of flow stoppage was performed. The model parameters were validated accounting for travelling distance of the front and for the reliability of flow velocity. Based on the acquired experience (Schippa & Pavan, 2011) and considering the limited reliability of the forecast from the triggering to the stoppage of the flow, the proposed method could be a useful tool for modeling the runout and velocity of design debris flows in the Campania region of Italy.

2 Case histories

In 1997, a fatal debris flow event occurred at Pozzano, which is located on the Sorrentina Peninsula (Naples, Campania region, see Fig. 1). The Pozzano debris flow involved the foothills of Castellammare di Stabia, whose slopes are covered by pyroclastic soils. The event occurred at 20:15 on January 10th, as a result of intense and prolonged rainfall in the area. The debris flow destroyed a civil building and flooded the 145 State Route, causing four deaths, twenty-two injuries and the interruption of the State Route for about two months. The case history of the Pozzano event is well-documented in the literature. Several pieces of information are available: the topography of the area before and after the event, the geotechnical characteristics of the materials involved, the geometry of the slope, the shape and the size of the triggering zone, the mobilized volume and the propagation path (Calcaterra & Santo, 1997; Iadanza et al., 2009). The landslide started as a translational slide and continued along the State Route, filling an old quarry before reaching the sea. The details of the morphology and the slope profile are shown in Fig. 2. The crown of the landslide is located at approximately 465 m above sea level. The flowing mass traveled for 1300 m, with a deposition lenght of approximately 665 m. The medium measured depth of the deposited material was 2.5 m, and the inclination of the deposition area was 7°. The depth of the flow was approximately 1.2 m, and the channel slope was 35° (Calcaterra & Santo, 1997; Iadanza et al., 2009).

In 1997, two debris flows occurred on a slope with a low hierarchized drainage basin at Corbara, a town located near Salerno (Campania region, see Fig. 1), Fig. 3. The event occurred on January 10th as a result of intense and prolonged rainfall in the region (Calcaterra & Santo, 1997). The flow was a mixed type (Scotto di Santolo & Evangelista, 2009; Calcaterra & Santo, 1997). On the east side, the flow started as a triangular shape and then became channeled on the drainage basin; on the west side, the flow was channeled instead. As shown in Fig. 3, the flows converged at the same point on the slope and were stopped completely at a quarry. In the present work, the debris flow that occurred on the east part of the hill has been considered (i.e., the landslide called EST in the left side of Fig. 3) because it involved a considerable initial volume of material (8547 m3). Several pieces of information are available: the topography of the area before and after the event, the geotechnical characteristics of the materials involved, the geometry of the slope, the shape and the size of the triggering zone, the mobilized volume and the propagation path (Di Crescenzo & Santo, 2005a; Scotto di Santolo, 2002). The landslide started as open, then became channeled and stopped near an old quarry. The details of the slope profile are shown in Fig. 2. The crown of the landslide is located at approximately 710 m above sea level. The flowing mass travelled for 1145 m, with a deposition lenght of approximately 720 m. The measured depth of the deposited material was 2 m, and the medium inclination of the deposition area was 10-15°. The depth of the flow was approximately 1 m, and the channel slope was 35° (Scotto di Santolo, 2002).

.

3 An overview on DAN-W code

The DAN code , developed by Hungr in 1995, is based on a continuum mechanics approach and it was especially developed to simulate the motion of flows, flow-like slides and avalanches. It reduces a complex and heterogeneous three dimensional problem into an extremely simple formulation. The simplicity of the model and the possibility of choice among different rheologies, some of which are particularly simple, make of DAN an interesting tool to be applied. DAN is a Windows-based program and it implements a Lagrangian solution of the equations of motion for a mass of earth material which starts from a prescribed static configuration and flows according to one of several rheological relationships. The model treats the slide mass as an "equivalent fluid", a hypothetical material governed by simple internal and basal rheological relationships (see Fig. 4). DAN-W is based on shallow flow equations and on the Lagrangian solution of St. Venant’s equation . This equation can be derived by applying a momentum balance equation to the thin slices of flowing mass that are perpendicular to the base of the flow. These “boundary blocks” divide the slide mass into n “mass elements” of constant volume. The resulting formula for the net driving force acting on each boundary block i is:

(1) $F = \rho \cdot g \cdot H_i \cdot ds \cdot B_i \cdot sin\vartheta - T - P$

Hi is the depth of a considered i-element in which the mass can be discretized, F is the net driving force equal to $F = \rho \cdot H \cdot ds \cdot B \cdot (dv/dt)$, where ρ is the bulk density of the flow material, H is the flow depth normal to the base, B is the channel width, ds is the infinitesimal length of the boundary block, θ is the angle of the base from horizontal, T is the resisting shear force acting on the base, P is the tangential internal pressure and v is the mean flow velocity. Eq. 1 can be solved for successive time steps after the initial, at-rest condition of the slide mass. For a single time step of Δt and a unit length of ds, the change in velocity of each boundary block is:

(2) $\Delta v = g(F\Delta t - M) / (\gamma \cdot H_i \cdot B_i \cdot ds)$

where γ is the unit weight of the boundary block, and F is the net force as defined in Eq. 1. M is a term for momentum flux which is caused by erosion or entrainment of material (Hungr, 1995). The velocity change can be represented by the difference between the new velocity at the end of time step Δt and the old velocity. Now, integrating Eq. 2 over the same time step Δt gives the curvilinear displacement S of each boundary block:

(3) $S_i = S_{i,old} + \Delta t / \left[2(v_i + v_{i,old})\right]$

This result can be used in conjunction with the constant-volume constraint to find the new height of each boundary block, defined by the mean depth h of adjacent mass elements j-1 and i:

(4) $H_{i,new} = (h_{j-1} + h_j) / 2$

where h_j is equal to (2 V_j / [(S_i+1 - S_i) (B_i+1 + B_i)]), and V_j is the constant volume of boundary element j. The basal flow resistance term, T, in Eq. 1 is governed by the rheology of the material. Several different rheologies are available in the DAN-W model. They are related to the appropriate equations for T. More details may be found in Hungr, 1995.

One of the most critical aspects in using a physically based debris-flow model is the choice of a representative and adequate constitutive relationship for the mixture. Among the rheological models available in the DAN -W code, the Bingham model was used because it was previously employed to describe the experimental data from tests on reconstituted samples of pyroclastic soils from debris flows in the Campania region (Scotto di Santolo & Evangelista, 2009; Scotto di Santolo et al., 2011). The Bingham model also seems adequate to represent real debris-flow in a variety of situations (Luna et al., 2011; Bertolo & Wieczorek, 2005; Nigussie, 2013; Jeong, 2013; Jeong, 2010; Bisantino et al., 2010; Genovese et al, 2014). In the Bingham rheology, the fluid initially assumes a solid-like behavior (shape- and volume-defined) and then reveals its liquid characteristics during the flow when the shear stress is higher than the yield shear stress τ_c. The resisting shear stress is assumed to depend on a constant strength. The viscous term depends on the velocity and on the inverse of the debris sheet thickness. The rheological equation depends upon two constants: the yield stress (τ_c) and the Bingham viscosity (μ_B). Accounting for zero shear stress, the flow becomes Newtonian. The mean flow velocity is derived from the assumption of a linear increase in shear stress with depth. In this model, the basal flow resistance term, T, is a function of flow depth, flow velocity, constant yield stress and Bingham viscosity as follows:

$$(5)\quad v_i = 1/6\, H_i / \mu_B \left(2\tau_c / A_i - 3\tau_c + \tau_c^3 A_i / T^2\right)$$

Where Ai is the boundary block base area equal to (ds·Bi).

4 Calibration procedure

The parameters of the Bingham model (e.g., yield stress τ_c and Bingham viscosity μ_B) used for numerical simulations were defined in three ways:

- a simplified method based on field observations (Model A);
- a method using experimental results of rheometer tests on soil-water mixtures prepared using field-collected soil samples (Model B);
- an intermediate original procedure proposed by the Authors, Model C, which is described below.

The parameters of each model were calibrated with reference to characteristics of a real debris flow event, including the travelling distance of the front and the reliability of the flow velocity.

As already mentioned (see par. 3), the Bingham model was selected from the rheological models available in the DAN code. The model was calibrated with reference to:

- distance L, calculated horizontally between the edge of the toe and the crown (Fig.);
- velocity of the front vf;
- height of the deposit.

