Abstract: - In the past, the most widely used model for the analysis of rapid landslides and similar phenomena has been the so-called “lumped mass” model, i.e. a model based on the dynamics of a rigid block sliding over an inclined plane. In recent years, the “lumped mass” model has been put aside in favour of more complex numerical models based on the continuum mechanics theory. The theories set to the continuum are able to describe both the evolution of a limited granular mass and the velocity distribution associated with a landslide on an inclined surface, applying the De Saint Venant equations to the analysis of the granular mass run-out. One of the most critical aspects of such a model is the choice of a representative and adequate constitutive model for the granular-fluid mixture. In order to analyze this aspect, we referred to the catastrophic debris flow event of Pozzano (Napoli), occurred in 1997, which is extensively documented in literature. We applied the two-dimensional code DAN –W (largely used in back analysis of debris flows occurred in Campania region). The constitutive model used is the Bingham ones with three different pair of parameters for the yield stress and Bingham viscosity. The numerical model was then used in order to highlight the differences between the numerical results with the three pairs of parameters adopted on the base of extensive laboratory investigation (e.g., model A), in situ observations (e.g., model B) and a hybrid procedure proposed (e.g., model C). The proposed procedure try to take into account the scale effect between the laboratory experiments (model) and the real events (prototype).

Key-Words: - debris-flow - run-out – numerical modeling – Bingham model – pyroclastic soil mixtures – hazards

1 Introduction
Periodically, debris flows, involving the volcanoclastic deposits mantling very steep slopes of carbonate bedrock, affect the north-western Campania region in Southern Italy. Sometimes, during these catastrophic events the debris-flow moves suddenly down-valley with high velocity, invading the plains at the mountain foothills and affecting towns, roads and factories [1]. This has
resulted in fatalities as well as considerable damage and injuries. Rapid long runout landslides represent a difficult challenge in hazard studies because they pose a risk to areas situated at a considerable distance from the source.

The prediction of runout distance, flow velocity and depth (hereafter referred to as dynamic parameters) is necessary for planning and designing protective measures and represents a key requirement for delineating the hazard zone. Existing prediction methods rely on empirical relationships between volume, travel distance, and the angle of reach (e.g. [2], [3], [4], and [5]) but they are not suitable to forecast all the dynamic parameters.

Reliable debris flow runout codes are therefore needed for flow dynamic prediction, hazard mapping and related risk assessment of the alluvial fan. Attempts to explain or predict the behavior of debris flows must take into account the dynamics of debris-flow motion which in turn is affected by the rheological characteristics of the mixture. Several mathematical models of unsteady, non-uniform debris flow have been developed. Most of them refer to shallow water equation. In the momentum balance equation, the friction term is usually computed according one of the following different schemes: one-phase model, two-phase model, multi-layer model [6]; and the treatment of the source term (i.e. gravity contribution) it is in general not trivial, therefore it has to be treated accurately [16].

A realistic model should represent the debris-flow dynamics as a whole, but very few models have been so far formulated to study the debris flow process from initiation to deposition.

This paper in particular concerns with a debris flow that has taken place in the pyroclastic deposits of the Campania region (southern Italy). The research work deals with the calibration procedure of the most suitable rheological model for the Campanian debris flows by means of:

- experimental activities on reconstitute samples with rheometer and inclined plane and
- back-analysis of a well-documented case history.

The case history reported here was analyzed using the commercial code DAN-W (Hungr, 2003) with the classic rheological model of Bingham. Three pairs of parameters were assigned to the model:

- the first pairs of parameters have been obtained on the base of the in situ observations used the theory proposed by Johnson [13] and Coussot [14], defined model A in the following;
- the second pairs have been obtained from the laboratory activities on pyroclastic Campanian soils reported in Scotto di Santolo et al. [11], defined model B in the following.
- the third pairs is evaluated by a hybrid procedure, defined model C and illustrated in the following.

On the base of the acquired experience [6] and taking into account the limited reliability of the forecast from the triggering to the stoppage of the flow, the constitutive parameters proposed could be a useful tool for modeling the run-out and velocity of probable debris flows in Campania (Italy).

2 Case history: debris flow of Pozzano (Naples)

In 1997 at Pozzano, a place located into the Sorrentina Peninsula (Naples, Campania region), a fatal event of debris flow happened. The Pozzano debris flow has been involved the foothill of the Castellammare di Stabia town (Naples), whose slopes are covered by pyroclastic soils. The event occurred on 10th of January 1997 at 20:15, as a result of intense and prolonged rainfall occurred in the area. The debris flow destroyed a civil building and flooded the 145 State Route, causing four deads, twenty two wounded, and the interruption of the State Route for about two months.

