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Deterministic analysis of the debris flow propagation phase for hazard zoning

Analyse déterministe de la phase de propagation des flux de débris pour le zonage des dangers

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ABSTRACT: Debris flows are generally characterized by an almost total absence of warning signals, high propagation velocities and long travelled distances. For these characteristics, debris flows are considered extremely dangerous. Their destructive power can be reduced by a sound design of risk mitigation measures based on an accurate forecasting of propagation and depositional phases aimed at identifying the velocities and depths of the moving mass as well as the depositional area. Indeed, kinematic characteristics of the moving mass and the geometry of propagation and depositional areas are key factors for both the debris flow susceptibility assessment and the estimation of the impact force on exposed elements. For this purpose, the present paper is aimed at underlying the role of the propagation path and debris fan simulated by the numerical code "smoothed particle hydrodynamics" (SPH) in landslide hazard zoning. In the SPH it is necessary to choose the rheological model of the soil-water mixture, to this regard laboratory tests have been carried out for different solid concentration by volume. The soils involved by propagation phase derive by weathering of crystalline rocks and are characterised by a high variability of weathering grade. The last aspect represents the main predisposing factor of debris flow inception that periodically occur in the study area located in the Municipality of Scilla (Calabria, Italy). The obtained results by the simulation of a significant debris flow occurred in the area show a good agreement with real run-out and debris fan and represent the starting point for the quantitative assessment of debris flow hazard.

RÉSUMÉ : Les coulées de débris se caractérisent généralement par une absence quasi totale de signaux d'alerte, des vitesses de propagation élevées et de longues distances parcourues. Pour ces caractéristiques, les écoulements de débris sont considérés comme extrêmement dangereux. Leur pouvoir destructeur peut être réduit par une conception judicieuse des mesures d'atténuation des risques basées sur une prévision précise des phases de propagation et de dépôt visant à identifier les vitesses et les profondeurs de la masse en mouvement ainsi que la zone de dépôt. En effet, les caractéristiques cinématiques de la masse en mouvement et la géométrie des zones de propagation et de dépôt sont des facteurs clés à la fois pour l'évaluation de la sensibilité à l'écoulement des débris et pour l'estimation de la force d'impact sur les éléments exposés. À cette fin, le présent article vise à sous-tendre le rôle du chemin de propagation et de l'éventail de débris simulé par le code numérique « hydrodynamique des particules lissées » (SPH) dans le zonage des risques de glissement de terrain. Dans le SPH, il est nécessaire de choisir le modèle rhéologique du mélange sol-eau, à cet égard des tests de laboratoire ont été effectués pour différentes concentrations de solides en volume. Les sols concernés par la phase de propagation proviennent de l'altération des roches cristallines et se caractérisent par une forte variabilité de la teneur en altération. Le dernier aspect représente le principal facteur prédisposant à l'apparition de coulées de débris qui se produisent périodiquement dans la zone d'étude située dans la municipalité de Scilla (Calabre, Italie). Les résultats obtenus par la simulation d'un flux de débris important survenu dans la zone montrent une bonne concordance avec le faux-rond réel et le ventilateur de débris et représentent le point de départ pour l'évaluation quantitative du risque de flux de débris.

KEYWORDS: debris flow, rheological tests, run-out, debris fan, SPH

1 INTRODUCTION

Rainfall induced debris flows are phenomena generally characterized by an almost total absence of warning signals, long traveled distances and high velocity reached during the propagation phase. They occur on established paths, usually gullies and first or second order drainage channels, they are extremely dangerous. Their destructive power can be reduced by a sound design of risk mitigation measures based on an accurate forecasting of propagation and depositional phases aimed at identifying the velocities and depths of the moving mass as well as the depositional area.

To this regards, it is known that a reliable prediction of debris flow track and debris fan by deterministic method can better define the area most susceptible to debris flows so providing a useful tool for land use planning.

On the other hand, an accurate estimation of debris flow height and debris flow velocity in a significant section can be used for evaluating the impact forces on the protection structures to design.