In the analyses undertaken for the study, the model was considered valid on the basis of a comparison of the distance (e.g., travel distance calculated with DAN code L_{DAN}close to the travel distance measured on site L). The second parameter for calculation was the maximum speed of the front. With regard to velocity, it should be noted that there is no on-site data. In the area of interest, estimates of velocity were obtained through the back analysis of the damage caused by the flows that took place in the area of Sarno- Quindici (Faella and Nigro, 2003) and through dynamic analysis related to geometrical characteristics of the flows (Revellino et al., 2004 and 2006). For this reason, we decided to consider as term of comparison also the indications from other work in which a numerical code (i.e., DAN or similar codes) was used to back calculated real debris flow events occurred not only in Campania region (Luna et al., 2011; Faella & Nigro, 2003; Bertolo & Wieczorek, 2005; Prochaska et al., 2008).

4.1 Model A

The method enables to estimate the Bingham parameters τ_c and μ_B of the prototype debris flow which are required when the flow and stopping process of viscous debris flows is modelled with a numerical code which bases on a simplified Bingham model (e.g., O'Brien et al. 1993). Note that the method here can also be applied for numerical codes which are based on a Herschel-Bulkley model. In this case the more sophisticated Herschel-Bulkley fluid is reduced to the simplified Bingham fluid. This method is a direct application of theories concerning the flowing and stopping processes of yield stress fluids in idealized steady uniform flow on an infinitely wide inclined plane (Johnson, 1970; Coussot, 1997), Fig.5.

The free surface is necessarily parallel to the inclined plane and the shear stress at the base is equal to the yield stress τ_c, evaluated for x=0 as:

(6) $$\tau_c = \rho \cdot g \cdot h_D \cdot \sin(i_D)$$

where ρ is the mixture density, *g* is the gravitational force, h_D is the deposit depth, and i_D is the slope of the deposition plane. Owing to the presence of the yield stress τ_c, it is fair to anticipate that there would be a plug-like region near the free surface, as shown schematically in Fig. 4. If this region extends up to $x = x_0$, the velocity of the plug will be constant in the region $0 < x < x_0$. Beyond $x > x_0$, the velocity will progressively decrease from the plug velocity to a zero value at the wall due to the no-slip condition.

The Bingham viscosity parameter μ_B is estimated accounting for the yield stresses τ_c, as well as the observed flow depth h and surface velocity v_s of the debris flow. The calculation of the Bingham viscosity parameter μ_B, is given as follows. The flow depth h of a yield stress fluid is roughly divided into a plug zone with the depth h_{plug} and a shear zone shear, Fig. 5. The velocity distribution within the shear zone is simplified to a linear distribution (Coussot, 1997). With knowledge of the yield stress τ_c, in the case of no effects of lateral boundaries, the thickness of the plug zone h_{plug} can be estimated as:

(7) $$h_{plug} = \frac{\tau_c}{\rho \cdot g \cdot \sin(i)}$$

where *i* is the inclination angle of the bed. In the case of a confined channel, the effects of lateral boundaries must be considered. For the simplified case of a semicircular channel (Johnson, 1970), it is:

(8) $$h_{plug} = \frac{2\tau_c}{\rho \cdot g \cdot \sin(i)}$$

Based on the calculated plug thickness h_{plug}, the thickness of the shear zone h_{shear}, is calculated as:

(9) $$h_{shear} = h - h_{plug}$$

where h is the observed flow depth. For a simplified linear velocity distribution, the apparent shear rate $\dot{\gamma}$ relative to the observed velocity v, is:

$$\dot{\gamma} = \frac{v_s}{h_{shear}} \qquad (10)$$

Assuming an identical density ρ over the entire flow depth h, the bed shear stress τ_{bed} is:

$$\tau_{bed} = h \cdot \rho \cdot g \cdot sin(i) \qquad (11)$$

The Bingham viscosity parameter μ_B can be eventually calculated as:

$$\mu_B = \frac{\tau_{bed} - \tau_c}{\dot{\gamma}} \qquad (12)$$

4.2 Model B

The rheological parameters assigned to Model B is determined using the experimental data from rheometrical tests performed on mixtures of water and sediment composed of pyroclastic soil similar to that involved in the real debris flow events considered. The material tested were collected from the source area of a debris flows occurred in the Campania region (southern Italy). The soil type, in a thickness of about a metre, depends on the most recent pyroclastic deposits deriving from the volcanic activity of Mount Somma/Vesuvius. The grain size distributions of the collected samples are reported in Fig. 6~~1~~. The soil is a sandy silt with a small clay fraction. The bedrock underlying the soil is a limestone. The main physical properties of the considered soil are the specific gravity of soil particles Gs equal to 2.61, the dry weight of soil per unit volume γd equal to 9.08 kN/m^3, the total weight of soil per unit volume γ equal to 11.35 kN/m^3, and the porosity n equal to 66%. The complete description of the laboratory activity carried out on the soil is illustrated in Scotto di Santolo et al. (2011). The rheometrical tests were performed on the soil fraction with a particle diameter less than 0.5 mm. Doing so we keep about 50 to 70% of the whole grain size distribution, as shown in Fig. 6~~1~~. Since the rest of the particles which are contained in the whole material are not colloidal, when they are mixed with the paste to get the complete mixture they can be expected to essentially increase the values of the rheological parameters but do not affect the behaviour type. Thus, we believe that if we were working with the whole mixtures we would get similar qualitative trends as described below.

For the present work, the parameters of the Bingham model obtained were used to describe the experimental data for a mixture of water and sediment having a solid volumetric concentration Φ equal to 42%. In Scotto di Santolo et al. (2012), a consistent study was done in order to have an overview of the behaviour of pyroclastic material as a function of the solid concentration and to identify the range of concentrations in which it may be considered as fluids and thus characterized with usual rheological tools. Three different possible states appeared. For sufficiently low solid volume fractions (less than 32%), the particles rapidly (within a few seconds) settle down, leading to an apparent phase separation. It was obviously impossible to carry out rheometrical tests because of when the particles have settled, no longer dealing with a homogeneous material, and nothing can be said about its viscosity. For high volume fractions (up to 42%), the suspension obtained is a kind of paste of high strength, which easily breaks like a solid when it is deformed. Such a material cannot be considered as a fluid able to undergo reversible large deformations without changing its basic properties and it was impossible to carry out with such materials rheometrical tests appropriate for fluids. For intermediate volume fractions ($32\%<\Phi<42\%$), the material thus remains homogeneous over a reasonable time of observation and can flow like a liquid. This is in its “fluid-like” intervals.

The experimental flow curve and the fitting curve obtained with the Bingham model are reported in Fig. 7. The best-fitting parameters are τ_c = 144 Pa and μ_B = 1.8 Pa·s. For the laboratory details and fitting procedures, see Scotto di Santolo et al. (2011).

4.3 Model C

The model C proposed by the authors is based on the observation that the evaluation of τ_c from the field is a very robust straight forward method using the natural materials on the right scale. This τ_c value can predict very well the run-out distance for the geographic area considered. Instead the viscosity values are less important on the estimation of the travel distance but assuming a great meaning to estimate the velocity. Moreover the validation on the velocity was very weak because of the poor information on real velocity data available in this studied area. From the data available in the literature (e.g., Major & Pierson, 1992; Coussot & Piau, 1995; ; Martino, 2003; Schatzmann, 2005; Kaitna et al., 2007; Pellegrino et al., 2010; Bisantino et al., 2010; Jeong et al., 2010;Scotto di Santolo et al., 2011) viscosities measured in the laboratory are lower than obtained from back analyses in the field (using mean velocities calculated from run-out time and run-out distances) as shown in Tab. 1.For these reasons in the model C, the viscosity is assumed equal to that estimated with laboratory activity (see Model B). Instead the yield stress τ_c is assumed equal to the value evaluated on the field observation according to the procedure described for Model A (e.g., using the Eq. 6).

5 Results and discussion

5.1 The Pozzano case study

The Pozzano's debris flow is a mixed type events. After an initia J-path, in the middle portion of the event, the landslide channelized into a preexisting gully (see Fig. 2). Here, the displaced mass started to flow and the mass movement transformed into an extremely rapid debris flow. A first part of this debris stopped in the landslide channel. Another part of the debris (about 10,000 m3) stopped on State Road no. 145. The remaining part of the mass reached the sea (see Fig. 2), moving away for about 50 m from the shoreline. As put in evidence by Calcaterra & Santo (2004), the Pozzano landslide can be defined as a complex movement: the first movement was a small rotational slide affecting a thin slab of deeply altered ashy pyroclastic; a translational slide then occurred; the event reached a preexisting gully, filled with some meters of altered and reworked pyroclastic deposits. A channelized debris flow was initiated here, favoured by the high water content. The soils involved show a wide grain-size distribution. They comprise a sandy silt that is sometimes clayey and slightly gravelly (Fig. 8). The volcaniclastic deposits offered low bulk and dry densities and did not show plastic behavior. The shear strength show a substantial dependence on the water content: when the soils were sheared with their ''natural'' water content, they showed a distinct but small cohesion (about 20 kPa) and a friction angle of

27–30°. After saturation, the same materials behaved as granular soils because the cohesion was reduced to nearly zero (Calcaterra & Santo, 2004).