The Pozzano event is a case history well documented in the literature. Several 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 ([4], [7], [8]). This landslide started as translational slide, continued along the State Route, filling an old quarry, and then reached the sea The details of the morphology and the slope profile are shown in Fig. 1.

The crown of the landslides is located at about 465 meters above the sea level. The flowing mass travelled for 1490 meters, with a deposition area of about 665 meters. The medium measured depth of the deposited material resulted 2.5 meters and the inclination of the deposition area was 7°. The depth of the flow was approximately equal to 1.2 meters and the channel slope was 35° ([7], [8]). Flow velocity has been estimated utilizing the work proposed by Faella & Nigro [9] accounting for the damages to the structures occurred during the debris
flows in Sarno-Quindici area (Salerno, Campania region).

3 An overview on DAN-W
DAN-W [10] is a windows-based program used to model the post-failure motion of rapid landslides. 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. DAN-W is based on shallow flow equation and on the Lagrangian solution of St. Venant’s equation (see Fig. 2). This equation can be derived by applying 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:

\[ F = \rho \cdot g \cdot H_{i} \cdot ds \cdot B_{i} \cdot \sin \theta - T - P \]  

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:

\[ H_{i,new} = \left( h_{j-1} + h_{i} \right) / 2 \]  

Where: \( h_{i} \) is equal to \( \left( 2 \cdot V_{j} / \left[ \left( S_{i+1} - S_{i} \right) \left( B_{i+1} + B_{j} \right) \right] \) \), 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 DAN-W model. They are outlined below along with the related appropriate equations for T. More details may be found in Hungr [10].

In the present work, the rheological Bingham model has been used. Fluid initially assumes a solid like behavior (shape and volume defined) and then it reveals its liquid characteristics during the flow. 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 \( \tau_{c} \) and the Bingham viscosity \( \mu_{B} \). Accounting for zero shear stress, the flow becomes Newtonian. The mean flow velocity is derived from the assumption of a linear increase of shear stress with the 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 follow:

\[ v_{i} = 1/6 \cdot H_{i} / \mu_{B} \left( 2 \tau_{c} / A_{i} - 3 \tau_{c} + \tau_{c}^{2} A_{i} / T^{2} \right) \]  

4 Testing simplified rheological model
One of the most critical aspects in using physically based debris-flow model is the choice of a representative and adequate constitutive relation for the mixture.

Among the rheological models available in the DAN-W code, the Bingham model has been used, since it has been employed to describe the experimental data related to several tests performed on reconstituted samples of pyroclastic soils involved in some real debris flow occurred in Campania region [11]. The Bingham model also seems adequate to represent real debris-flow in a variety of situation [12].

The parameters of Bingham model used for the numerical simulations (e.g., yield stress \( \tau_{c} \) and
Bingham viscosity $\mu_B$) have been defined in three different ways: first referring to a simplified method based on field observations (Model A); second considering the experimental results of a rheometer tests on soil-water mixture prepared using the field collected soil samples (Model B); third as an intermediate procedure illustrated in the following (Model C).

The model parameters were validated accounting for travelling distance of the front, and for the reliability of flow velocity.

### 4.1 Model A

The method is a direct application of the theories by Johnson [13] and Coussot [14] concerning the flowing and stopping process of Yield Stress Fluids in idealized flow geometries. The yield stress $\tau_c$ is calculated as:

$$\tau_c = \rho \cdot g \cdot h_D \cdot \sin(i_D)$$  \hspace{1cm} (6)

Where $\rho$ is the mixture density, $g$ is the gravity force, $h_D$ is the deposit depth and $i_D$ is the angle of inclination of the deposition plane.

The Bingham viscosity parameter $\mu_B$ is estimated accounting for the yield stresses $\tau_c$ as well as the observed flow depth $h$ and surface velocity $v_s$ of the debris flow. The calculation of the Bingham viscosity parameter $\mu_B$ is given in the following.