In this work the propagation path and depositional area of a debris flow occurred in 2001 in a study area located in the province of Reggio Calabria (Italy) was simulated using the numerical code Geo-Flow SPH. The analyzed landslide, representative of similar phenomena that occur in the study area, involved residual, colluvial and detrital soils deriving from the weathering of gneiss both in triggering and propagation phases. Due to their heterogeneous nature and the highly variable grade of weathering, these soils are difficult to characterize from a geotechnical point of view.

The paper highlights the importance of the rheological characterization of the soil water mixture at the laboratory scale for the simulation of propagation and deposition phases of the debris flows for the assessment of hazard zoning.

2 STUDY AREA

The study area is located in the province of Reggio Calabria (Italy) along the SW coast of the Calabria Region between Bagnara Calabra and Scilla.

This area (Fig. 1), with an extension of about 1 km^2, is bounded, upstream, by the Piano delle Aquile (terrace of marine origin located at about 630 m asl), and downstream by a densely urbanized coastal plain represented by the Favazzina hamlet located in the Municipality of Scilla.

The area is interested by the presence of important infrastructural works. In particular, the railway line, the Tyrrhenian state road SS18, the SNAM methane pipeline and the old Highway A3 (SA-RC) which currently crosses the same slopes in tunnel, Fig. 1.

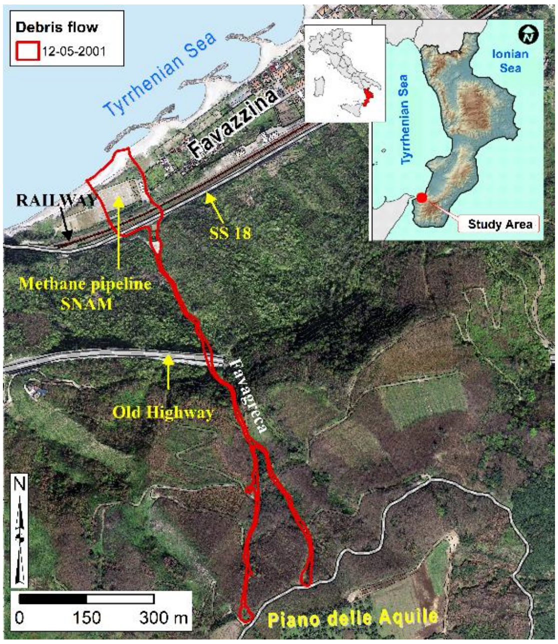

Figure 1. Study area and the 2001 debris flow.

The studied area is characterized by a Paleozoic basement, consisting of metamorphic rocks affected by weathering processes which, according to GCO (1988), Borrelli et al. (2012), Gioffrè et al. (2016), can be divided into six classes of weathering. Among these, the residual, colluvial and detrital soils (gneiss of class VI) emerge for about 60% of the study area and are those most affected by debris flows.

In recent decades, the upstream slopes of the Favazzina hamlet have been involved by several landslides, including the debris flow of 12 May 2001 in which two landslides were triggered by the head of Vallone Favagreca respectively at about 567 and 558 m a.s.l. in correspondence of two incisions that joined at about 300 m s.l.m. The two landslides evolved into a rapid flow which hit the old highway A3 (Fig. 1), the methane pipeline SNAM, the state road (SS18) and the railway line causing the derailment of the ICN Turin - Reggio Calabria.

A topographical analysis, which contemplates the use of the basin area and the slope of the fan, made it possible to provide more information on the type of dominant flow in the basin. This analysis used in scientific literature for mapping debris flow susceptibility and hazard (Wilford et al., 2004; Bertrand et al., 2013), consists of comparing the Melton Index with the slope of the fan representative of the dominant transport process.

The Melton index provides information about the gravitational energy of the basin as it represents the ratio between the difference in altitude existing between the maximum elevation of the basin and the elevation of the fan apex by the square root of the studied basin area.

Figure 2 shows where the flow type of the studied areas falls according to the Bertrand et al. approach (2013) based on a database of 620 basins subject to flow phenomena, separated by means of the red curve fluvial processes (hyperconcentrated flows, solid transport, etc.) and debris flows. As it can be noticed the basin is characterized by a debris flow regime (black full circle).