The numerical simulations performed with DAN-W on the Pozzano debris flow was carried out considering a soil profile reconstructed from in situ survey and geometrical data taken from literature (Calcaterra & Santo, 1997; Iadanza et al., 2009). The debris flow profile, post event, is schematically represented in Fig. 9 with the channel width according to the path reported in Fig. 2. The values of the rheological parameters used for the back-analyses of this case, assumed as benchmark, are reported in Tab. 2. They was estimated according to the proposed procedures, explained in section 4, for models A, B and C. In detail the parameters obtained from field data and used for Model A are shown in Tab. 3.

The results of the numerical analyses for models are showed in Fig. 10 in terms of runout distance and in Fig. 11 in terms of velocity assumed during the travel path. Table 4 reports all the results of the numerical analysis in terms of runout distance, deposit thickness, maximum velocity reached during propagation and angle of extension (i.e. Fahrböschung). The predicted runout distances for Models A, B and C were 385 m, 2736 m and 1267 m, respectively. For comparison, the runout distance measured on-site was 1300 m. This value is most closely to the value predicted by Model C.

Fig. 11shows the results of the numerical analyses for Models A, B and C in terms of maximum flow velocity reached by the flowing mass during propagation. In the graph, the maximum values of velocity for debris flow type events from literature are reported as straight line. Due to the lack of on-site measures of velocity, we refers to the following values of velocity:

- the debris flow velocity calculated by Faella & Nigro (2003) through the back analysis of the damage caused by the flows that took place in the area of Sarno- Quindici (Campania region). The value reported by the authors is 21 m/s;
- the debris flow velocity calculated by Revellino et al. (2006) through dynamic analysis related to geometrical characteristics of some flow events occurred in Campania region. The value reported by the authors is 20 m/s;

- the debris flow velocity calculated by Bertolo & Wieczorek (2005) through the back analysis of some debris flows that took place in California (United States). The value reported by the authors is 35 m/s;
- the debris flow velocity calculated by Prochaska et al. (2008) through the back analysis of some debris flows occurred in Colorado (United States). The value reported by the authors is 21 m/s;
- the debris flow velocity calculated by Luna et al. (2011) through the back analysis of some debris flows occurred at Faucon torrent (France). The value reported by the authors is 16 m/s;

The results from models A and B do not satisfactorily match the on-site measurement of maximum flow velocity. The results from model C match the on-site measurement fairly well in terms of maximum flow velocity, although the model overestimates the plausible values reported in the literature (Luna et al., 2011; Faella & Nigro, 2003; Bertolo & Wieczorek, 2005; Prochaska et al., 2008).

From the numerical results obtained the Model C seems to be the most accurate in terms of total runout, debris spread, spatial distribution and flow velocity. The results show that past events in this area can be modeled with reasonable accuracy using a combination of field and laboratory results for the calibration of the run-out models. Recall that Model C evaluates the yield stress τ_c from the geometric characteristic of the debris flow deposit and the viscosity from the conventional rheometer tests.

5.2 The Corbara case study

The back analysis conducted for the Pozzano case, which was chosen as a benchmark, have shown that Model C is the most accurate procedure for calibrating the rheological parameters of the constitutive model in terms of runout distance and maximum velocity of the front. The Corbara debris flow event was used to validate the proposed procedure, Model C, and its parameters. The values of the parameters of the geometric fan for the Corbara debris flow are not well defined in the literature. . For this reason, four scenarios (c1, c2, c3 andc4) were considered on the base of the values of the deposit characteristics reported in the literature (Calcaterra & Santo, 1997; Di Crescenzo & Santo, 2005a; Scotto di Santolo, 2002). To define the four scenarios, a parametric study was conducted to evaluate the minimum and the maximum range of the runout parameters.

These scenarios arise from the dependence of the yield stress τ_c on the deposit's shape when the hypothesis of the uniform flow was assumed and the rheological parameter considered are calculated using equation (6) (see Model A in Par. 4.1). The cases considered and the values of the rheological parameters used for the present case study are reported in Tab. 5. For comparison, a numerical simulation has been performed with Model B, as well.

The numerical simulations with DAN-W on the Corbara debris flow were performed considering a flow profile reconstructed from the geometric characteristics of the event taken from literature and field survey (Di Crescenzo & Santo, 2005a; Scotto di Santolo, 2002).

The longitudinal slope profile is schematically represented in Fig. 12. In Fig. 13, the results of the numerical analysis are shown for the cases considered in terms of runout distance. The predicted runout distances for the Model C cases c1, c2 and c3 are 699 m, 1363 m and 1157 m, respectively. No numerical results were obtained for Model B because the model predicted no motion. For comparison, the runout distance measured on field was 1145 m. The runout distance was most closely predicted by case c3. Fig. 14 shows the results of the numerical analysis in terms of maximum front velocity reached by the flowing mass during propagation. For each case, the results match fairly well in terms of maximum front velocity. The back-calculated values for maximum flow velocity are compatible with the reasonable range of values reported in literature as explained in par. 5.2. Model B overestimated the maximum flow velocity. The results of the numerical simulations for the Corbara case are summarized in Tab. 6.

6 Conclusion

In the present work, two well-documented debris flow case histories suitable for back analysis were selected. The case histories of Pozzano and Corbara were analyzed in 2D using DAN-W

(Hungr, 1995). The classic, one-phase Bingham rheological model was chosen. For the Pozzano case study, three approaches were adopted to set the characteristics parameters of the model (i.e., the yield stress, τ_c, and the Bingham viscosity, μ_B). Using the first approach, Model A, the rheological parameters were determined based on the geometric characteristics of the debris flow event measured on-site. For Model B, the rheological parameters were derived using experimental data obtained through rheometer tests performed on mixtures of water and sediment using a pyroclastic soil similar to that involved in the debris flow event being considered (Scotto di Santolo et al., 2011). A hybrid procedure to fit model C, in which the yield stress parameter τc was calculated from the geometric characteristic of the considered debris flow event measured on-site, and the Bingham viscosity μB was calculated from the experimental data obtained from the rheometer test. The numerical results for each model were assessed by matching the total horizontal runout and the flow velocities to the values measured on-site. Model C is the most accurate in terms of total runout, debris spread, spatial distribution and flow velocity. The results show that past events can be modeled with reasonable accuracy using yield stress τc calculated from geometric characteristics of the debris flow event measured on-site and Bingham viscosity that has been measured experimentally. Based on the results of Model C, the Corbara debris flow study has been back-calculated using Model B. To investigate the influence of deposit shape on runout, four combinations of geometric features were considered. These results have highlighted significant considerations regarding the flow dynamics for the events analyzed. In particular, when estimating resistance stress (i.e., yield stress), accurate measurement of deposits leads to very good predictions of travel distance, velocity and depth of the flow. The calibration of the rheological parameters is clearly scale-dependent. However, the application of a combined approach for fitting rheological parameters of a model enables us to identify a procedure suitable for assessing the dynamic characteristics of debris flow.

Integrated with back analysis of historical cases, use of both on-site observations and laboratory experience can lead to accurate methods for the prediction of the dynamic parameters of potential debris flow events. The simulated, order-of-magnitude effects of the analyzed case studies could be helpful for predicting future events not only in the area considered but also in other areas with geology, morphology and climate conditions similar to the Campania region. Although it is still difficult to make accurate predictions about the most likely runout, the simple analysis conducted in this study provides useful hints about dynamic behavior of possible debris flows in the area studied. It is worth noting that the properties of the granular-fluid mixture as a whole change as the mixture flows downhill, and they affect the reliability of the model prediction. Further research, including experimental tests, should address this topic.

References

Bertolo P. & Wieczorek F., Calibration of a numerical models for small debris flows in Yosemite Valley, California, USA, Nat. Hazards Earth SYst. Sci., 5, 2005, 993-1001

Bisantino T., Fischer P. & Gentile F., Rheological characteristics of debris-flow material in South-Gargano watersheds, Nat. Hazards Earth Syst. Sci., 54, 2010, 209-223.

Blanco A., Rodriguez C. & Garcìa R., Can we accurately use laboratori-scale rheological parameters to model field-scale debris flow?, Revista de la Facultad de Ingegnerìa, 1 (24), 2009, 45-55.

Calcaterra D. & Santo A., The January 10, 1997 Pozzano landslide, Sorrento Peninsula, Italy, Eng. Geol, 175, 1997, pp. 181-200.

Cannon S.H., An empirical model for the volume-change behaviour of debris flows, in Hydraulic Engineering, American Society of Civil Engineering, 93, 1993, 1768-1993, 25-30 July, San Francisco.

Chen H. & Lee C.F., Numerical simulation of debris flows, Can. Geot. J., 37, 2000, 146-160.

