A Method to Evaluate Debris Flow Triggering and Propagation by Numerical Analyses

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Abstract. Debris flows travel at very rapid to extremely rapid velocity, often involve significant entrainment of soil and occur periodically along gullies and first or second order drainage channels. Owing to their characteristics, these phenomena can cause losses of human lives and significant socio-economic disasters. In weathered gneiss, the analysis of these phenomena is very complex due to the heterogeneity of soils and the difficulty of undisturbed sample taking. On these soils, a preliminary characterization of triggering and propagation phases could be carried out through a debris flow numerical analysis. The paper proposes a methodology for the analysis of a debris flow based on the combined use of two physically based models (TRIGRS and SPH). TRIGRS was used for the analysis of the triggering phase and allowed estimating the mobilized triggering volumes; SPH, using the triggering volumes, allowed the analysis of the propagation phase. The methodology has been applied to a debris flow occurred in Calabria (southern Italy). The obtained results show a good agreement with the real case in terms of both triggering phase, propagation zones as well as of depositional area, and represent the starting point on which to identify debris flow risk mitigation measures.

Keywords: Weathered gneiss · Debris flow · Physically based models · TRIGRS · SPH · Risk mitigation

1 Introduction

Landslide risk analysis and assessment is considered a useful tool for the identification of risk mitigation measures. In the last few years, scientific literature provided several studies on landslide risk assessment and mitigation and almost all of these studies started from the analysis of past landslides (Borrelli et al. 2018; Ciurleo et al. 2016; 2017; Mandaglio et al. 2015; Mandaglio et al. 2016a, b; Moraci et al. 2017). This is due to several factors including the severity of consequences that depends on landslide characteristics, therefore, the choice of the most appropriate risk mitigation measures is strictly linked to the landslide type and a skilled analysis of the past phenomena represents the starting point of landslide risk assessment and mitigation.

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In case of very rapid to extremely rapid phenomena characterised by triggering and propagation phases, such as rainfall induced debris flows, a correct analysis should assess the factors predisposing landslide triggering and delineate the main path and the depositional area.

Several studies specifically focus on modelling triggering phase (Cascini et al. 2017; Ciurleo et al. 2019; Schilirò et al. 2016) others refer to propagation phase (Borrelli et al. 2012; Gioffrè et al. 2016; Hungr 1995; Pastor et al. 2009) and only few papers deal with a combined numerical modelling of both (e.g., Ciurleo et al. 2018; Gomes et al. 2013).

Particularly, in the analysis of the triggering phase is necessary to identify the pore water pressure regime and mechanical parameters corresponding to landslide triggering; while, in the propagation analysis, the characteristics of soil-water mixture such as the rheological law and rheological parameters have to be defined. To do this, in situ investigations and laboratory tests should be carried out for the geotechnical characterization of different soils involved by these phenomena.

In order to use this analysis in the context of landslide susceptibility and hazard zoning, it should be carried out with models that can be easily implemented over large area. In this regard, the present paper provides a methodological approach for the analysis of debris flows based on the combined use of two physically based models: the Transient Rainfall Infiltration and Grid-based Slope-Stability (TRIGRS) model and the numerical code Smoothed Particle Hydrodynamics (SPH).

TRIGRS was used for the analysis of the triggering phase and allowed estimating the mobilized triggering volumes.

SPH, using TRIGRS results (triggering volumes), allowed the analysis of the propagation phase. The proposed methodology, already implemented in Ciurleo et al. (2018) to analyse a debris flow occurred in 2001 in the Scilla municipality (Calabria, Southern Italy), has been herein used to analyse triggering and propagation phases of a landslide occurred in 2005 in the same study area. The main goal pursued has been to identify the values of geotechnical parameters able to reproduce triggering and propagation phases of the analysed debris flow.

2 Methodology

The analysed debris flow occurred on 31 March 2005 in the Scilla municipality (Reggio Calabria, Italy). This phenomenon (Fig. 1) classified as very rapid to extremely rapid debris flow, initially began as translational landslide and rapidly evolved into flow-like phenomenon. Three main source areas (A_{01}, A_{02}, A_{03} in Fig. 1) affected the residual soils (gneiss of class VI) with slip surfaces located at a depth less than 2 m. During the motion, it involved significant entrainment of soil and at the end of the path it struck the village of Favazzina, the SR 18 state road, and the railway causing the derailment of the intercity train Reggio Calabria-Milan.

The analysis of the 2005 debris flow has been carried out by a three stages methodology; each one considers as input data the output of the previous one (Fig. 2). In particular, stage I, or data base creation, is aimed to identify rainfall and topographical data; mechanical and hydraulic properties of weathered gneiss, pore water pressure regime and rheological model of the soil-water mixture.