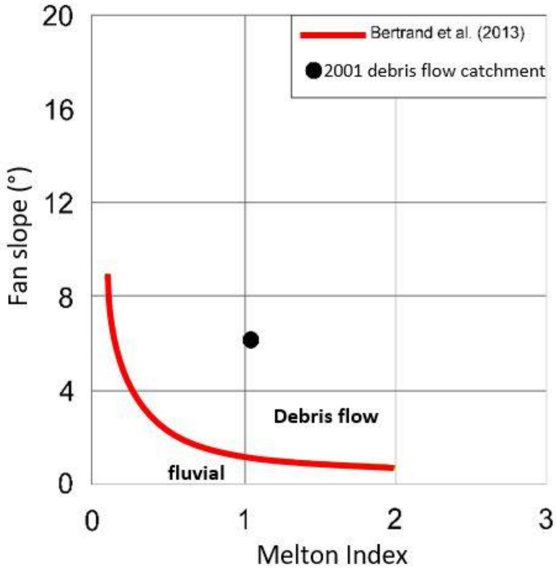

Figure 2. Classification of flow type of the studied area according to Bertrand et al. (2013).

3 CHARACTERIZATION OF THE SOIL-WATER MIXTURE OF DEBRIS FLOW OCCURRED ON 12 MAY 2001

In order to characterize the outcropping soils from a geotechnical point of view, a large survey campaign consisted of 5 continuous boreholes, 14 seismic refraction tomographies, 10 SPTs, 8 undisturbed cubic samples and 5 undisturbed samples was carried out (Fig. 3).

Standard and advanced laboratory tests are in progress for the geotechnical characterization of residual, colluvial and detrital soils constituting the shallowest layers that are more susceptible to debris flow inception. In particular, direct shear tests, triaxial tests in saturated and unsaturated conditions, Richards pressure plate tests, tests in traditional and controlled suction oedometer and analyses using the scanning electron microscope (SEM) are in progress, while classification tests, diffractometric analyses (XRF) and rheological analyses have been carried out on Q3 samples.

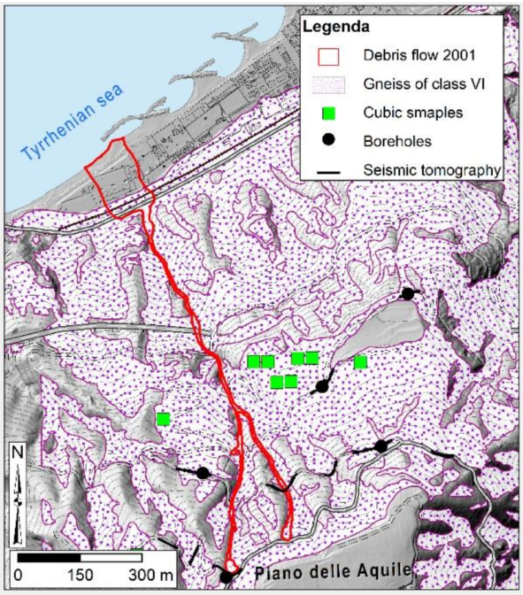

Figure 3. Gneiss of class VI and location of in-situ surveys for its characterization.

From a mineralogical point of view, Fig. 4, two XRF tests have been performed on specimens taken from samples collected on two different boreholes at depth ranging from 0.5 m and 1.0 m. The X-ray diffraction patterns perfectly overlap and show a high presence of quartz followed by feldspars (albite and microcline), phyllosilicates (biotite) and Kaolinite. This mineral composition is typical of weathered gneiss as found also by other researchers (Biondino et al., 2020).

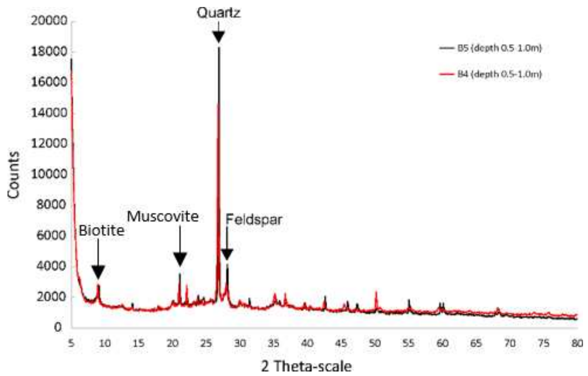

Figure 4. X-ray diffraction patterns.

