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Debris flow hazard assessment: laboratory experiences and numerical modelling

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Abstract. In the last years, the study of debris flow has become very important in the research activity and in the engineering practice. The use of numerical models is able for the study of debris flow's propagation. The study area is located in the north-east Sicilian coast and in particular in the municipality of Gioiosa Marea, severely affected by landslides occurred from 2000 to 2013. In this case study, the FLO-2D code has been used. The soil parameters has been determined by means of in situ investigations and laboratory tests. The knowledge of the physical and mechanical properties is very important to define the input parameters of the model, including the volumetric concentration associated with the soil friction angle.

1 Introduction

Debris flows are a moving mass of loose soil particles ranging from clays to rocks with high water content, driven by gravity [1]. The speed and volume of debris flows make them very dangerous.

The use of numerical models capable of simulating the propagation of a debris flow are a suitable support tool for the drafting of hazard maps [2-5]. Overall, a debris flow event can be modelled [6] through three data sets: digital terrain model, hydrological data and rheological properties of the water and sediment mixture.

To define the input parameters of the model that define the rheology of the soil, a physical and mechanical characterization is required, in order to determine the volumetric concentration associated with the friction angle of the soil.

Often due to extreme meteoric events, the process of meteoric infiltration results in an increase in the degree of saturation that involves the increase of the weight unit volume and therefore of the unstable actions and the reduction of the soil strength which can cause the collapse.

Although the soil has good strength characteristics on high slopes, the soil stability is linked to the beneficial effect that partial saturation conditions give on the soil shear strength. Due to intense extreme meteoric events, increments of degree of saturation and the consequent suction's decrease lead to reductions in shear strength that are incompatible with the stability condition.

To analyze this aspect and evaluate the soil failure parameters, some controlled suction triaxial tests were performed. At the aim to obtain the friction angle of unsatured soil to link with numerical modelling of debris flows through the volumetric concentration, the results of suction controlled triaxial tests were interpreted.

2 The case study of Capo Calavà

The study of interaction between debris flows and linear infrastructures is part of the research project TEMI MIRATI - Technologies and Innovative Models for Risk Mitigation in Critical Infrastructures - funded by MUR (Italian Ministry of University and Research) at the University Kore of Enna with reference to the Sicily.

From 2003 to 2013, several districts of Gioiosa Marea in the north-east Sicilian coast, such as Capo Calavà, Contrada Ridente and Scoglio Nero, were affected by several landslides that involved large volumes of soil, by including the highway SS113, known as "Settentrionale Sicula" (Figure 1).

2.1 Soil geotechnical characterization

A detailed geotechnical investigation including in situ and laboratory tests for the evaluation of the physical and mechanical properties of the soil involved in the debris flows has been performed in the study area. In particular, n.3 boreholes have been carried out of which S1 and S2 at a depth of up to 10 m and S3 at a depth of up to 15 m (Figure 2).

To determine physical and mechanical parameters, standard laboratory tests have been performed on some samples retrieved by the boreholes. The results of standard classification tests are reported in Table 1 in terms of unit weight γ, grains specific density γ_s, natural water content w_n and liquid limit w_l for each tested sample.

The mechanical properties in terms of friction angle have been evaluated for the sample S2C2 by means of direct shear test. The shear strength parameters [7] for the tested sample are $\varphi' = 26°$ and $c' = 0$ kPa.

Fig. 1. Debris flow in SS 113 km 84+800 in the municipality of Gioiosa Marea (ME) in December 2011.

Fig. 2. Location of boreholes within the study area.

Table 1. Physical parameters of the soil

Sample	Depth [m]	γ [kN/m³]	γ_s [kN/m³]	w_n (%)	w_l (%)
S1C1	2.70 - 3.00	18.76	24.49	5.30	-
S1C2	5.20 - 5.60	-	26.18	6.62	-
S2C1	4.00 - 4.40	-	25.50	5.53	-
S2C2	8.00 - 8.40	17.99	27.18	8.11	16.42
S3C1	1.70 - 2.00	-	24.82	9.23	-

2.2 Controlled suction triaxial tests

Controlled suction triaxial tests were carried out applying the axis translation technique on unsaturated reconstituted specimens with 50 mm in diameter and 100 mm in height by means of the triaxial testing machine for unsaturated soils available at the *Soil Dynamics and Geotechnical Engineering Laboratory* of the University of Enna (Figure 3).

The value of matrix suction $s = u_a - u_w$ was between 100 and 200 kPa, being u_a air and u_w pore-water pressures. The specimens were prepared with a water content above the liquid limit and consolidated under the pre-consolidation pressure. Air and water pressure were applied to the initially saturated specimens, depending on the aimed suction. Then, the specimens reached to failure, keeping the matrix suction constant.