Christen M., Barlett P., Kowalski J. & Stoffel L., Calculation of dense snow avalanches in three-dimensional terrain, Cold. Reg. Sc. Technol., 63, 2010, 1-14.

Corominas, J., The angle of reach as a mobility index for small and large landslides, Can Geotech J, 33, 1996, 260–271.

Coussot P., Mudflow Rheology and Dynamics, IAHR Monograph series, Balkema Rotterdam, 1997.

Cruden D.M. & Varnes D.J., Landslides: Investigation and Mitigation, Landslides Types and Processes. In: Turner A.K. & Schuster R.L. (Eds.), Transportation Research Board Special Report 247, National Academy Press, WA,1996, pp. 36-75

Di Crescenzo G. & Santo A., Debris slides-rapid earth flows in the carbonate massifs Campania region (Southern Italy): morphological and morphometric data for evaluating triggering susceptibility, Geomorphology, 66, 2005a, 255-276.

Faella C. & Nigro E., Dynamic impact of the debris flow on the constructions during the hydrogeological disaster in Campania-1998: failure mechanical models and evaluation of the impact velocity. In "Fast slope movements - prediction and prevention for risk mitigation, Naples, vol. 1, 2003, pp. 179-186.

Fannin R.J.& Rollerson T.P., Debris flow: some physical characteristics and behaviour, Can. Geotech. J., 30, 1993, 71-81.

Fannin R.J.& Rollerson T.P., Assessing debris flow hazard in British Columbia: runout behaviour, in Proceeding of the Int. Mountain Logging and Pacific Northwest Skyline Symposium, Campbell River, 1996, Special Report, SR-116, 30-44, 13-16 May.

Fannin R.J. & Wise M.P., An empirical-statistical model for debris flow travel distance, Canadian Geotechnical Journal, 38, 2001, pp. 982-994.

Genovese M., Viccione G., Rossi F., Guida D., Luigi T. & Lenza L., Using the Sodium Carboxymethylcellulose (CMC) asviscosity modifier to model the interstitial fluid in laboratory debris flows, Latest Trends in Engineering Mechanics, Structures, Engineering Geology, 2014, 3-5 June, Salerno (Italy), 179-186.

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

Hungr O. & McDougall S., Two numerical models for landslides dynamic analysis, Computer Geosciences, 35, 2009, 978-992.

Iadanza C., Triglia A., Vittori E. & Serva L., Landslides in Coastal Areas, in Geohazard in Rocky Coastal Areas, Edited by C. Violante, Geological Society Special Publication, 322, 2009, pp. 121-142.

Jeong S.W., The viscosity of fine-grained sediments: A comparison of low-to medium-activity and high-activity clays, Eng. Geol., 154, 2013, 1-5

Jeong S.W., Grain size dependent rheology on the mobility of debris flows, Geosc. J., 14(4), 2010, 359-369.

Johnson A.M., A method for interpretation of natural phenomena intrusions in igneous rocks, fractures and folds, flow of debris and ice. Physical processes in geology. Freeman, Cooper and Co., San Francisco, California, 1970.

Luna B.Q., Remaître A., van Asch Th.W.J., Malet J.P. & Van Westen C.J., Analysis of debris flow behaviour with a one dimensional run-out model incorporating entrainment, Eng. Geol., 2011, doi: 10.1016/j.enggeo.2011.04.007.

Mangeney A., Vilotte J.P, Bristeau M.O., Perthame B., Bouchut F., Simeoni C. & Yerneni S., Numerical modelling of avalanche based on Saint Venant equations using kinetic scheme, J. Goephys. Res., 108, 2003, 2527.

McDougall S. & Hungr O., A model for the analysis of a rapid landslide runout motion across three-dimensional terrain, Can. Geotec. J., 41(6), 2004, 1084-1097.

Medina V. & Bateman A., Debris flow entrainment experiments at UPC, interpretation and challenges, Latest Trends in Engineering Mechanics, Structures, Engineering Geology, 2014, 3-5 June, Salerno (Italy), 38-44.

Naef D., Rickenmann D.,Rutschmann P. & McArdell B.W., Comparison of flow resistance relations for a debris flows using a one-dimensional finite element simulation model, Nat. Hazards Earth SYst. Sci.,6, 2006, 155-165.

Nigussie D.G., Numerical modelling of run-out of sensitive clay slide debris, Master Thesis, 2013, 95p.Pellegrino A.M., Scotto di Santolo A. & Schippa L., Numerical Modeling of a Debris Flow Event Occurred in Campania Region, Southern Italy: Consideration on the Rheological Model Parameters on the Run-Out, Latest Trends in Engineering Mechanics, Structures, Engineering Geology, 2014, 3-5 June, Salerno (Italy), 62-71.

Pirulli M., On the use of the calibration-based approach for debris-flow fowards-analyses, Nat. Hazards Earth SYst. Sci., 10, 2010, 1009-1019.

Prochaska A.B., Santi, P.M., Higgins & Cannon S.H., A study of methods to estimate debris flow velocity, Lanslides, 2008, DOI 10.1007/S10346-008-0137-0.

Pudasaini S.P. & Hutter K., Avalache dynamics-dynamics of rapid flows of dense granular avalanches, 2007, Springer-Verlan, Berlin.

Rickenmann D., Runout prediction methods, in Debris-Flow Hazards and Related Phenomena, edited by Jakob M. and Hungr O., 2005, 305-324.

Savage S.B. & Hutter K., The motion of a finite mass of a granular material down a rough incline, J. Fluid Mech., 199, 1989, 177-215.

Schatzmann M., Rheometry for large particle fluids and debris flows. Ph.D. dissertation No. 16093, ETH, Zürich, Switzerland, 2005.

Schippa, L. & Pavan, S., Numerical modelling of catastrophic events produced by mud or debris flows; International journal of safety and security engineering; vol.1, n.4, 2011, pp. 403-422.

Scotto di Santolo a., Le collate rapide, Hevelius, 2002, 120p.

Scotto di Santolo A. & Evangelista A., Some observations on the prediction of the dynamic parameters of debris flows in pyroclastic deposits in the Campania region of Italy, Natural Hazards, 50, 2009, pp. 605-622.

Scotto di Santolo A., Pellegrino A.M., Evangelista A., Coussot P., Rheological behaviour of reconstituted pyroclastic debris flow, Geotechnique Journal, Vol. 62, Issue 1, 2011, pp. 19 –27.

Sheidegger A.E., On the prediction of the Reach and Velocity of Catastrophic Landslides. Rock Mechanics, vol.5., 1973.

Van Westen C.J., van Asch Th.W.J. & Soeters R., Landslides hazards and risk zonation- why is it still do difficult?, Bull. Eng. Geol. Env., 65, 2006, pp. 167-184.

Zhang M, Yin Y. “Dynamics, mobility-controlling factors and transport mechanisms of rapid long-runout rock avalanches in China”, Engineering Geology, 167, 2013, pp.37-58

Table 1 Data available in literature on rheological modeling of debris flow materials. (LS-rheo=large scale rheometer; BMS=ball measuring system; Rheo=conventional rheometer; DF=debris flow material; DF Campania=debris flow material from Campania region).

Author/s	Year	Set up	Materials	d_{max} (mm)	Φ (%)	Model	τ_c (Pa)	μ (Pa·s)	K (Pa·s^n)
Major & Pierson	1992	LS-rheo	DF	2	52-66	Bingham generalized	12-405	-	0,4-16
Coussot & Piau	1994	LS-rheo	DF	20	69-71	Bingham generalized	90-200	-	48-78
Schatzmann	2005	BMS	DF	10	35-64	Bingham generalized	2,7-265	-	0,41-47
Kaitna et al.	2007	Rotating flume	DF	5	47-62	Bingham	10-80	0,1-2	-
O'Brien & Julien	1988	Rheo	DF	2	15-45	Bingham	0,2-100	0,4-10	-
Coussot & Piau	1995	Rheo	DF	0,4	35-40	Bingham generalized	29-220	-	18-242
Martino	2003	Rheo	DF Campania	0,4	25-53	Bingham generalized	1,1-39	-	0,02-0,3
Schatzmann	2005	Rheo and BMS	DF material	0,4	22-30	Bingham generalized	30-98	-	1,18-14
Pellegrino	2010	Rheo	DF Campania	0,5	30-42	Bingham generalized	1,2-90	0,2-2	0,34-4,7

Table 2 Rheological parameters assumed for Models A, B and C (see § 4).

