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The use of a physically based model for susceptibility assessment of debris flow source areas

L'utilisation d'un modèle à base physique pour l'évaluation de la susceptibilité des zones de source d'écoulement de débris

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ABSTRACT: Rainfall-induced debris flows are very rapid to extremely rapid phenomena, they occur periodically on established paths, usually gullies and first-or second order drainage channels. They may be triggered by a slide and during the propagation phase increase in volume due to soil erosion along the downhill path. These phenomena can cause loss of human life and huge socio-economic disasters. Owing to their characteristics and consequences, in the last years, debris flow susceptibility assessment became a main topic to be investigated for an appropriate spatial planning and management of the territory and, above all, for a proper design of risk mitigation works. The paper is aimed to preliminarily simulate and forecast debris flow triggering areas in weathered gneiss by means of a physically based approach. The approach consists of two successive phases: Phase I, data base creation in order to identify the input parameters to be used in the second phase; Phase II, to forecasting debris flow triggering areas by TRIGRS.
The proposed approach has been tested and validate, at large scale (1:5000), in an area of southern Italy frequently affected by this kind of landslides. The obtained results, compared with the landslide triggering zones that affected the study area from 2001 to 2016, show an Area Under the receiver operator characteristic Curve (AUC) of 0.84 that can be considered satisfactory both in terms of location of triggering sources and forecasting of potentially unstable areas.

RÉSUMÉ: Les écoulements de débris induits par les précipitations sont très rapides à des phénomènes extrêmement rapides, ils se produisent périodiquement sur des chemins établis, habituellement des ravins et des canaux de drainage de premier ou de deuxième ordre. Ils peuvent être déclenchés par une lame et, pendant la phase de propagation, augmenter en volume en raison de l'érosion du sol le long de la descente. Ces phénomènes peuvent causer la perte de la vie humaine et d'énormes catastrophes socio-économiques. En raison de leurs caractéristiques et de leurs conséquences, au cours des dernières années, l'évaluation de la susceptibilité aux écoulements de débris est devenue un sujet à étudier pour une planification et une gestion spatiales appropriées du territoire et, surtout, pour une conception appropriée de l'atténuation des risques Mesures. Le document vise à simuler et à prévoir de façon préliminaire les zones d'écoulement des débris dans les gneiss altérés au moyen d'une approche à base physique. L'approche consiste en deux étapes successives: l'étape I consiste en la création de bases de

données afin d'identifier les paramètres d'entrée à utiliser dans la deuxième étape; l'étape II vise à prévoir les zones de source d'écoulement de débris par les trigrs.
L'approche proposée a été testée et validée, à grande échelle (1:5000), dans une région du sud de l'Italie fréquemment affectée par ce type de glissements de terrain. Les résultats obtenus, comparés aux zones de déclenchement des glissements de terrain qui ont affecté la zone d'étude de 2001 à 2016, présentent une zone sous la courbe caractéristique de l'opérateur récepteur (AUC) de 0,84 qui peut être considérée comme satisfaisante tant en termes d'emplacement de déclenchement des sources et prévision des zones potentiellement instables.

Keywords: debris flows; triggering; susceptibility assessment; TRIGRS

1 INTRODUCTION

Debris flows periodically occur on established paths, usually gullies and first or second order drainage channels. The flows may be often initiated by a slide. The bulk of the material involved in a debris flow event usually originates from entrainment from the path, while the volume of the initiating slide is much smaller than the final volume (Hungr et al., 2014). The debris flows are considered one of the most insidious landslides due to the high velocity reached during the downhill path and the high potential to cause damage and loss of human life. In this perspective, susceptibility assessment of debris flows is a relevant issue not only for territorial planning and management but above all to design debris flow risk mitigation works.