Fig. 3. Triaxial testing machine for unsatured soil.

The compression phases were carried out for three different suction matrix values (100 kPa, 150 kPa and 200 kPa) for the mean stress value ($p-u_a$) equal to 120 kPa, 240 kPa and 360 kPa.

Constant water (CW) content conditions tests were performed at strain rates of 0.1 mm/min. As an example, in Figure 4 the stress-strain curves for 3 specimens with mean stress value equal to 360 kPa are compared (Figure 4). As the suction (u_a-u_w) increases, both the values of the deviator and the peak axial deformation increase and the specimens show a tendency towards a more fragile failure, with deviatoric stress values that degrade more quickly in the post-peak phase.

Applying the extend Mohr-Coulomb failure envelope for unsaturated soils proposed by [8], it was possible to calculate the shear stress at failure τ_f for suction s values equal to 100 kPa, 150 kPa and 200 kPa:

$$\tau_f = c' + (\sigma - u_a)tan\varphi' + (u_a - u_w)tan\varphi_b \tag{1}$$

where c' and φ' are the effective cohesion and the effective friction angle obtained from saturated test, (σ-u_a) is stress at failure, (u_a- u_w) is suction matrix at failure and φ^b is angle describing increase in shear strength with matric suction. Equation (1) can be written as:

$$\tau_f = c + (\sigma - u_a)tan\varphi' \tag{2}$$

$$c = c' + (u_a - u_w)tan\varphi_b \tag{3}$$

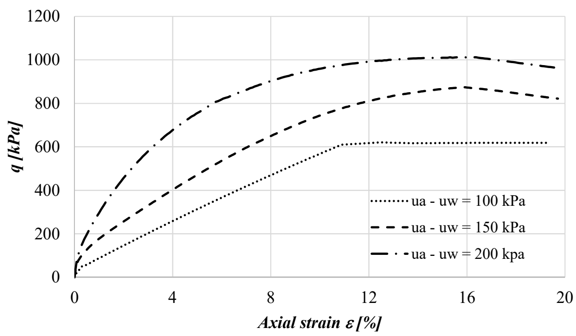

Fig. 4. Stress-strain curves obtained by CW test.

The effective shear strength parameters for saturated soils c' = 0 kPa and φ' = 26° were obtained by direct shear test. The extended Mohr-Coulomb failure envelope for CW tests was plotted using Equation 2.

Peak deviator stress was used to plot the Mohr circles to obtain the extended failure envelopes for unsaturated soils (Figure 5). The values of total cohesion intercept increase with matric suctions. The φ_b angle for CW tests [9] was obtained by plotting the total cohesion intercept with matric suction (Figure 6).

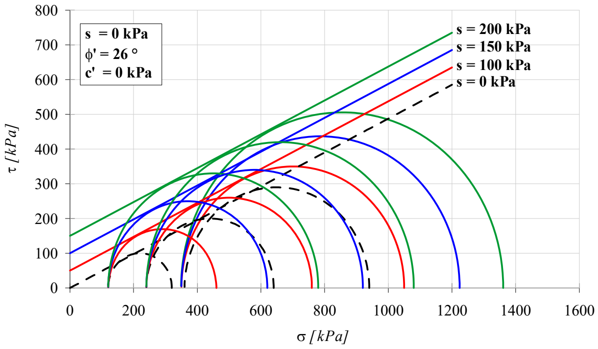

Fig. 5. Mohr circles as a function of suction.

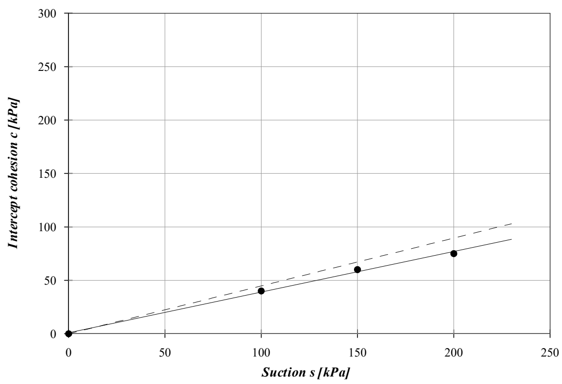

Fig. 6. Intercept cohesion versus suction.

3 Numerical Modelling

The numerical models are useful to simulate the propagation of debris flow. In this case-study, the FLO-2D code was used. FLO-2D [6] is a two-dimensional hydraulic model which, starting from one or more flood hydrograms as input and using a completely dynamic approach, predicts the flood area, the speed and depth of the water or debris flow for each cell in which the topography has been discretized.

A debris flow event can be modelled through three data sets: digital terrain model (DTM), hydrological data, and rheological properties of the water and sediment mixture.

