The combined use of physically based models for the analysis of debris flows

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ABSTRACT
The paper presents a methodology for the analysis of debris flows through the combined use of two physically based models (TRIGRS, SPH) for the study of triggering and propagation phases, respectively. In particular, TRIGRS, used to analyse the triggering phase, allowed the identification of triggering areas and the estimation of mobilized volumes. These volumes were used as input data of the SPH model for the back analysis of the propagation phase in terms of both main pathway and depositional area. The implementation of both models required the use of geotechnical data obtained from in situ surveys and laboratory tests. The methodology, applied to a landslide event occurred in the province of Reggio Calabria, showed that the results obtained combining these models are coherent with the back-analysis of the real event, in terms of both triggering areas and propagation zones.

1 INTRODUCTION
Debris flows are very complex phenomena, characterized by velocities ranging from very rapid (higher than 3 m/min) to extremely rapid (higher than 5 m/s), often involve significant entrainment of soil and occur periodically along gullies and first or second order drainage channels (Hungr et al., 2014). These phenomena can cause losses of human lives and significant socio-economic disasters. In weathered gneiss, debris flows present a failure surface generally located at the contact between residual soils and less weathered soil layers. Due to the heterogeneity of these soils and the difficulty of undisturbed sample taking, the geotechnical characterization is very complex, and as consequence experimental studies on naturally weathered rocks are limited (Gullà et al., 2006). On these weathered soils, a preliminary analysis of triggering and propagation phases could be carried out through a back-analysis of debris flows. The paper proposes a methodology for the back-analysis of real debris flows based on the combined use of two physically based models (TRIGRS, SPH). TRIGRS was used for the analysis of the triggering phase and allowed estimating the mobilized triggering volumes; SPH, using TRIGRS results, allowed the analysis of the propagation phase. The proposed methodology has been applied to a debris flow occurred in Calabria (southern Italy) and the obtained results show a good agreement with the real case in terms of both triggering phase and propagation zones.

2 THE STUDY AREA AND THE PROPOSED METHODOLOGY
The study area is located in the Favazzina hamlet (Reggio Calabria, Italy). About 60% of the study area is covered by residual, colluvial and detrital soils (gneiss of Class VI according to GCO 1988 and Gioffrè et al. 2016) periodically involved by several debris flows. In particular, on May 2001 a debris flow, initiated by two translational slides, hit the SNAM station of the methane pipeline, the state road SR 18 and the railway causing the derailment of the intercity train Turin - Reggio Calabria (Borrelli et al. 2012) (Figure 1).
The methodology proposed for the back analysis of the 2001 debris flow needs a preliminary identification of landslide geometry and rainfall data. It can be divided into 3 stages; each one considers as input data the output of the previous one (Figure 2). In particular, the aim of the first stage is the creation of a database that consists of: rainfall, topographical and geomorphological data; mechanical and hydraulic properties of weathered gneiss, pore water pressure regime and rheological model of the soil-water mixture. Stage II is aimed to back-analyse the debris flow triggering zones by a physically based model TRIGRS that couples an infiltration model (Iverson, 2000; Baum et al., 2002) with an infinite slope stability model (Taylor, 1948). In this stage, several parametric analyses should be carried out varying TRIGRS input parameters in the range identified in the stage I. Triggering areas and mobilized initial volumes are the results of stage II. These results are the input data of stage III that uses the SPH model (Pastor et al., 2009) for analysing the
propagation phase and the depositional area. The input data for SPH analyses are: triggering volumes identified in the stage II, rheological parameters and the Digital Elevation Model (DEM) of the study area.

![Image 1: 2001 Debris flow](image1.png)

The back analysis is verified using three dimensionless indices ($I_d$) defined for triggering and propagation phases and for debris fan, as follows:

\[
I_{trg} = \frac{A_{trg}}{A_{TL}} \times 100
\]

(1)

\[
I_{prop} = \frac{A_{prop}}{A_{SR}} \times 100
\]

(2)

\[
I_{dep} = \frac{A_{dep}}{A_{TDF}} \times 100
\]

(3)

where $A_{TL}$ are the landslide source areas according to the landslide inventory (observed source areas), $A_{UTL}$ are the areas computed as unstable located within the $A_{TL}$, $A_{SR}$ is the run-out area according to the landslide inventory, $A_{SR}$ is the numerically computed run-out area located within the $A_{TR}$, $A_{TDF}$ is the debris fan mapped in the landslide inventory and $A_{SDF}$ is the numerically computed debris fan located within the $A_{TDF}$.

### 3 ANALYSES AND RESULTS

#### 4.1 Stage I

The 2001 debris flow had a slip surface located at 1.5 m of depth and occurred on gneiss of Class VI. According to USCS, these soils were classified as silty sand (SM) and inorganic silt of medium compressibility with sand (ML). The main physical properties of the studied soils are showed in table 1.

<table>
<thead>
<tr>
<th>$\gamma$ (kN/m$^3$)</th>
<th>$\gamma_{sat}$ (kN/m$^3$)</th>
<th>$\gamma_d$ (kN/m$^3$)</th>
<th>$e$</th>
<th>$n$</th>
<th>$S$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-20</td>
<td>19-22</td>
<td>12.5-16</td>
<td>0.65-1.15</td>
<td>0.40-0.55</td>
<td>43-99</td>
</tr>
</tbody>
</table>

Direct shear test results showed a cohesion value ($c'$) of 0 kPa and shear strength angle values ($\phi'$) ranging from 38° to 44° (Antronico et al. 2006). Several authors (Schilirò et al. 2015) investigated soils similar for genesis and stress history to those of Fuvazzina that showed values of $c'$ ranging from 0 kPa to 5 kPa and $\phi'$ between 30° and 40°.