Landslide susceptibility assessment, intended here as “a quantitative or qualitative assessment of the classification, volume (or area), and spatial distribution of landslides which exist or potentially may occur in an area”, can be pursued by means of basic, intermediate or advanced methods (Fell et al., 2008), depending on scales of analysis and zoning purposes. The choice of the most appropriate zoning method depends on several factors, as follows: the landslide characteristics, the knowledge and experience of who leads the analysis, the quality and accuracy of the available data (topographic, geophysical, geotechnical, hydrogeological, geo-structural, geomorphological, pluviometric) that influence the validity of results. An advanced level of zoning can be pursued by using physically based models that are able to reproduce physical processes governing triggering and propagation stages (Mandaglio et al. 2015, 2016a; Moraci et al., 2017; Cascini et al., 2015; 2017; Ciurleo et al., 2017; 2018). Distributed physically based models generally combine an infiltration model, for the analysis of pore water pressures, with a slope stability model for the calculation of the safety factor. Clearly, in order to achieve significant results, the application of these models requires on the one hand a skilled use of the model and, on the other hand, a correct identification, over large area, of geotechnical properties of soils, pore water pressure regime and triggering mechanisms.
In this context, the present work aims to provide a contribution to the susceptibility assessment of debris flow source areas in weathered gneiss. To pursue this goal, a methodological approach has been proposed, and its validity has been tested in a study area located in the province of Reggio Calabria (Calabria region, southern Italy). The methodological approach consists of two phases: Phase I, data base creation of geotechnical properties of soils; Phase II, debris flow source area susceptibility assessment by a physically based model (TRIGRS).

2 METHODOLOGY

The proposed methodology consists of two consecutive phases.

Phase I involves collecting and combining all the available information for debris flows in weathered gneiss of class VI (see Section 3). To pursue this aim, all the data available from scientific literature, in coherence with the analysed soils, have been taken into account in order to identify and sum up the range of variation of the main geotechnical properties of class VI weathered gneiss.

Phase II, consisting of several parametric analyses, is aimed to produce shallow landslide susceptibility maps by the physically based model TRIGRS. The parametric analyses have been performed by varying the geotechnical input data, on the basis of the information gathered from Phase I. TRIGRS is a physically based model largely used for determining shallow landslide source areas in different geo-environmental contexts (Godt et al., 2008; Schilirò et al., 2015). TRIGRS couples an infiltration model with a slope stability model. The infiltration model is based on the linearized solution of Richards equation proposed by Iverson (2000) and extended by Baum et al. (2002) to the case of impermeable bedrock located at a given depth from the ground surface. The limit equilibrium condition has been analysed by an infinite slope stability analysis (Taylor, 1948). TRIGRS allows to calculate the safety factor for each cell of grid and, combined with a GIS (Geographic Information System), allows us to visualize unstable (FS $\leq$1) and stable cells (FS >1).

TRIGRS is able to back-analyse shallow landslides over large area but, to correctly work, it needs of several data, as follows: digital elevation model (DEM); rainfall data before the landslide event; geomorphological data; soil cover thickness; hydraulic and mechanical characteristics of soils involved by landslides; the initial location of water table.

Different combination of geotechnical input data produced different susceptibility maps, the best one has been chosen on the base of its ability to better back-analyse the landslide inventory. Finally, the reliability of the best map has been evaluated by the Area Under the receiver operator characteristic Curve (AUC) (Metz 1978; Swets 1988).

3 STUDY AREA

The study area, about 1 km^2, is located in the S-W coast of the Calabria region, between Bagnara Calabra and Scilla, in the Favazzina hamlet. It is bordered by a flat surface of marine origin (Piano delle Aquile) at 630 m a.s.l., and by the Favazzina village (Fig. 1).

The slope is crossed by several infrastructures as the highway A3, the railway and the southern Tyrrhenian state road SS 18 (Fig. 1).

In the study area, a Paleozoic crystalline basement (para and ortho-gneiss) is overlapped by Upper Pliocene to Holocene sedimentary deposits (Borrelli et al. 2012; Gioffrè et al. 2016). The intense and deeply weathered conditions affecting the crystalline basement have produced the formation of weathered gneiss that, according to GCO (1988), can be classified in five classes (from class VI to class II). Particularly, residual, colluvial and detrital soils (Class VI) are widespread on the slope, actually cover about 60% of the study area (Fig. 1) and represent the main predisposing factor to shallow landslide susceptibility (e.g., Borrelli et al. 2018). Moreover, due to their heterogeneity and the difficulty of undisturbed sampling, the geotechnical characterization of these soils is highly complex (Mandaglio et al. 2016b).

Completely weathered rocks (Class V) prevail in the upper portions of the slope while highly and moderately weathered rocks (respectively classes IV and III) prevail in the middle-lower portions.