Model	Model parameters	
	τ_C	μ_B
	(Pa)	(Pa s)
A	3112	484
B	144	1,8
C	3112	1,8

Table 3 Pozzano's debris flow. Results of the parameter calculations for Model A

τ_C	h_{plug}	h_{shear}	$\dot{\gamma}$	τ_{bed}	μ_B
(Pa)	(m)	(m)	(s^{-1})	(Pa)	(Pa s)
3112	0,21	0,987	8,10	7029	484

Table 4 Pozzano’s debris flow. Results of the numerical analysis using Models A, B and C (see § 4).

Model	Runout distance	Thickness of deposit	Maximum velocity	Slope inclination
	(m)	(m)	(m/s)	(°)
A	385	0,3	4,47	29,84
B	2763	0,09	87	13,63
C	1267	0,2	67	24,36

Table 5 Corbara’s debris flow. Values assigned to the rheological parameters for cases 1a, 1b, 1c, 2 and Model B.

Cases considered		Geometric features		Rheological parameters	
		h_D	i_D	τ_C	μ_B
		(m)	(°)	(Pa)	(Pa s)
Model C	c1	2	10	4434	1,8
	c2	1	10	1862	1,8
	c3	1,5	10	2793	1,8
	c4	4	15	15779	1,8
Model B		-	-	144	1,8

Table 6 Corbara’s debris flow. Results of the numerical analysis for cases 1a, 1b, 1c, 2 and Model B.

Cases considered		Runout distance	Thickness of deposit	Maximum velocity
		(m)	(m)	(m/s)
Model C	1a	699	1	12,50
	1b	1363	0,5	44,69
	1c	1157	0,5	34,98
	2	443	-	0
Model B		2677	0,3	70,65

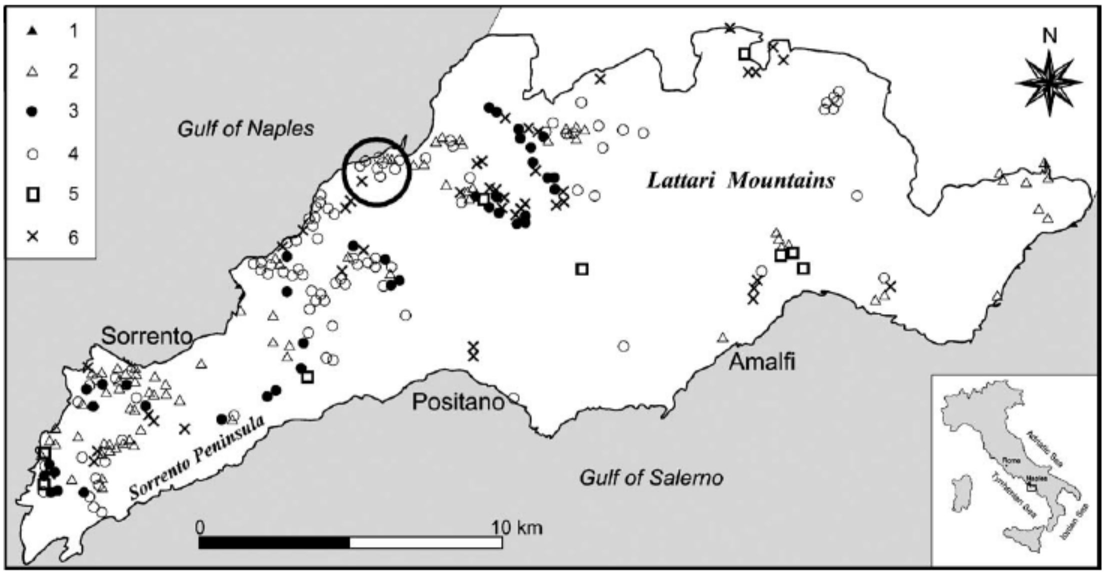

Figure 1 Inventory map of the January 1997 landslides in the Sorrento Peninsula from Calcaterra & Santo, 2004. (1) Debris or earth fall; (2) rock fall; (3) rotational slide; (4) translational slide; (5) flow; (6) complex landslide. The circle refers to the area of interest.

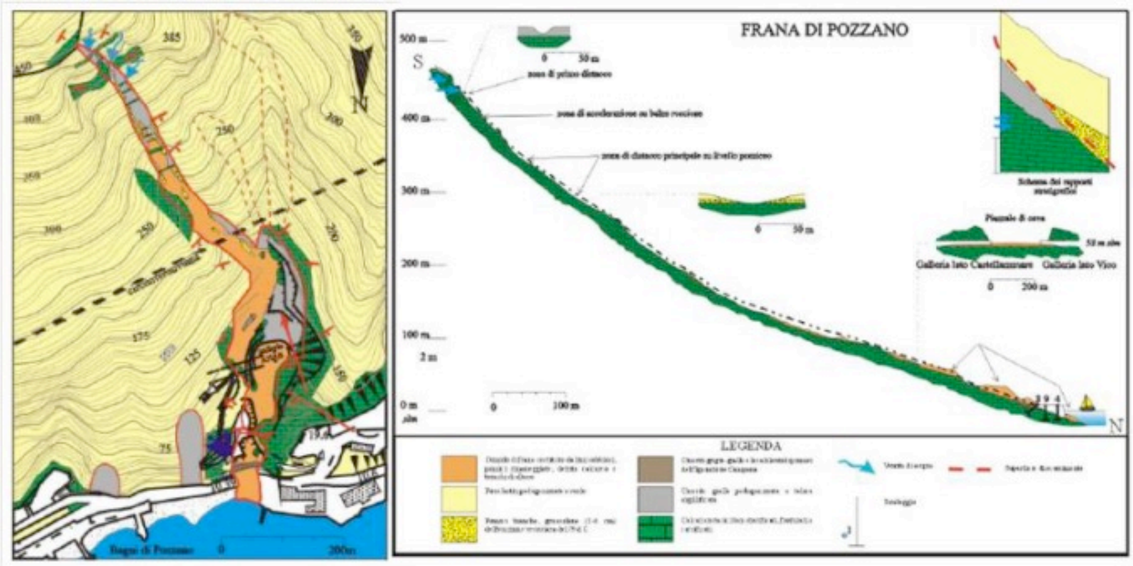

Figure 2 Pozzano's debris flow (Naples, 1997). Event landform (on the left) and elevation profile (on the right) with stratigraphy of pre and post event (modified from Calcaterra & Santo, 1997).

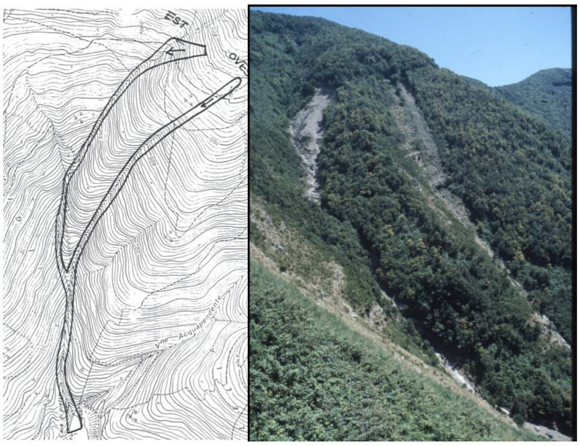

Figure 3 Corbara’s debris flow (Salerno, 1997). Layout of the event (on the left) and picture of the debris flow (on the right).

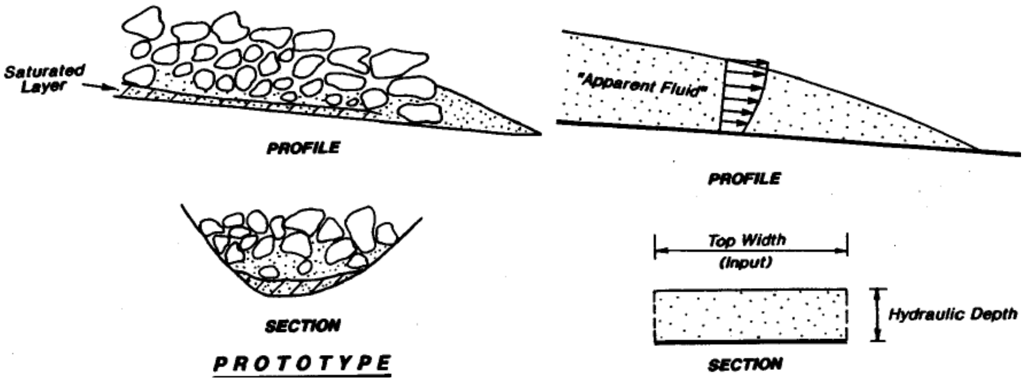

Figure 4 Prototype of a heterogeneous and complex moving mass; a homogeneous “apparent fluid” replaces the slide mass (from Hungr, 1995).