The classification tests carried out on the samples taken in correspondence of the most superficial layer made it possible to classify the soil. According to the USCS classification system, the soil is a silty sand SM with liquid limit LL = 60.7% and plasticity index PI = 6.97%.

The soil sample taken from a greater depth has also been classified as silty sands SM, according to the USCS classification system, and with a fine non-plastic fraction.

The particle size distributions of the soils collected at different depths, between 0.5 m and 1.0 m (sample S4_CR 0.5-1.0 m, red dashed curve), between 1.5 m and 2.0 m (S4_CR 1.5-2.0 m, red continuous curve) and between 4.1 m and 4.5 m (S4_CR 4.1-4.5, black continuous curve), are shown in Fig. 5.

The simulation of the rheological behavior of debris flows are generally performed using viscoplastic (i.e., Herschel-Bukley or Bingham model) or collisional-frictional models (i.e., Coulomb or Voellmy model).

The Bingham rheological model has been successfully used by the authors for the study of debris flow propagation (Moraci et al., 2017).

Bardou et al. (2003) identify two grain size distribution zones with a typical viscoplastic or collisional-frictional behavior (Fig. 5).

In the studied case, the most superficial soils, involved by debris flows, fall within the viscoplastic behavior, while the deepest ones, not involved by debris flows, falls within the zone with a collision-friction behavior (Fig. 5).

In order to verify the rheological behavior of the superficial soils involved in the 2001 landslide event, laboratory tests with rotary viscometer have been carried out. This tests have been performed on a mixture constituted by the fine fraction of the analysed soils and water in different solid concentration by volume (varying from 30% to 42.5%).

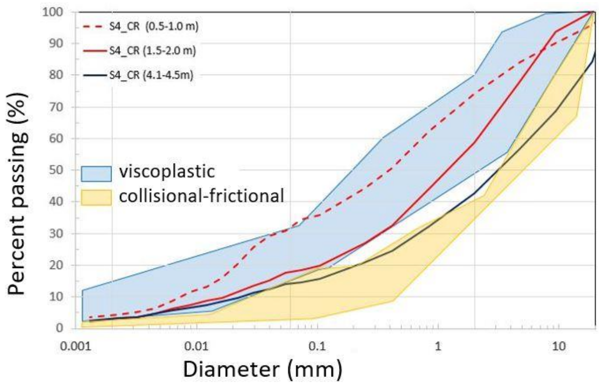

Figure 5. Grain size distribution of the studied soil and its location within the two rheological classes proposed by Bardou et al. (2003).

Viscometer tests have been interpreted by Bingham rheological law according to Moraci et al. (2017) and considering that the superficial soils fall into a viscoplastic rheological behavior (Fig. 5).

The equation at the base of the Bingham model is as follows:

$$\tau = \tau_0 + \frac{du}{dy} \tag{1}$$

Where τ_0 (Pa) is the yield stress and μ is the dynamic viscosity (Pa s).

It is generally accepted that yield stress and dynamic viscosity exponentially increase by increasing the solid concentration in volume Cv according to the laws listed below:

$$\tau_0 = \alpha_1 \cdot e^{\beta_1 C_v} \tag{2}$$

$$\mu = \alpha_2 \cdot e^{\beta_2 C_v} \tag{3}$$

Both values are linked to two empirical coefficients α_i and β_i obtained by a regression analysis on experimental data for each one of the tested specimens.

The interpretation of the experimental results indicates that the previous equations 2 and 3 well represent the variation of τ_0 (Pa) and μ (Pa s) respectively as a function of the solid concentration by volume Cv (Fig. 6). Particularly, the regression analysis provided the following values of α_1=0.0002 Pa and β_1=0.27; α_2=0.001 Pa s and β_2=0.21 (Ciurleo et al., 2021).