Fig. 1. 2005 debris flow

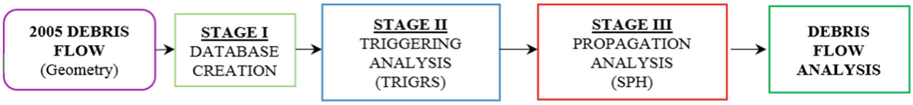

Fig. 2. Flow chart of the proposed methodology

Stage II, or triggering analysis, consists of identifying initial mobilized volumes by TRIGRS. TRIGRS is a distributed physically based model 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 geotechnical parameters in the range identified in stage I.

The initial mobilised volumes identified in stage II, combined with the rheological law, rheological parameters and Digital Elevation Model (DEM), have been used as input data of stage III or propagation analysis. In stage III, the numerical code SPH (Pastor et al. 2009), a fully mesh-free, Lagrangian particle numerical method, has been used for analysing the propagation path, the travel distance, the velocity of flowing mass and the shape of debris fan.

The computed source areas, the main path and the depositional area of the 2005 debris flow have been verified using three dimensionless indices (I_x) defined as follows:

$$I_{trig} = \frac{A_{UTL}}{A_{TL}} \times 100 \tag{1}$$

$$I_{prop} = \frac{A_{SR}}{A_{TR}} \times 100 \tag{2}$$

$$I_{dep} = \frac{A_{SDF}}{A_{TDF}} \times 100 \tag{3}$$

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_{TR} 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 Analysis and Results

3.1 Stage I

The 2005 debris flow presents three main triggering areas involving gneiss of class VI that, according to USCS, were classified as silty sand (SM) and inorganic silt of medium compressibility with sand (ML). The main physical properties of these soils are showed in Table 1.

Table 1. Physical properties of soils of Class VI

γ (kN/m^3)	γ_{sat} (kN/m^3)	γ_d (kN/m^3)	e	n	S (%)
15–20	19–22	12.5–16	0.65–1.15	0.4–0.55	43–99

Referring to mechanical properties, Antronico et al. (2006) identified, for gneiss of class VI outcropping on Favazzina slope, a cohesion value (c’) of 0 kPa and shear strength angle values (φ’) ranging from 38° to 44°. Schilirò et al. (2015) investigated soils similar for genesis and stress history to those of Favazzina and found values of c’ ranging from 0 kPa to 5 kPa and φ’ between 30° and 40°.

Regarding hydraulic properties, due to the lack of data, the values of saturated conductivity (K_{sat}) and saturated volumetric water content θ_s 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. Particularly, Cascini et al. (2006) and Schilirò et al. (2015) identified values of K_{sat} ranging from 1.27E−06 m/s to 6.60E−05 m/s and values of θ_s ranging from 0.38 to 0.4.

Referring to rheological data, the available information have been obtained by Gioffrè et al. (2016) and Moraci et al. (2017). Particularly, Gioffrè et al. (2016), by means of parametric analyses performed on debris flows occurred in the Favazzina slope, identified the Bingham rheological model as the law that better simulate the behaviour of the soil-water mixture. Once the model was selected, Moraci et al. (2017) performed viscometer laboratory tests to derive the Bingham model parameters (τ_0 and μ_b), as follows:

$$\tau_0 = 0.251 \cdot \exp(0.132 \cdot C_v) \tag{4}$$

$$\mu = 0.0112 \cdot \exp(0.163 \cdot C_v) \tag{5}$$

where C_v is the solid concentration by volume.

Regarding to the soil cover thickness, according to Ciurleo et al. (2019), the thickness of class VI involved by debris flow triggering areas was assumed equal to 1.5 m.

Referring to rainfall data, the Scilla rain gauge has been used; it recorded a peak value of 13.6 mm of rainfall on 31 March 2005.

3.2 Stage II

Stage I allowed to identify physical, hydraulic and mechanical properties of soils (Table 2) as well as rainfall data, digital elevation model (DEM) and soil cover thickness that are input data of Stage II implemented by TRIGRS. Regarding hydraulic properties, the average values of saturated permeability and saturated water content have been considered in the analysis. The saturated hydraulic diffusivity (D_0) was calculated according to Grelle et al. (2014) and Schilirò et al. (2015) using the formula below:

$$D_0 = \frac{K_s H}{S_y} \tag{6}$$

where K_s is the saturated hydraulic conductivity, H the average soil thickness (assumed constant and equal to 1.5 m) and S_y the specific yield that can be assumed equal to 0.34 for the analysed soils according to Johnson (1967), Loheide II et al. (2005) and Schilirò et al. (2015). Referring to pore water pressure regime, due to the lack of data, the water table was assumed at the contact between class VI and less weathered gneiss. So doing, stage II mainly consisted of an iterative analysis of mechanical soil properties in the range of variation identified in Stage I and summarised in Table 2.