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 $h_{shear}$ (see Fig. 4). For the present method the velocity distribution within the sheared zone is simplified to a linear distribution (see Fig. 4). With knowledge of the yield stress $\tau_c$, in the case of no effects of lateral boundaries, the thickness of the plug zone $h_{plug}$ can be estimated as:

$$h_{plug} = \frac{\tau_c}{\rho \cdot g \cdot \sin (i)}$$  \hspace{1cm} (7)

where $i$ is the inclination angle of the bed.

In the case of confined channel, the effects of lateral boundaries must be considered. For the simplified case of a semicircular channel [12], it is:

$$h_{plug} = \frac{2 \tau_c}{\rho \cdot g \cdot \sin (i)}$$  \hspace{1cm} (8)

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

$$h_{shear} = h - h_{plug}$$  \hspace{1cm} (9)

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

$$\dot{\gamma} = \frac{v_s}{h_{shear}}$$  \hspace{1cm} (10)

Assuming an identical density $\rho$ over the entire flow depth $h$, the bed shear stress $\tau_{bed}$ is:

$$\tau_{bed} = h \cdot \rho \cdot g \cdot \sin (i)$$  \hspace{1cm} (11)

The Bingham viscosity parameter $\mu_B$ can be eventually calculated as:

$$\mu_B = \frac{\tau_{bed} - \tau_c}{\dot{\gamma}}$$  \hspace{1cm} (12)

The results of calculation using these equation for the case analyzed (see § 2) are summarized in Tab. 1. The rheological parameters adopted in this case are $\tau_c$ equal to 3112 Pa and $\mu_B$ equal to 484 Pa/s.

### 4.2 Model B

The rheological parameters assigned to the model B have been determined using the experimental data related to a rheometrical tests performed on mixtures of water and sediment composed with a pyroclastic soil similar to that involved in the real debris flow event considered.

For the present work, the parameters of the Bingham model used to described the experimental data, for a mixture of water and sediment having a solid volumetric concentration $\Phi$ equal to 42%, have been considered. The experimental flow curve and the fitting curve obtained with Bingham model are reported in Fig. 5. The best fitting parameters are $\tau_c = 144$ Pa and $\mu_B = 1.8$ Pa s.

For the laboratory details and fitting procedures see Scotto di Santolo et al. [11].

### 4.3 Model C

In the model C, the viscosity is assumed equal to that estimated with laboratory activity (see Model
models used (e.g., the Model A, Model B and Model C) are shown in Fig. 7 and summarized in Tab. 2. In Fig. 7 the results have been represented in terms of runout distance and maximum velocity reached by the flowing mass during propagation. In Tab. 2 the results of the numerical analysis have been reported in terms of runout distance, deposit thickness, maximum velocity reached during propagation and angle of extension (i.e., Fahrböschung).

Using the model A (i.e., using rheological parameters derived from the geometric characteristics of the real debris flow measured on site) the numerical results do not match very good in terms of runout distance and maximum velocity reached by the flowing mass during propagation. Indeed, while the runout distance measured on site is about 1490 m, using the model A the flowing mass have been covered a distance of about 385 m.

Using the Model B (i.e., using rheological parameters derived from rheometer tests performed on mixtures of water and sediment similar to that of real debris-flow), results do not match satisfactorily in terms of runout distance and in terms of maximum flow velocity. In fact, while the runout distance measured on site is about 1490 m, using this model the estimated distance is of about 2763 m.

Using the model C (i.e., calculating the yield stress $\tau_c$ from the geometric characteristic of the real debris flow event measured on site, and the Bingham viscosity parameter $\mu_B$ from rheometer tests on similar mixtures of water and sediment), results match fairly good both in terms of runout distance and of maximum flow velocity, although this latter being overestimated [9].

5 Results of numerical analysis

The numerical simulations performed with the code DAN-W have been carried out considering a profile of the flow reconstructed from the geometric characteristics of the event taken from literature ([4], [7], [8]). The debris flow profile is schematically represented on Fig. 6.

The results of the numerical analysis for the three models used (e.g., the Model A, Model B and Model C) are shown in Fig. 7 and summarized in Tab. 2. In Fig. 7 the results have been represented in terms of runout distance and maximum velocity reached by the flowing mass during propagation. In Tab. 2 the results of the numerical analysis have been reported in terms of runout distance, deposit thickness, maximum velocity reached during propagation and angle of extension (i.e., Fahrböschung)

Using the model A (i.e., using rheological parameters derived from the geometric characteristics of the real debris flow measured on site) the numerical results do not match very good in terms of runout distance and maximum velocity reached by the flowing mass during propagation. Indeed, while the runout distance measured on site is about 1490 m, using the model A the flowing mass have been covered a distance of about 385 m.