Using the equations 2 and 3 with the above mentioned values of empirical coefficients, it is possible to obtain the values of τ_0 and μ for other values of the solid concentration by volume Cv.

These results have been drawn in Fig. 7, where results obtained by other authors are also shown. The results fall within the ranges identified in previous experimental studies (Hurlimann et al., 2015).

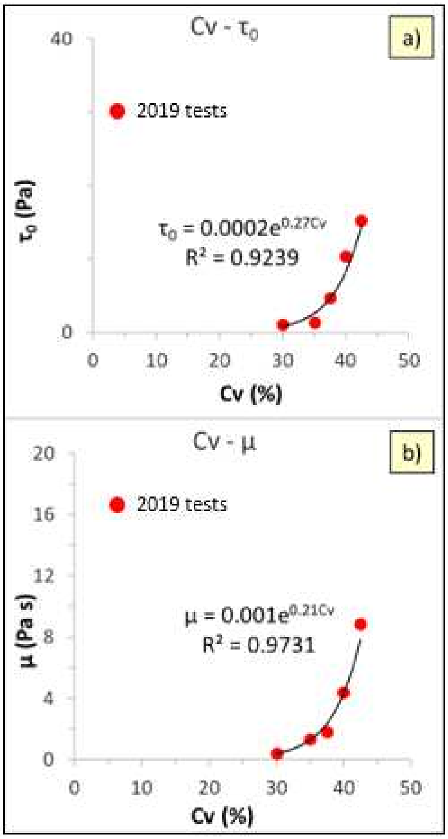

Figure 6. a) Critical stress τ_0 and b) dynamic viscosity μ versus solid concentration by volume Cv obtained by laboratory tests.

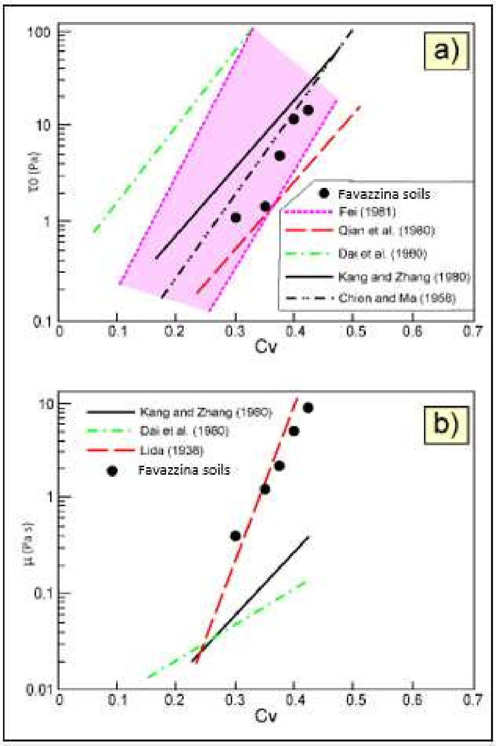

Figure 7. Comparison between literature and laboratory data (modified from Hürlimann et al., 2015). (a) Critical stress τ_0 versus solid concentration by volume; (b) dynamic viscosity μ versus solid concentration by volume.

4 SIMULATION OF DEBRIS FLOW PROPAGATION

The simulation of debris flow propagation was carried out by means of the numerical model SPH (Pastor et al., 2009) which allowed the evaluation of debris flow path, the travel distance and depositional area.

The model requires as input data the Digital Surface Model (DSM) of the study area (in this case taken with 2 m x 2 m resolution), the triggering volumes, the rheological model and its parameters and the erosion law.

With regard to the triggering volumes, the data reported by several studies have been used. In particular, referring to the shape of triggering volume, Bonavina et al. (2005) quoted that this volume has a prismatic geometry with a slip surface located at a depth of about 1.5 m. The triggering volumes of 900 m^3 and 1125 m^3 reported by previous studies carried out by the same authors were used (Ciurleo et al., 2019, 2020). As regards the rheological parameters, the values of τ_0 and μ reported in table 1 were adopted in the analyses and were obtained by using the regression laws found from viscometer tests and considering a solid concentration by volume varying between 50% and 60%.