Referring to hydraulic properties, specific data for the study area were not available from scientific literature. To this purpose, the values of saturated conductivity ($K_{sat}$) ranging from 1.27E-06 m/s to 6.60E-05 m/s and saturated volumetric water content $\theta_s$ ranging from 0.38 to 0.4, obtained by Cascini et al. (2006) and Schilirò et al. (2015) for gneiss similar for genesis and stress history with those studied, have been used.
Viscometer laboratory tests, performed by Moraci et al. (2017) on soil-water mixtures using the soil sampled in the studied area, allowed to identify the Bingham rheological parameters, $\tau_0$ (yield stress) and $\mu_b$ (Bingham viscosity), for different values of solid concentration by volume $C_v$.

Referring to rainfall data, the only available information can be gathered by the Scilla rain gauge that recorded a peak value of 20 mm of rainfall on 12 May 2001.

4.2 Stage II
The input data of TRIGRS, identified in stage I, were: rainfall data, digital elevation model (DEM), soil cover thickness, hydraulic and mechanical properties of soils (table 2).

<table>
<thead>
<tr>
<th>$\gamma$ (kN/m$^3$)</th>
<th>$c'$ (kPa)</th>
<th>$\phi$' (°)</th>
<th>Thickness (m)</th>
<th>$K_{sat}$ (m/s)</th>
<th>$D_0$ (m$^2$/s)</th>
<th>$\theta_{sat}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0 - 5</td>
<td>30 - 40</td>
<td>1.5</td>
<td>1.75e-05</td>
<td>7.92e-05</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Regarding pore water pressure regime, due to the lack of data, the water table was assumed at the ground surface in the upper part of the slope and at the contact between class VI and less weathered gneiss in the remaining part of the study area.

Several analyses have been performed and the best fitting between the source areas triggered in 2001 and the numerical analyses ($I_{trig} = 90.3\%$) was achieved considering an average value of cohesion ($c'=2.5$ kPa) and the minimum value of shear strength angle ($\phi'=30°$) (Figure 3a). The computed triggering volumes of the translational landslide source areas are 900 m$^3$ and 1125 m$^3$.

4.3 Stage III
In stage III, the SPH model used the following input data: triggering volumes identified in stage II, DEM, rheological parameters and erosion rate, considering the “growth rate” $E_s$ (Hungr 1995) (Table 3).

<table>
<thead>
<tr>
<th>$C_v$ (%)</th>
<th>$\tau_0$ (Pa)</th>
<th>$\mu_b$ (Pa·s)</th>
<th>$E_s$ (m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>55 - 60</td>
<td>357 - 690</td>
<td>87 - 198</td>
<td>0.001 – 0.002</td>
</tr>
</tbody>
</table>

Stage III consisted of an iterative analysis of rheological parameters and erosion coefficient. Particularly, previous studies (Gioffrè et al. 2016) demonstrated that the Bingham model provided the best propagation analysis of the debris flow occurred in 2001. Once the model was selected, viscometer laboratory tests have been performed to derive the Bingham model parameters ($\tau_0$ and $\mu_b$) as a function of the solid concentration by volume ($C_v$) in the range reported in table 3 according to the classification proposed by Pierson and Costa (1987). $E_s$ has been considered to vary in a range from 0.001 m$^{-1}$ to 0.002 m$^{-1}$. The numerical simulations have been compared with the main pathway and depositional area of the debris flow occurred in 2001. Particularly, considering the area above the AA’ section, the simulation well fits the real phenomenon ($I_{dep}=100\%$), whereas considering the area below the AA’ section the value of $I_{dep}$ is equal to about 60%. The last result could be due to the fact that the DEM does not consider the presence of obstacles located in the area which certainly helped to divert the debris fan.

These results have been obtained considering $C_v=55\%$ and $E_s=0.00135$ m$^{-1}$ (Figure 3b).

![Figure 3](image-url)
4 CONCLUSIONS

The paper deals with a methodology for the back-analysis of debris flow through a combined use of two physically based models. The first stage, database creation, is aimed to identify the input data to be used for the implementation of numerical models in stage II and III. Particularly, stage II analysed the triggering phase by TRIGRS, and its validation was performed through $I_{\text{trig}}$. The highest value of $I_{\text{trig}}$ (90.3%) was obtained considering a cohesion value of 2.5 kPa and shear strength angle equal to 30°. In addition, TRIGRS provided two triggering volumes that were used as input data in stage III, in which the propagation phase was analysed using the SPH model. In this case the validation was carried out by means $I_{\text{prop}}$ and $I_{\text{dep}},$ and the highest value of $I_{\text{prop}}$ (100%) and $I_{\text{dep}}$ (about 60%) were obtained considering $C_v = 55\%$ and $E_s = 0.00135 \text{ m}^4$. The obtained results show a good performance of the proposed methodology in the analysis of both the triggering zones and the debris flow main pathway. Referring to debris fan, $I_{\text{dep}}$ equal to 60% is due to the lack in the topographical model of natural and manmade obstacles in the depositional area. For this reason, further analyses will be performed using a digital surface model (DSM) with 1m x 1m resolution. The provided results are considered preliminary because using the data actually available. More advanced results could be achieved through a better geotechnical characterization of weathered rocks of class VI involved in debris flows.

REFERENCES


