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Modelling of a debris flow event in the Enna area for hazard assessment

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Abstract

In the paper a modelling of a real debris flow in the Enna area in the south of Italy is described. Starting from the study of the geological framework and the historical background for landslides of the Enna district, the research has focused on the causes triggering the landslides. In order to study the performance of debris flow, the real case of 1st-2nd February 2014 which affected Enna city has been modeled. The event caused damage to private buildings and above all the interruption of the main infrastructure connecting Enna city at the motorway, due to the material on the road. The modelling of the real debris flow using a mono-phase model (FLO-2D) was carried out in order to investigate the global dynamic of the event. The study allows to acquire a better knowledge of the hydraulic parameters that can be used in other modelling events for areas with a similar soil composition in order to assess the most appropriate mitigation works, reducing damage to structures and infrastructures.

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Keywords: landslide; early warning system; debris flow.

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1. Introduction

Debris flow occurrences are among natural phenomena which produce damage and fatalities. Therefore, in the last decades many efforts have been put in place to develop models able to simulate numerically the debris flow propagation, aiming at producing reliable landslides maps. The information about the three components of risk, that are, hazard, elements at risk and vulnerability as well as geological and geotechnical data, are necessary to define

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landslide maps. It is possible to find several propagation models applicable to hyper-concentrated flows, which mainly differ for the adopted rheological schemes. In particular, they can be separated into single-phase models and two-phase models. Single-phase models assume that a debris flow acts as a homogeneous Bingham fluid composed of a mixture of water and sediment. From a rheological point of view, such a mixture can be described by Herschel-Bulkley [1] or even more complex models as, for example, that described by a quadratic law which assumes that the total friction stresses can be divided into different terms: yield stresses, viscosity stresses and turbulent-dispersive stresses; all of them being functions of the sediment concentration in the mixture. In any case, the hypothesis of the Binghamian nature of the fluid is necessary in order to simulate the arrest of the flow. In the two-phase models, the exchange of mass between the erodible bed and the flow is taken into account as well. The fundamentals of such models were first developed by [2] and then applied to the debris flows by [3]. In such models the solid concentration is an unknown variable which influences the global behavior of the flow that can be properly accounted for by the model itself.

In particular, it has been noticed that the first type of model is more suitable for cases characterized by fine sediments, when the viscous shear rate is high. The second type of model is more suitable in cases in which the viscosity of the interstitial fluid is negligible and the solid fraction is composed of coarser material, so that the inertial shear rate acts predominately due to the collisions between gravels. Furthermore, as was stressed by [4] the debris flow during the propagation does not behave with a fixed rheology, since it changes its rheological characteristics in space and time. In order to understand the real behavior of the propagation of a debris flow on a large scale, a real debris flow event was analyzed by the FLO-2D [5] which assumes a single-phase model.

The FLO-2D model is a code for analyzing debris flow dynamics widely adopted by researchers and practitioners. Indeed, several applications of such a model can be found in literature, which mainly differ in relation to the sediment characteristics, and hence, in relation to the adopted rheological parameters [6-9]. Various comparisons with other methodologies [10-11] demonstrated that FLO-2D, if appropriately calibrated, represents a useful tool for predicting the behavior of future landslides of the same type and in similar settings. In order to study the performance of debris flow, the propagation stage of the real case of 1st-2nd February 2014 which affected Enna municipality (Italy) has been modeled trough FLO-2D.

2. FLO-2D

FLO-2D is a commercial code developed by [12] and adopted worldwide for debris flow phenomena modelling and delineating flood hazards. It is a pseudo 2-D model in space which adopts depth-integrated flow equations. Hyper-concentrated sediment flows are simulated considering the flow as a homogeneous (monophasic) non-linear Bing- ham fluid, based on an empirical quadratic rheological relation developed by [13]. The basic equations implemented in the model consist mainly of the continuity equation and the equation of motion:

$$\frac{\partial h}{\partial t}+\frac{\partial (hV)}{\partial x}=i \tag{1}$$

$$S_f=S_o-\frac{\partial h}{\partial x}-\frac{V}{g}\frac{\partial V}{\partial x}-\frac{1}{g}\frac{\partial V}{\partial t}=i \tag{2}$$

where *h* is flow depth, *V* is depth-averaged velocity, *i* is excess rainfall intensity (assumed equal to zero in the present application), *x* is the generic direction of motion, S_f is the total friction slope, S_o is the bed slope, and *g* is gravitational acceleration.