Using the Model B (i.e., using rheological parameters derived from rheometer tests performed on mixtures of water and sediment similar to that of real debris-flow), results do not match satisfactorily in terms of runout distance and in terms of maximum flow velocity. In fact, while the runout distance measured on site is about 1490 m, using this model the estimated distance is of about 2763 m.

Using the model C (i.e., calculating the yield stress $\tau_c$ from the geometric characteristic of the real debris flow event measured on site, and the Bingham viscosity parameter $\mu_B$ from rheometer tests on similar mixtures of water and sediment), results match fairly good both in terms of runout distance and of maximum flow velocity, although this latter being overestimated [9].

6 Conclusion

Rapid long runout landslides represent a significant challenge in hazard studies because they endanger areas situated far from the source. Predictions of the runout distance, flow velocity and depth are necessary for planning and designing protective measures and are a key requirement for delineating the hazard zone.

Despite several physically based numerical models are available, the choice of the appropriate constitutive equation of the mixture still remains a critical aspect.

A well-documented case history which was suitable for back-analysis has been selected for the study. The case history of Pozzano (Naples, Campania region) has been analyzed in 3D using the code DAN-W [10]. The rheological model of Bingham have been chosen; three different approaches has been adopted in order to set the characteristics parameters of the model (i.e., the yield stress $\tau_c$ and the Bingham viscosity $\mu_B$). The model A, in which the rheological parameters assigned have been determined using a simplified method based on the geometric characteristics of the debris flow event measured on site. The model B, in which the rheological parameters have been derived using the experimental data obtained through the rheometer tests performed on mixtures of water and sediment using a pyroclastic soil similar to that involved in the debris flow event considered [11]. The model C, in which the yield stress parameter $\tau_c$ has been calculated from the geometric characteristic of the considered debris flow event measured on site, and the Bingham viscosity $\mu_B$ has been calculated from the experimental data obtained from the rheometer test.

The results of numerical debris-flow modeling, corresponding to each different rheological approach, have been assessed by matching the total horizontal runout and the flow velocities.

The model C seems the most consistent in terms of total runout, debris spread and spatial distribution as well as flow velocity. The results show that past events can be modeled with reasonable accuracy using a model in which the yield stress $\tau_c$ has been calculated from the geometric characteristic of the considered debris flow event, measured on site, and the Bingham viscosity has been measured from the experimental data like for instance from rheometer tests. Although it is still difficult making accurate predictions about the most likely runout, the simple analysis carried out in this study provides useful hint about dynamic behavior of possible debris flows in the studied area.

It is worth noting that the properties of the granular-fluid mixture as a whole change flowing downhill, and they affect the reliability of the model...
prediction. Further research should be addressed to this topic, also involving experimental tests.

References:


Table 1 Results of the parameters calculation for Model A

<table>
<thead>
<tr>
<th>$\tau_C$ (Pa)</th>
<th>$h_{plug}$ (m)</th>
<th>$h_{shear}$ (m)</th>
<th>$\dot{\gamma}$ (s^{-1})</th>
<th>$\tau_C$ (Pa)</th>
<th>$\mu_B$ (Pa s)</th>
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</thead>
<tbody>
<tr>
<td>3112</td>
<td>0,21</td>
<td>0,987</td>
<td>8,10</td>
<td>7029</td>
<td>484</td>
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</table>

Table 2 Results of the numerical analysis

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

Figure 1 Pozzano’s debris flow (Naples, 1997). Event landform (on the left) and elevation profile (on the right). From Calcaterra & Santo [8].
Figure 2: Depth-averaged approximation.

Figure 3 a) Prototype of a heterogeneous and complex moving mass; (b) A homogeneous “apparent fluid” replaces the slide mass (from Hungr, [10]).

Figure 4 Simplified scheme of stress and velocity distribution in a flowing Yield Stress Fluid/viscous debris flow and distinction of plug and shear zone (from Schatzmann [15]).
Figure 5 Flow curve (symbols, diamonds) and theoretical model (continuous line) of a mixture of water and soil at solid volumetric concentration of 42%.

Figure 6 Geometric profile of the Pozzano Bivio debris flow reconstructed with the code DAN-W.
Figure 7 Velocity profiles calculated with the code DAN-W using the three models considered. The light brown line is the reconstructed debris flow profile.