Table 1 - SPH input data

C_v (%)	τ_0 (Pa)	μ (Pa s)
50-60	145.88 – 2170.7	36.3-296.6

With reference to the erosion law, Hungr's law (1995) was used by means of the “grow rate” parameter (Es), which is a function of the final volume of the moving mass, the initial volume and the distance traveled by the debris flow. In this study, Es values varying between 0.001 m^{-1} and 0.002 m^{-1} were considered.

Several numerical analyses have been carried out by varying both the parameters of the rheological model and the value of Es in the range considered.

The validation of the numerical analyses was carried out using the two dimensionless indices I_{prop} (propagation index) and I_{dep} (deposition index), defined by Ciurleo et al. (2020) as follows:

$$I_{prop} = \frac{ASR}{ATR} \cdot 100 \qquad (4)$$

$$I_{dep} = \frac{A_{SDF}}{A_{TDF}} \cdot 100 \qquad (5)$$

where: ATR is the propagation area mapped after the event, ASR is the propagation area numerically computed and located within ATR, ATDF is the depositional area mapped after the event and ASDF is the numerically computed depositional area located within ATDF.

The results of the simulations were compared with the propagation path and the depositional area of the 2001 debris flow. In particular, considering the areas above and below the section O-O' (Fig. 8), the simulation that best fits the areas really affected by the propagation and deposition phases is the one obtained considering a Cv= 54% and a value of Es= 0.0015 m^{-1}. In this case, I_{prop} and I_{dep} indices assumed values of 100% and 72% respectively.

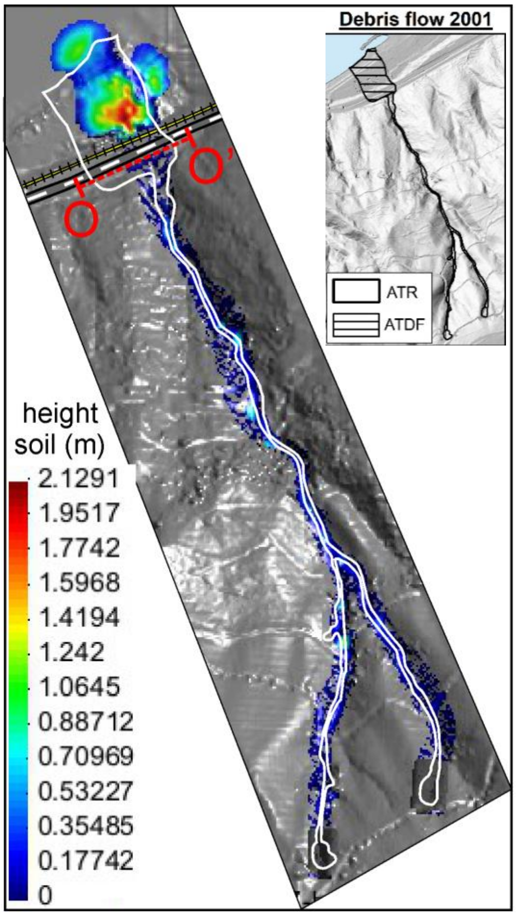

Figure 8. The best numerical modelling simulation obtained considering Cv=54% and Es=0.0015 m^{-1}.

5 CONCLUSIONS

The simulation of the 2001 debris flow has provided satisfactory results both in terms of propagation and depositional areas.

The rheological model, solid concentration by volume and erosion law that best simulated the propagation and depositional areas observed in the real event can be used for the simulation of potential similar phenomena of debris flows that could occur in the study area.

It should be noted that one of the used input data of the propagation model is represented by the estimated initial triggering volumes which should be obtained through physically based models that use a geotechnical model of the involved slopes. This rigorous geotechnical model can be obtained only by scientifically robust on-site and laboratory tests such as those described above and currently underway.

Furthermore, it should be noted that the parameters τ_0 and μ of the rheological law used for 2001 debris flow simulation were obtained from viscometer tests carried out only on the fine fraction of the soil due to the limits of the test equipment. Parameters of the rheological model will be further investigated using tests able of simulating the entire grain size distribution of the soils involved in the landslides.

6 ACKNOWLEDGEMENTS

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