In the last decade, the study area has been frequently affected by shallow landslides of flow type and, among these, the phenomena dated 2001 and 2005, severely affected the urbanized area and transportation infrastructures located along the coastal plain (Fig. 1). Particularly, debris flows occurred on the 12th May 2001 involved the SNAM methane pipeline, and the one occurred on the 31th March 2005 hit the Favazzina village (Fig. 1). These landslides initiated by translational slides, involved class VI and rapidly evolved as surging flows. The width of the source areas ranged from 15 m to 40 m and the main path was longer than 1 km.

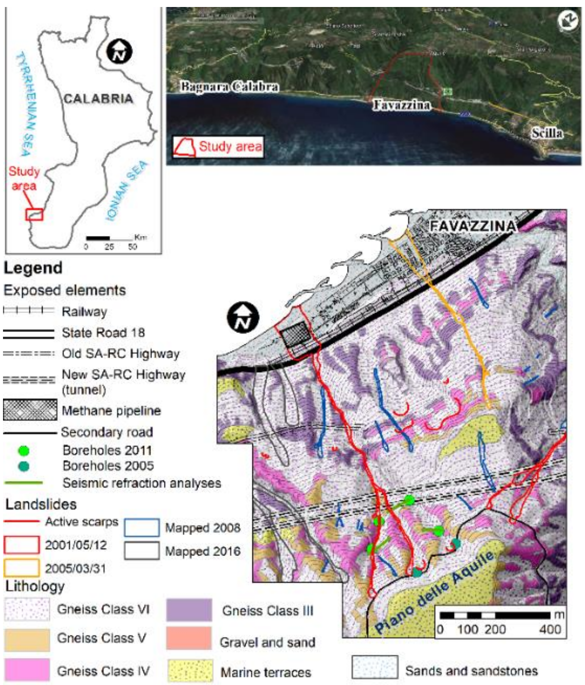

Figure 1. Geographical localization of the study area and weathering grade map of the Favazzina slope

As far as rainfall data is concerned, the Scilla rain gauge of the Centro Funzionale Multirischi—ARPACAL (Calabria Region, cod. 2510) was used to identify the rain fallen ten days before the 2001 and 2005 events (Fig. 2).

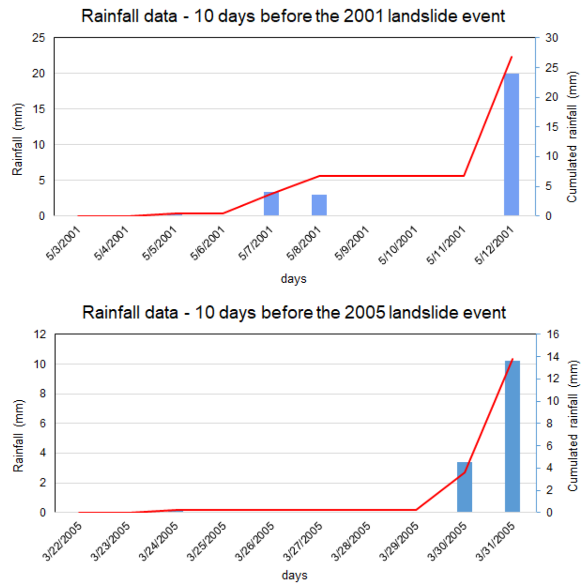

Figure 2. Rainfall data.

4 PHASE I

The geotechnical database has been created by collecting and combining all the available information for debris flows in weathered gneiss of class VI, as follows.

Geotechnical properties of gneiss of class VI have been deduced by literature data (Gioffrè et al., 2016; Antronico et al., 2006). In-situ investigations (continuous drilling boreholes and seismic refraction analyses) (Fig. 1) show that class VI ranges in thickness from 1.5 m to 3 m.

Referring to grain size distribution, the analysed soil can be classified as silty sand (SM) – according to Unified Soil Classification System (USCS) – with a percentage of sand = 50.6%, gravel = 27.3%, silt = 19%, and clay = 3.1%.

The plastic index and liquid limit of the sampled soil are 9% and 33%, respectively.

Referring to physical properties of weathered gneiss of class VI, the saturated unit weight (γ_{sat}) varies from 19 kN/m^3 to 22 kN/m^3; the void ratio (e) is ranging from 0.6 to 1.1; the soil porosity (n) values vary from 0.4 to 0.54 and the saturation degree (S) from 43% to 99% (Antronico et al. 2006).