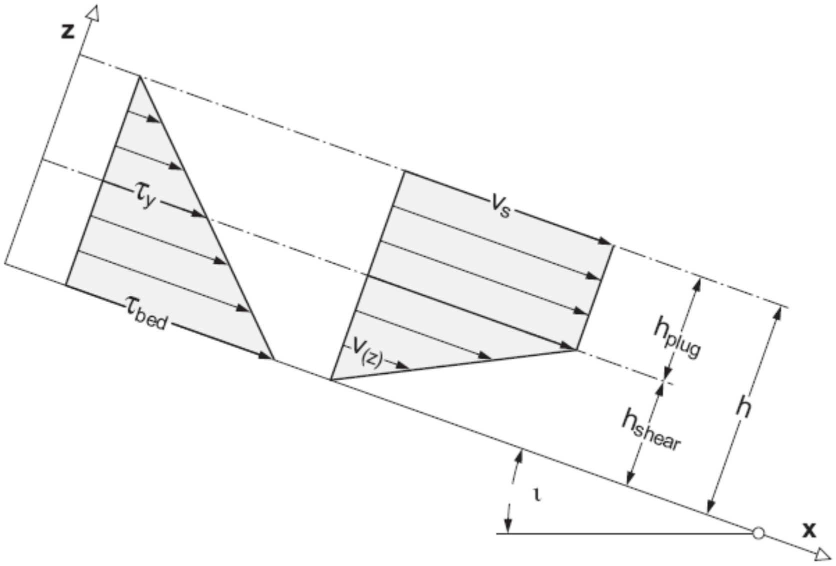

Figure 5 Free Surface flow on an infinitely wide inclined plane: simplified scheme of stress and velocity distribution in a flowing yield stress fluid/viscous debris flow and distinction of plug and shear zone.

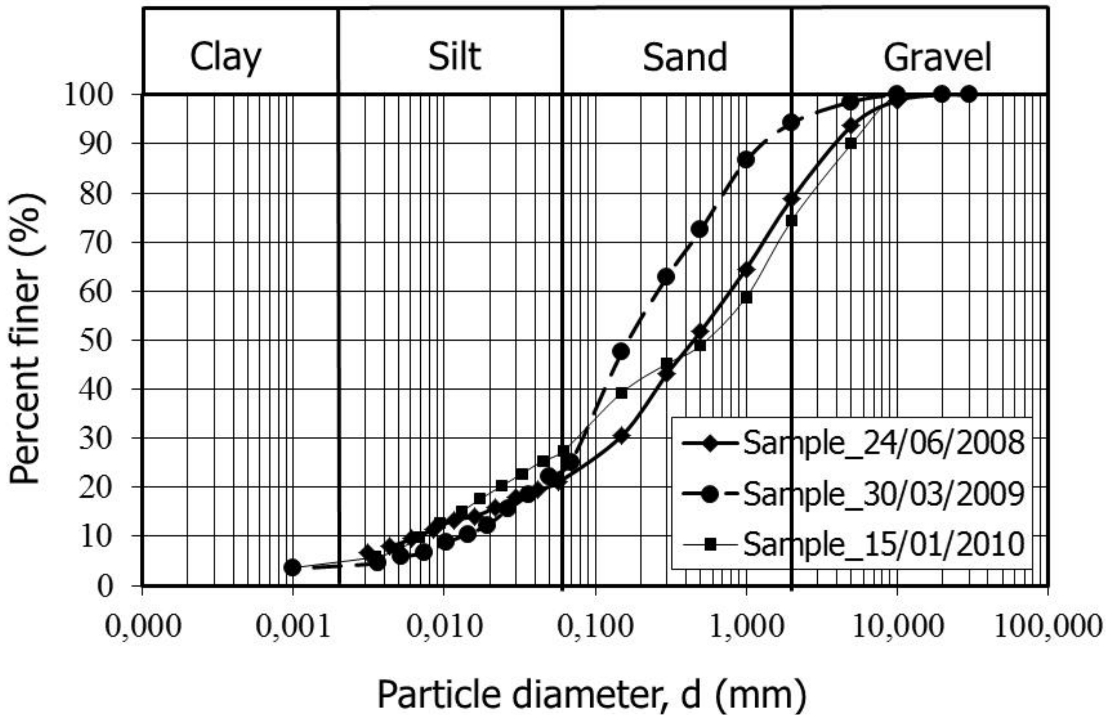

Figure 6 Grain size distribution of some samples taken from a pyroclastic deposit in Campania region.

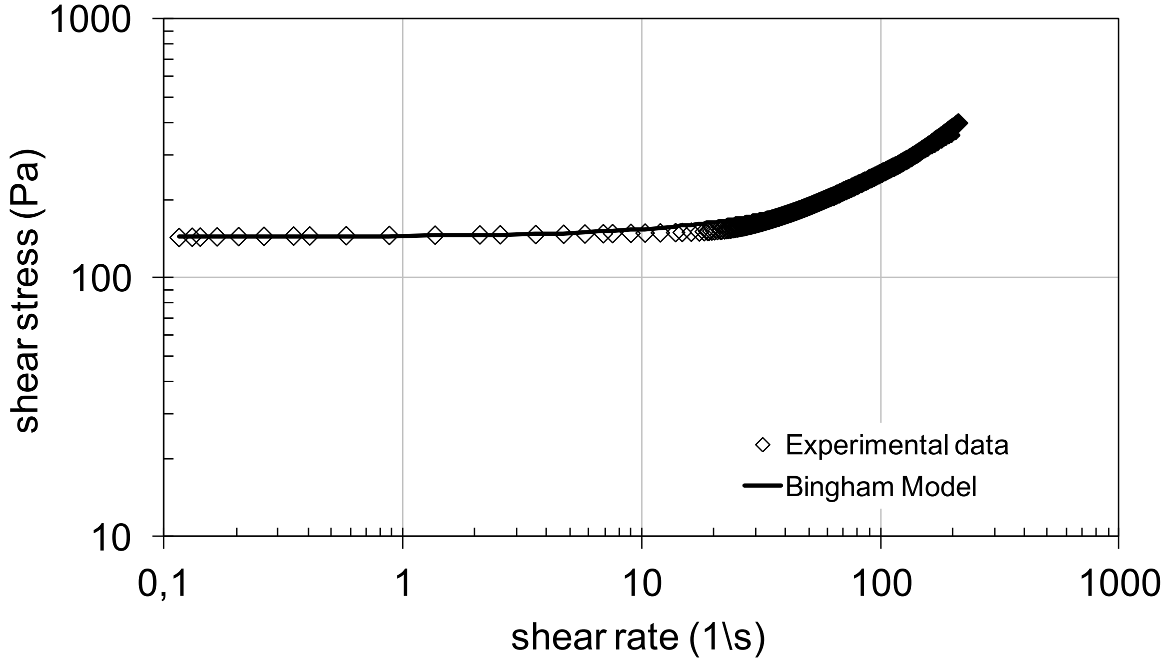

Figure 7 Laboratory flow curve (symbols, diamonds) and theoretical model (continuous line) of a mixture of water and pyroclastic soil at a solid volumetric concentration of 42%.

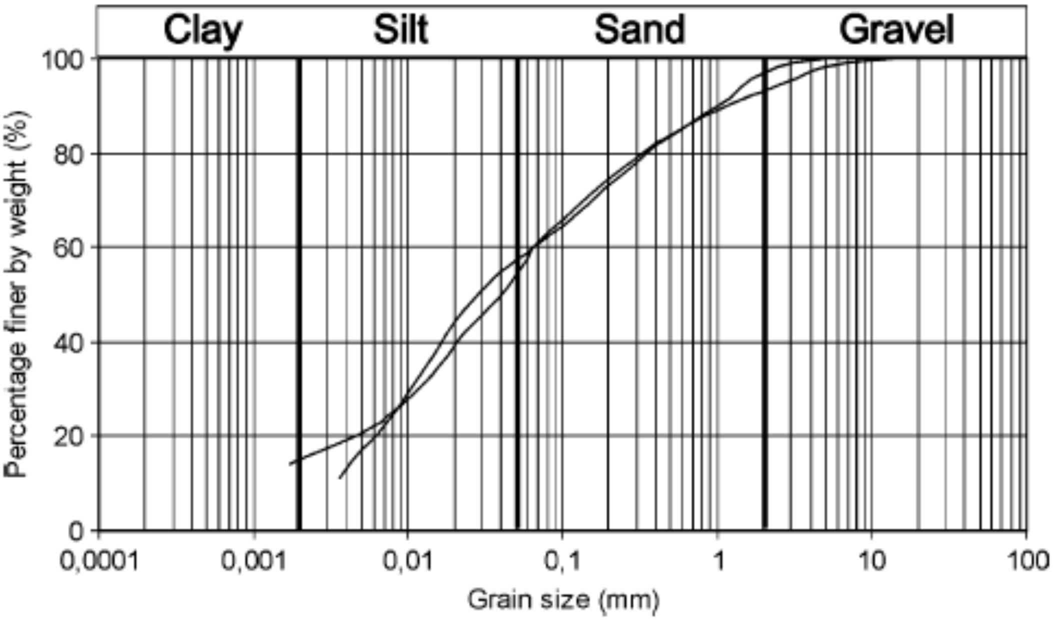

Figure 8 Grain size distribution of some samples taken from the pyroclastic cover of Pozzano (from Calcaterra & Santo, 2004).