The surface topography is discretized into uniform square grid elements. In order to solve the momentum equation [5], FLO-2D considers, for each cell, eight potential flow directions. Each velocity computation is essentially one-dimensional and solved independently from the other seven directions, so *h* and *V* are related to one of the eight flow directions *x*. The total friction slope S_f can be expressed as follows:

$$S_f=\frac{\tau_B}{\rho g h}+\frac{K\mu_B V}{8\rho g h^2}+\frac{n^2V^2}{h^{\frac{4}{3}}} \tag{3}$$

where τ_B is Bingham yield stress, ρ is mixture density, K is the laminar flow resistance coefficient, μ_B is Bingham viscosity, and n is the pseudo-Manning resistance coefficient which accounts for both turbulent boundary friction and internal collisional stresses. In particular, the yield stress τ_B, the dynamic viscosity μ_B and the resistance coefficient n are influenced by the sediment concentration relationships and can be described by the following equations (4):

$$\tau_B=\alpha_1 e^{\beta_1 C_v} \tag{4}$$

$$\mu_B=\alpha_2 e^{\beta_2 C_v} \tag{5}$$

$$n=0.538\ n_t e^{6.0896 C_v} \tag{6}$$

where C_v is the volumetric concentration and α_1, β_1, α_2, β_2 are empirical coefficients defined by laboratory tests performed by [14] and n_t is the turbulent n value.

3. Case study of Enna in south Italy

During the night between the 1st and the 2nd of February 2014 a heavy rainfall struck the Province of Enna causing several damage to public and private structures. This area, located in the middle of the Sicily, is characterized by a morphology with high hill slope angles (within a range of 30 - 60◦) and with catchment areas of small or moderate extensions (about 0.3 km^2). The area is made up geologically of Numidian Flysch of Holigocene-lower age, marly and sandy brown clay of medium Miocene age and river alluvium of Holocene age. The lithostratigraphic units are the following: trubi, marls, calcarenites, grey - dark brown brecciated clays and grey - blue clays.

The climate is characterized by an average daily temperature of about 14°C with fluctuations between the day and the night of about 15 °C. Usually short and intense rainstorms occur between October and March. The event occurred in an area characterized by catchments having small extension of 0.158 km^2, generating a debris flow. The area has a high-density urban with narrow streets, that become, during the event, the bed over which the runoff flows. The overall effect of the rainfall event is deducible by a comparison between photos gathered respectively before and after the debris flow (Fig. 1).

Fig. 1. (a) the area prior of the debris flow; (b) the area after the debris flow.

4. Geotechnical characterization

The characterization of the foundation soil plays an important rule in the geotechnical design [15-21]. In the test site has been performed several surveys in the periods from August to September 2006 (no.1 borehole at the depth of 20 m, no.2 Multichannel Analysis of Surface Waves MASW surveys, no.4 Standard Penetration Tests SPT and laboratory tests) from March to April 2009 (no.2 boreholes at the depth of 35 m, no.4 MASW surveys, no.4 SPTs, no.1 Down-Hole DH test and laboratory tests), from December 2009 to January 2010 (no.9 boreholes, no.4 MASW surveys, no.8 SPTs, no.1 Down-Hole DH test and laboratory tests) and from July to August 2010 (no.4 boreholes, no.3 MASW surveys, no.7 SPTs and laboratory tests).

The geotechnical parameters, that are strength properties of the soil were obtained from the geotechnical laboratory tests such as unconfined compression test, standard unconsolidated undrained triaxial tests, direct shear tests on undisturbed samples retrieved by geotechnical survey. Table 1 reports some of the physical parameters in terms of soil unit weight γ, water content w_n, consistence index I_C, and the strength parameters in terms of friction angle φ', cohesion c', and undrained cohesion c_u, obtained from laboratory tests performed for the 2006 field investigation.

Table 1. Geotechnical parameters.

Sample	γ (kN/m^3)	w_n (%)	w_l (%)	I_C	c' (kN/m^2)	φ' (°)	c_u (kN/m^2)
S1C1	20.1	21.0	-	-	-	-	-
S1C2	20.9	20.4	37	1.50	39.44	25	-
S1C3	19.5	20.0	35	1.23	-	-	223.0
S1C5	20.2	26.0	39	0.67	25.36	24	255.0

5. Numerical modelling and results

In order to model the debris flows occurred in Enna [22-24], three principal data sets are needed: a digital terrain model (DTM), hydrological data, and rheological properties of the sediment - water mixture. For the construction of the DTM a grid system with cell size 2.0 m x 2.0 m was implemented by FLO-2D model. The hydrological input (Fig.2) is applied at the upstream section of the basin where the triggering was observed. The discharge rate value of the debris flows for the basin has been calculated by [25]:

$$Q_{df}=Q_l\,\frac{c_b}{c_{b}-c} \qquad (7)$$

where Q_{df} is the discharge of debris flow, Q_l is the liquid discharge rate (given by the hydrograph), c and c_b are the concentration of the solid phase in the debris flow and into the soil, respectively. The debris flow concentration is calculated, according to the following expressions, where α if the slope angle in the upstream section of the model:

$$c=\frac{1}{\Delta}\frac{\tan\alpha}{\tan\varphi-\tan\alpha} \qquad \text{for } \alpha \leq 21° \qquad (8)$$