The discharge rate value of the debris flows for the basin has been calculated by the Equation:

$$Q_{df} = Q_l \frac{c_b}{c_b - c} \tag{4}$$

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:

$$c = \frac{1}{\Delta} \frac{\tan\alpha}{\tan\varphi - \tan\alpha} \qquad \text{for } \alpha \le 21° \tag{5}$$

$$c = 0{,}9 c_b \qquad \text{for } \alpha \ge 21° \tag{6}$$

In the simulations with the FLO-2D model, the values of the empirical parameters $\alpha_1 = 0.006032$, $\beta_1 = 19.9$, $\alpha_2 = 0.000707$ and $\beta_1 = 29.8$ have been chosen from literature [10] by selecting those that have similar geomorphological and lithological characteristics with the studied area.

3.1 Hydrological study

A preliminary hydrological study was carried out in order to characterize morphologically the hydrographic basin. The flood hydrograms were obtained for the return times taken into consideration (T=5, 10, 20, 50, 100, 300 years). These hydrograms constitute the input data to be assigned to the inflow cell within the FLO-2D calculation code.

3.2 Input data

For the purposes of debris flow modelling with the FLO-2D, a discretized DTM was used with grid of 2 m x 2 m squares. A Manning coefficient of 0.02 and 0.03 [s/m$^{1/3}$] was assigned taking into account the road, some buildings and wooded patches. Subsequently, the outflow data (cells in which the water leaves the system) and inflow data (flood hydrograms) were attributed to the cells. The inlet flow is calculated according to Equation (4) as a function of the volumetric concentration and dependent on the value of the internal friction angle of the material, obtained for both saturated and unsaturated soil.

In this study, several simulations were carried out, by varying the volumetric concentration ($c_v = 0.436$ for saturated soil and $c_v = 0.569$ for partially saturated soil) and for different return times.

3.3 Numerical results

The results obtained by numerical simulations are presented in terms of maximum depth (Figure 7 and 8) and maximum flow velocity (Figure 9 and 10).

The simulations carried out by attributing higher concentration values to the input hydrogram return greater deposit depths and lesser extent-flooded areas than those with a lower concentration; on the contrary, as the concentration value decreases, there is an increase in the debris area with a global decrease in depths, attributable to a greater fluidity of the mixture.

The increase in flow depths is recorded above all in correspondence of the inhabited centre where the hydrogeological risk is greater due to the huge damage that a debris flow can cause to structures and infrastructures and to the loss of human life.

The results are in good agreement with previously recorded real events, by confirming the possibility of using input parameters available in literature for materials with similar geotechnical characteristics.

Fig. 7. Maximum flow depths for $c_v = 0.436$ and $T_r = 50$ years.

Fig. 8. Maximum flow depths for $c_v = 0.569$ and $T_r = 50$ years.

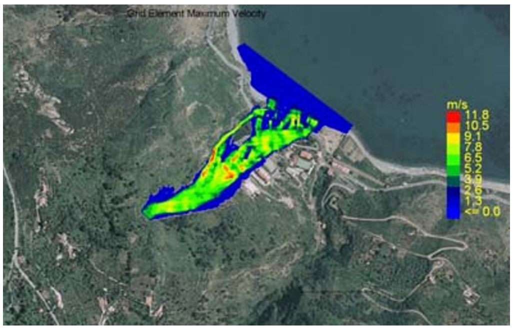

Fig. 9. Maximum flow velocities for $c_v = 0.436$ and $T_r = 50$ years.

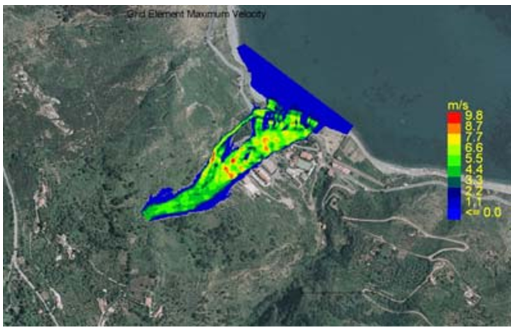

Fig. 10. Maximum flow velocities for $c_v = 0.569$ and $T_r = 50$ years.

4 Conclusions

The present study concerns the assessment hazard of landslides with rapid kinematics, connecting laboratory experiences and numerical modelling, in order to define a prediction methodology, capable of providing useful information on the dynamics of debris flows.

The laboratory tests were essential to understand the behaviour of unsaturated soil and to derive the parameters to be implemented in the calculation code to achieve debris flows numerical modelling. Triaxial tests with controlled suction were indispensable to estimate the value of the friction angle.

The numerical results, obtained by varying the return time and the volumetric concentration, are in good agreement with the real events and confirming the possibility to use input parameters available in literature involving materials with similar geotechnical properties.

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