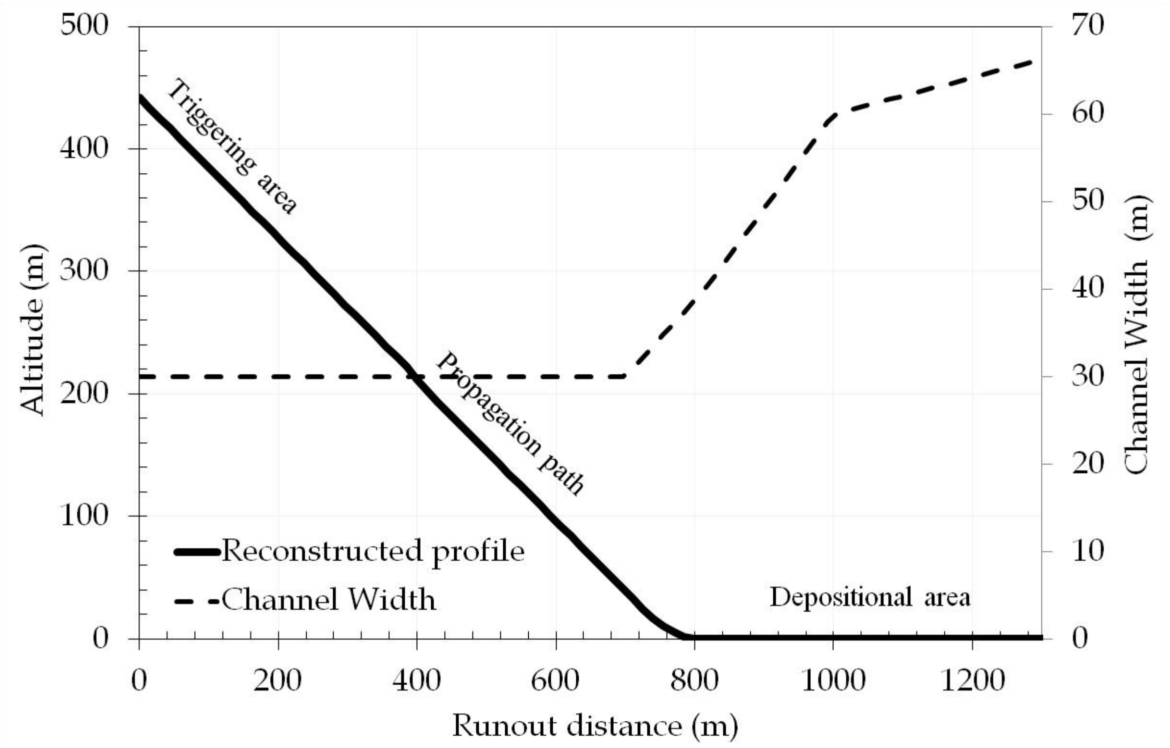

Figure 9 Longitudinal and transversal profile of Pozzano's event reconstructed using DAN-W.

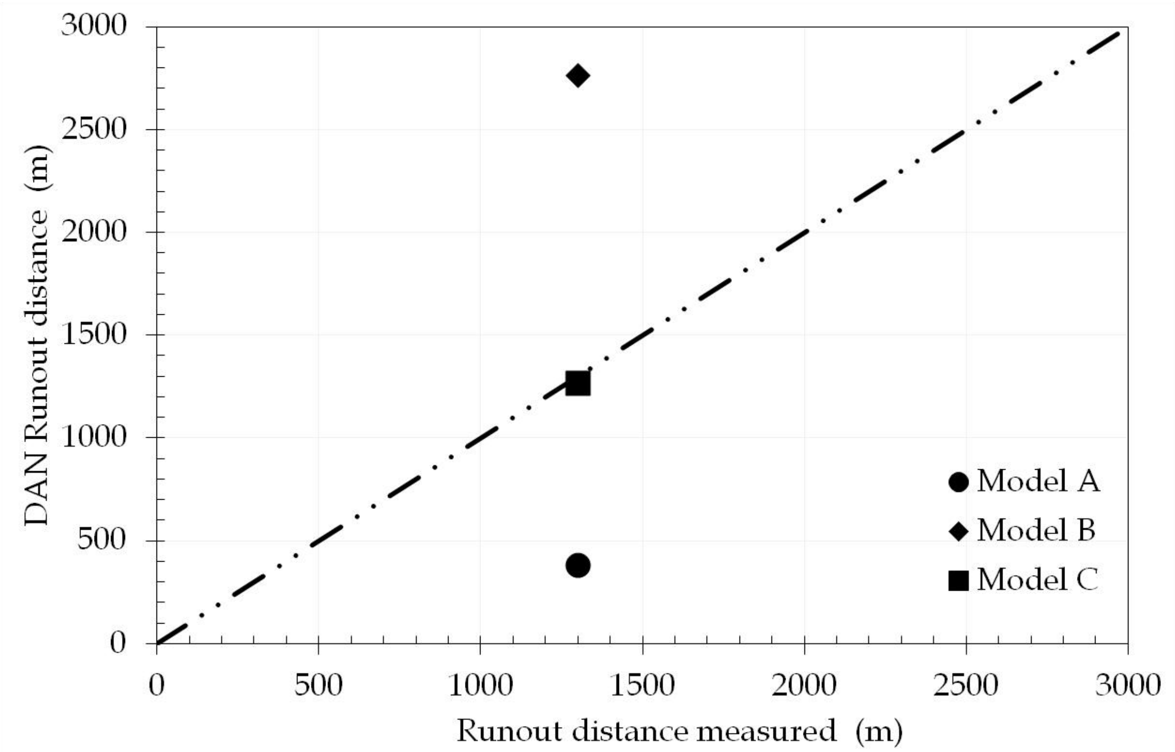

Figure 10 Pozzano's debris flow: comparison between the measured runout distance and the runout distance calculated with DAN-W for the three different models proposed.

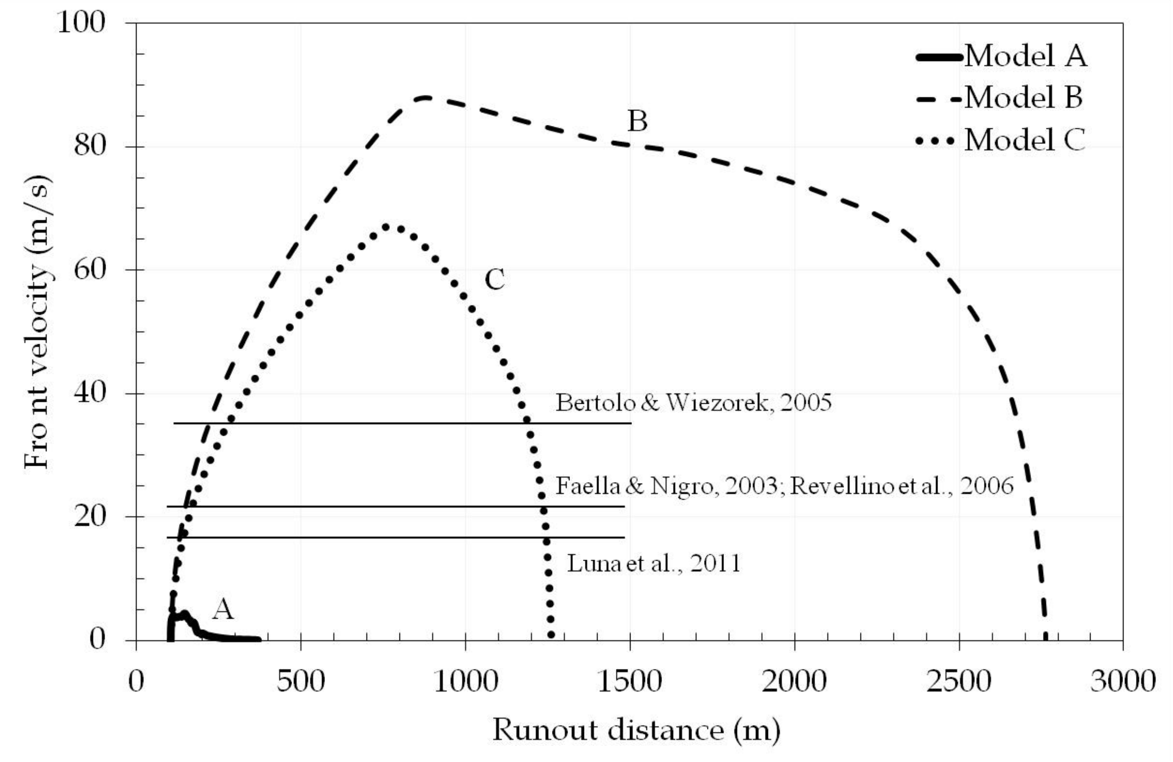

Figure 11 Back analysis of Pozzano's debris flow. Velocity profiles along the path for Models A, B and C. The continuous lines represent the velocity limits for debris flow type event reported in the literature.