Table 2. TRIGRS input data

γ (kN/m^3)	c' (kPa)	ϕ' (°)	K_s (m/s)	D_0 (m^2/s)	θ_{sat}
20	0–5	30–40	1.795e−05	7.92e−05	0.4

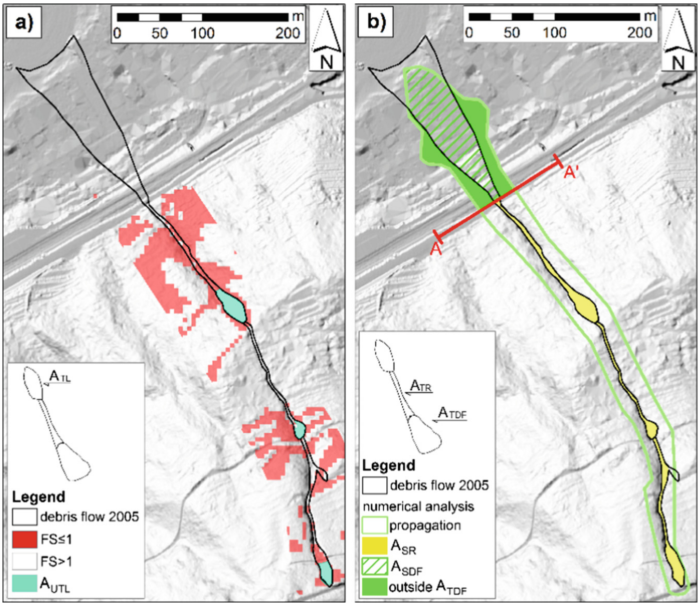

Fig. 3. Comparison between the 2005 debris flow and numerical results. (a) TRIGRS analysis, (b) SPH simulation.

Several analyses have been performed by TRIGRS and the best fitting between the source areas triggered in 2005 and the numerical analyses (I_{trig} = 95%) was achieved considering an average value of cohesion (c' = 2.5 kPa) and the minimum value of shear strength angle (φ' = 30°) (Fig. 3a).

The computed triggering volumes of the translational landslide source areas have been obtained by intersecting the real triggering areas by the areas computed as unstable (FS $\leq$ 1) by TRIGRS and considering a 1.5 m deep failure surface.

3.3 Stage III

Stage III, implemented by the SPH model, used as input data the triggering volumes computed in Stage II plus DEM, rheological parameters and erosion rate. According to Moraci et al. (2017), the bed erosion process was considered implementing the erosion law of Hungr (1995) using the “growth rate” E_s.

Table 3. SPH input data

C_v (%)	τ_0 (Pa)	μ_b (Pa s)	E_s (m^{-1})
50–60	184.51–690.69	38.79–197.98	0.001–0.002

Stage III consisted of an iterative analysis of rheological parameters (τ_0 and μ_b) and the "grow rate" Es.

Referring to τ_0 and μ_b, several analyses have been performed varying the values of C_v in the range reported in Table 3 that is well-suited with the classification proposed by Pierson and Costa (1987). E_s has been considered to vary in a range going 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 2005. Particularly, considering the area above the AA' section, the best simulation fits the real phenomenon with an I_{prop} = 100%, whereas considering the area below the AA' section the value of I_{dep} becomes equal to about 75%. These results have been obtained considering C_v = 52% and E_s = 0.0018 m^{-1} (Fig. 3b).

4 Conclusions

In the present study, a methodology for the analysis of a debris flow through a combined use of two physically based models has been presented.

The methodology, already successfully implemented for the analysis of the 2001 debris flow, herein shows a good performance with reference to the 2005 debris flow. Particularly, in the triggering analysis (Stage II) a high value of I_{trig} equal to 95% was obtained considering a cohesion value of 2.5 kPa and shear strength angle equal to 30°. In addition, TRIGRS provided three triggering volumes that were used as input data in the propagation analysis (Stage III). In this stage, the best result has been obtained considering C_v = 52% and E_s = 0.0018 m^{-1}. Particularly, for the propagation phase I_{prop} shows a value of 100% while, for the depositional area I_{dep} is equal to 75%. The last value could be due to the lack in the topographical model of natural and manmade obstacles that clearly influence the geometry of debris fan. Further analyses have been scheduled in order to investigate the improvement of the model performance when a better geotechnical characterization of gneiss of class VI will being available.

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