$$c=0.9\,c_b \qquad \text{for } \alpha \geq 21° \qquad (9)$$

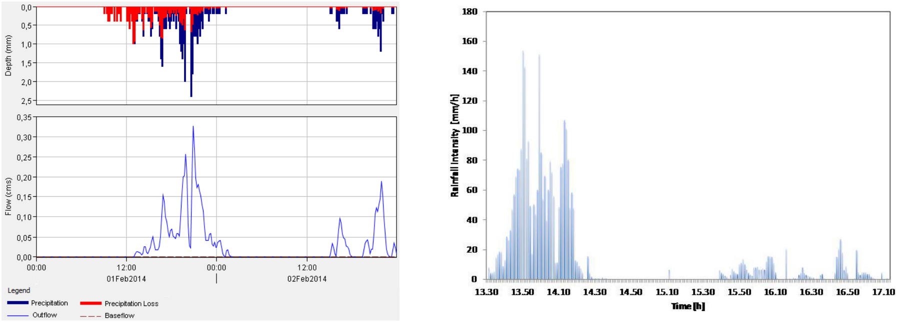

Fig. 2. (left) hydrological input adopted in FLO-2D simulations; (right) rainfall intensity recorded by Enna meteorological station.

In the simulations with the FLO-2D model, the values of the parameters $\alpha_1 = 0.006032$, $\beta_1 = 19.9$, $\alpha_2 = 0.000707$ and $\beta_2 = 29.8$ have been chosen from those available in literature [8] with the aim of selecting those that have similar geomorphological and lithological characteristics with the studied area. A reconstruction of the area was obtained as output of the simulations performed by the FLO-2D (Fig. 3).

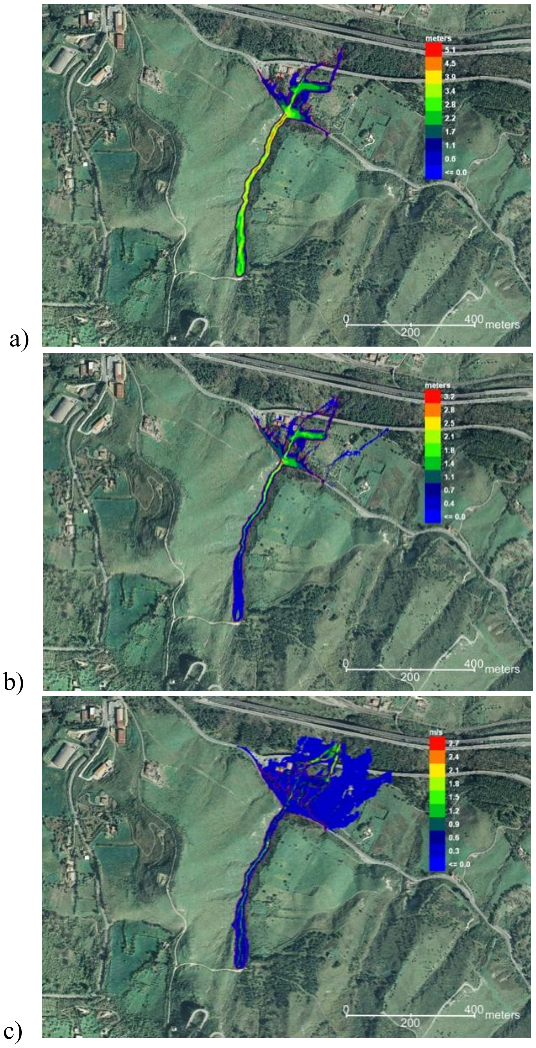

Fig. 3. Scenarios simulated with the FLO-2D (rheological parameters $\alpha_1 = 0.006032$, $\beta_1 = 19.9$, $\alpha_2 = 0.000707$, $\beta_2 = 29.8$): (a) maximum flow depth; (b) final flow depth (c) maximum velocity.

The debris flow discharge to assign in the simulation with FLO-2D was determined by applying equation (7) in the upper part of the basin, where the triggering of the phenomenon was observed. The debris flow concentration has been calculated for $\alpha \leq 21°$ and it is equal to 0.57.

The maximum flow depths during the event obtained from the FLO-2D simulation are presented in Fig. 3a. The highest predicted flow depth is about 4 m. Figure 3b represents the final flow depths. The highest value of the predicted final flow depth is about 1.4 m. Finally, the predicted maximum velocities are shown in Fig. 3c. It is easy to recognize that the maximum velocities are registered in correspondence of the upper part of the basins, where the slope is the highest, with values ranging from 1 to 2 m/s. The FLO-2D predicted values are, in general, in good agreement with those observed. This is supported by the comparison between the calculated volume from the hydrograph through FLO-2D and the volume of deposited material resulting from the surveys taken after the event by the Civil Protection.

6. Concluding remarks

The simulation of the event of 1st - 2nd February 2014 in Enna (south Italy) was reproduced by means of the FLO-2D, based on a mono-phase approach through an empirical quadratic rheological relation. The results of numerical modelling are reported in terms of maximum flow depth, final flow depth and maximum velocity and show a good agreement with the real event. At the aim an accurate representation of the topography in the grid system is an essential step to obtain a reasonable replication of the observed deposition patterns.

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