Regarding the shear strength properties, the results of direct and triaxial shear tests carried out on these cohesionless soils by Antronico et al. (2006) have shown that the shear strength envelope ranges from an upper to a lower limit respectively associated with a shear strength angle (φ') equalling 44° or 38°.

Soils, similar for genesis and stress history to those of Favazzina, have been also analysed by Schilirò et al. (2015) who retrieved a cohesion (c') value ranging from 0 kPa to 5 kPa and a shear strength angle from 30° to 40°.

Referring to hydraulic properties, due to the lack of data for the study area, we refer to the information provided by Calvello et al. (2008), Cascini et al. (2006) and Schilirò et al. (2015) who investigated contexts involved by weathered gneiss similar for genesis and stress history to those analysed. Particularly, Calvello et al. (2008) and Cascini et al. (2006) associated class VI of the Unit of Sila (Calabria) with values of saturated conductivity (K_{sat}) ranging from 1.27E-06 m/s to 3.50E-05 m/s; whereas, according to Schilirò et al. (2015), the values of saturated conductivity that pertain to gneiss of the Unit of Aspromonte (Sicily) are ranging from 7.91E-06 m/s to 6.60E-05 m/s.

Moreover Schilirò et al. (2015) found values of saturated volumetric water content θs ranging from 0.38 to 0.39.

5 PHASE II

Phase II has been involved carrying out parametric analyses by means of TRIGRS.

These analyses have been performed assuming totally saturated conditions and using different combinations of shear strength data. Particularly, all cases have been implemented considering the average values of saturated hydraulic conductivity and volumetric water content (K_s = 1.79E−05 m/s and θ_{sat} = 0.39). Regarding the saturated hydraulic diffusivity (D_0), according to Grelle et al. (2014) and Schilirò et al. (2015), it has been used the following formula:

$$D_0 = \frac{K_{sat} H}{S_y} \tag{1}$$

where K_{sat} is the saturated hydraulic conductivity (K_{sat} = 1.79E-05 m/s), H the average soil thickness (assumed constant and equal to 1.5 m for the whole study area) 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 shear strength properties, the analyses have been carried out considering: i) the average value of shear strength angle (φ'=38°) and varying the cohesion value between 0 kPa (minimum value) and 2.5 kPa (average value); ii) the average value of cohesion (2.5 kPa) and varying the shear strength angle from 30° (minimum value) to 38° (average value).

To sum up, Phase II mainly consisted of an iterative analysis of mechanical soil properties in the range of variation identified in Phase I and just summarised.

As for spatial data, we considered the DEM, cover thickness and initial water table location.

The spatial data are expressed in raster format using 5×5 m^2 square grid cells; slope gradient and flow direction were derived by the DEM. The cover thickness was posed equal to 1.5 m for the whole study area, in agreement with data gathered from in-situ investigations (i.e. continuous drilling boreholes and seismic refraction tests). Referring to pore water pressure regime, due to the lack of in-situ measurements, the water table was located at the contact between class VI and less weathered gneiss for the whole study area, except for the upper part of the slope near the road; here, the water table was considered at the ground surface in order to take into account the influence of the road on the rainfall infiltration processes (Ciurleo et al., 2019).

As for as rainfall data is concerned, we used the data regarding the 2001 rainfall event since it is more critical than that occurred in 2005 (Fig. 2).

Furthermore, considering that debris flows periodically occur on gullies and first or second order channels, only morphological hollows characterized by negative slope curvature were selected.

The obtained results highlighted that the best analysis (in terms of unstable computed cells and real source areas) corresponds to the following geotechnical parameters: γ_{sat} = 20 kN/m^3, c' = 2.5 kPa, φ' = 30°, K_{sat} = 1.79E-05 m/s, D_0 = 7.92E-05 m^2/s and θs = 0.39.

The best obtained map (Fig. 3a) shows that most part of the areas affected by instabilities from 2001 to 2016 has been correctly back-analysed by the model (unstable computed cells, FS ≤ 1). Furthermore, some areas not involved by landslides yet have been computed as unstable by the model.