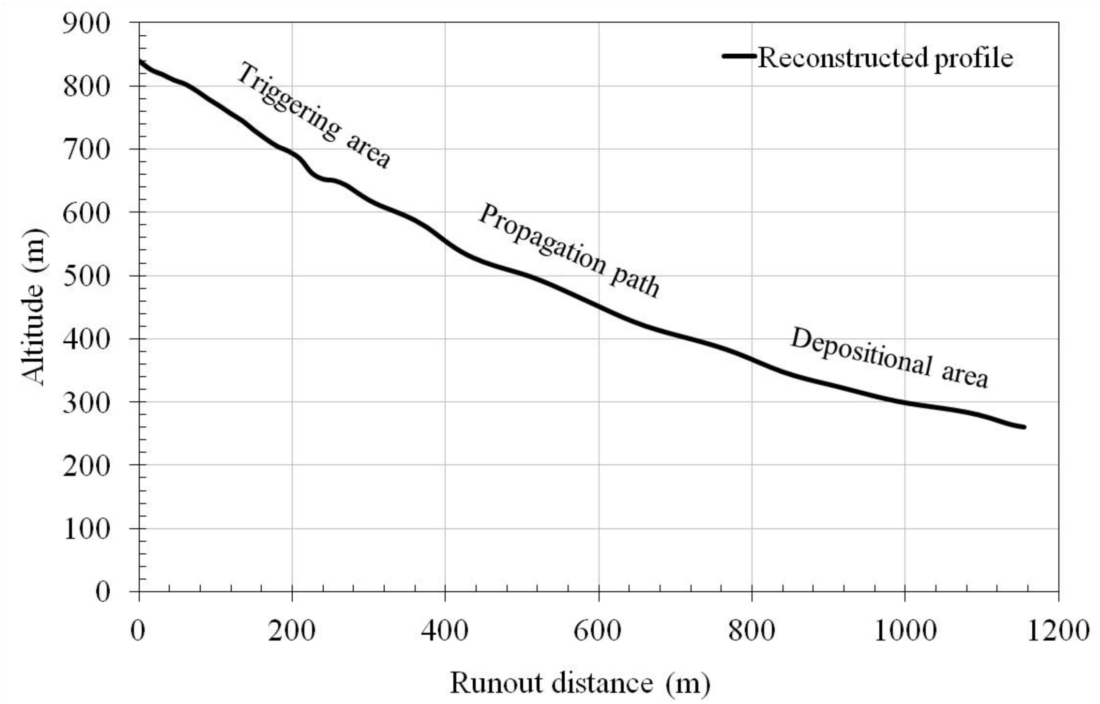

Figure 12 Longitudinal profile of Corbara's debris flow reconstructed using DAN-W.

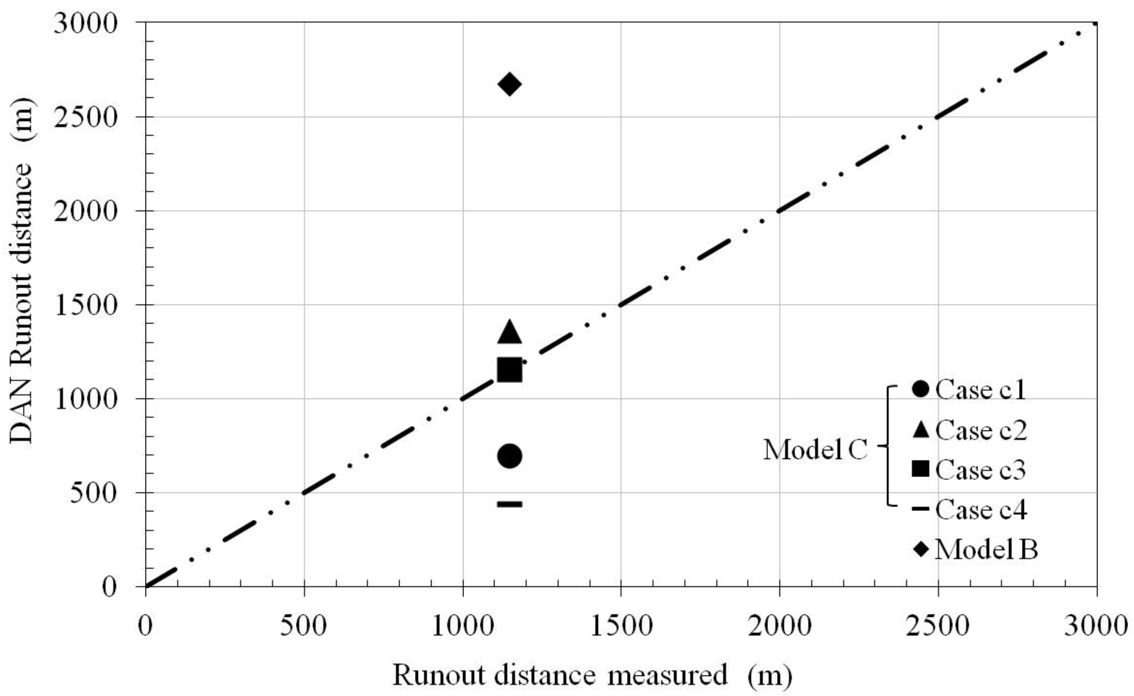

Figure 13 Corbara's debris flow. comparison between the measured runout distance and the runout distance calculated with DAN-W for the different models and scenarios proposed.

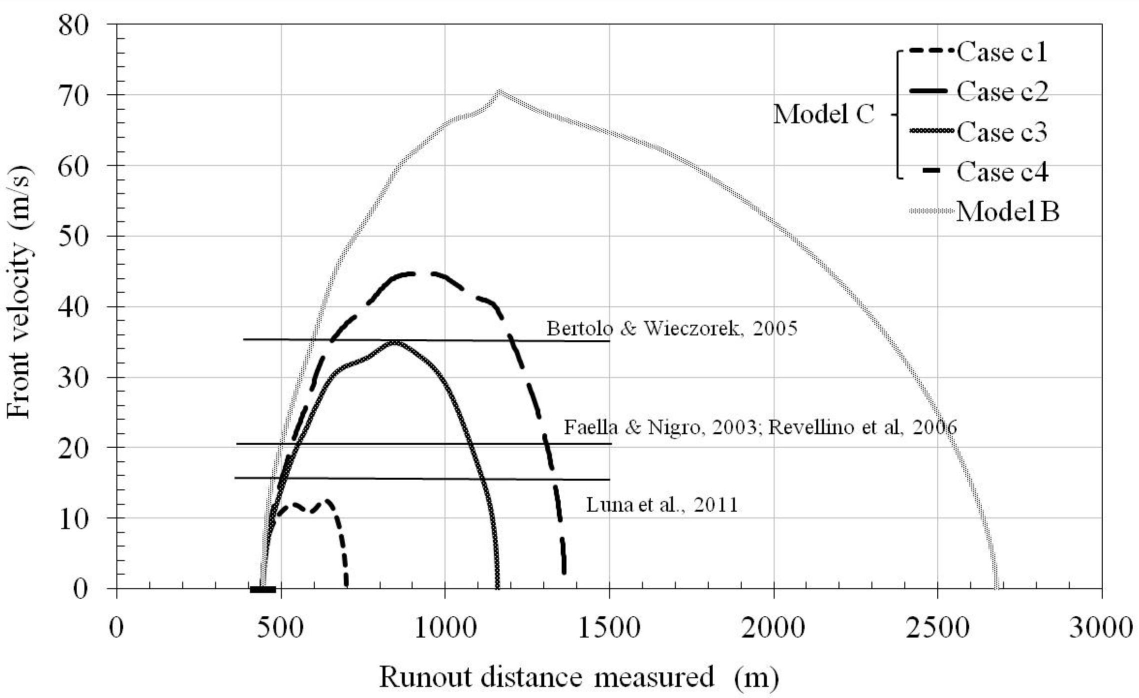

Figure 14 Back calculation results for Corbara's debris flow. Velocity profiles obtained with DAN-W for the five cases considered. The arrows represent the velocity limits for a typical debris flow event deducted from the literature.