Finally, the resulting map has been evaluated by means of the area under the receiver operating characteristic (ROC) curve plotted in the sensitivity versus (1 −specificity) space (Metz, 1978).

The best obtained map (Fig. 3a), compared with the inventory map of landslides occurred from 2001 to 2016, shows an area under the ROC curve (Fig. 3b) equal to 0.84.

To this regard, it should be noted that, according to Fressard et al. (2014), values of AUC under 0.7 can be considered to be poor, values between 0.7 and 0.8 reflect a fair performance of the model while values between 0.8 and 0.9 reflect a good performance of the model.

However, the result obtained in terms of AUC (0.84) can be considered to reflect a good performance of the model.

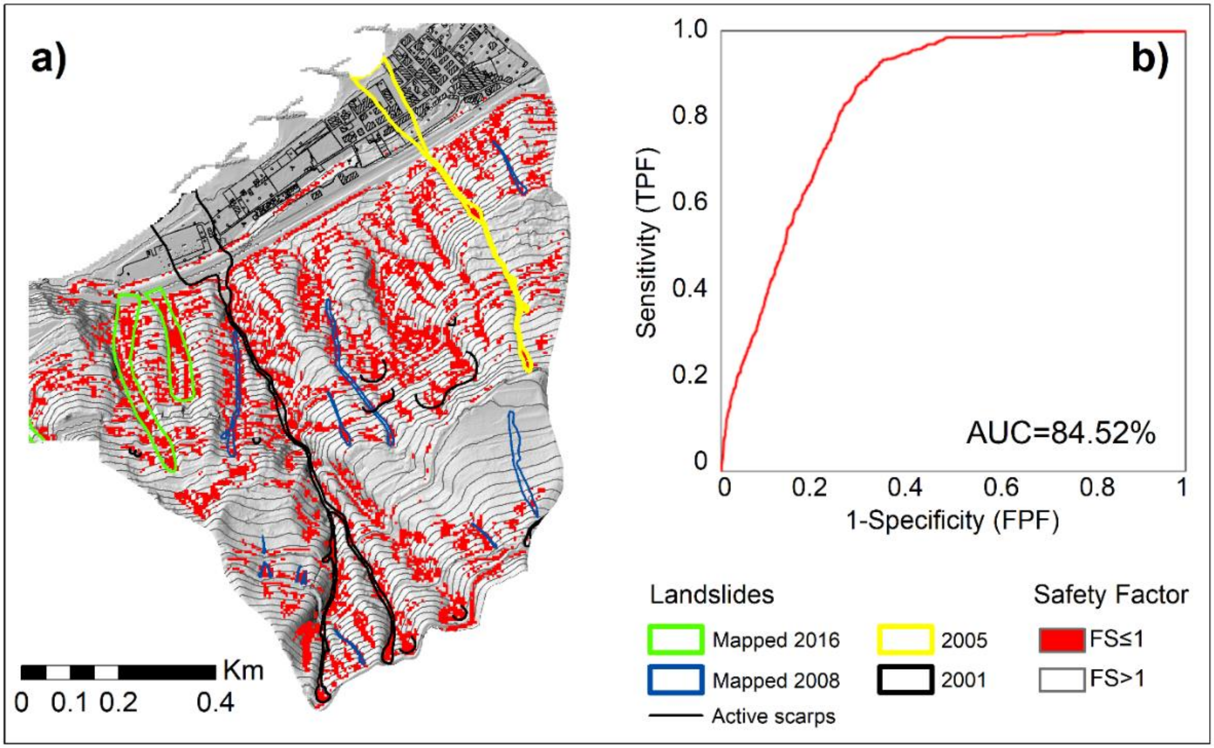

Figure 3. TRIGRS result. a) The best obtained map; b) ROC curve

6 CONCLUSIONS

The proposed approach for the susceptibility analysis at source areas of debris flows that might occur in the study area leaded to satisfactory results, providing a good comparison between the TRIGRS-computed unstable cells and the areas affected by the landslide events occurred from 2001 to 2016.

The obtained results can be refined by way of TRIGRS analyses to be carried out in unsaturated conditions. In this regard, further insights, based on specific geotechnical surveys, are planned for the reconstruction of cover thicknesses, a better characterization of mechanical and hydraulic properties of weathered gneiss, and the reconstruction of pore water pressure regime.

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