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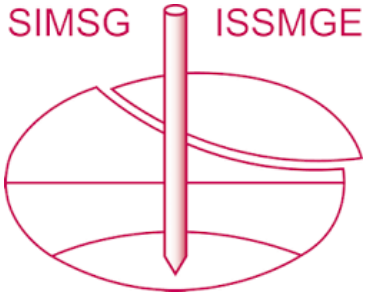

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Seismic slope stability analysis of rainfall-induced landslides in Sicily (Italy)

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ABSTRACT: During the 2010, due to intense meteoric events, some municipalities in Sicily were affected by rainfall-induced landslides. These events caused considerable damage to structures so it was necessary to realize some stabilization works. The aim of this paper is to present the dynamic stability analysis of a hill on top of which there are three multi-storey residential buildings. An accurate geotechnical characterisation was carried out, which involved the execution of boreholes and piezometers, Down-Hole and MASW tests, inclinometer measurements and laboratory tests. It was also carried out a laser scanner survey, in order to allow an accurate reconstruction of the post-event orography. The stabilization works for the landslide risk mitigation, were realized with bulkhead micropiles anchors on multiple rows. Results of the slope stability analyses obtained by finite element codes Quake/W and Slope/W are presented, using some synthetic seismograms, related to the Messina earthquake of December 28, 1908.

1 INTRODUCTION

The intense meteoric events that affected the northern part of Sicily in the 2009 and 2010, in terms of intensity and duration, caused numerous and large instability phenomena in several municipalities that were affected by more than one thousand different types of mass movements (i.e. debris flows, complex, rotational and translational landslides, rock falls) in the Messina province (southern Italy).

One of the largest landslides affected the Caronia Municipality, located in the southern part of the town, where the landslide extends for a length of about 1,000 m and a width of more than 400 m. The landslide caused damages to urbanized areas, infrastructures (national highways, rural roads and railroads), cultivated and pasture lands by involving the Lineri and Ricchiò districts in the Caronia Municipality, where about 120 inhabitants in an area of about 50 hectares were evacuated. The landslide involved a school, some houses, warehouses and agricultural and commercial activities, causing also significant damage also in economic and social terms.

The Regional Sicilian Department for Civil Defence activated since the first hours after the landslide activation, providing aid to the population and preparing an investigation campaign for the geotechnical and geological model definition of soil, as well as the instrumental monitoring activities of the landslide and topographic survey by laser scanner in order to have an accurate digital terrain model of the area.

This paper deals with the dynamic stability analysis of part of the landslide on top of which there are three multi-storey residential buildings named "Case Cuffari" (Cuffari Houses). Figure 1 shows the location of the damage area and the landslide perimeter; Figure 2 shows the landslide perimeter and the "Case Cuffari" location.

Figure 1. The damaged area and the landslide perimeter.

Figure 2. Aerial view of the landslide and Case Cuffari.

2 SITE CHARACTERISATION

2.1 *Hydrological data*

Using the time series related to two available historical series, by pluviometric stations located in the study area, the Regional Sicilian Department for Civil Defence determined the trend of the cumulative net rain and the specific infiltrated volume, assessed by the Soil Conservation Service Curve Number (SCS-CN) methodology (Mishra and Singh, 2003), for soil type C and CN=82. The obtained results by analising pluviometric data from station 1 and station 2, related to the January 2005 - May 2010 period, are respectively shown in Figures 3 and 4, where, by different colors, the effective cumulative rain (green line) and the specific cumulate infiltrate volume (red line) time histories are indicated.

The results show that although in the last years before the collapse there has been a significant increase in terms of rainfall, the specific infiltrated volume and the net rainfall in the months of February and March 2010 show lower values than in previous years: it follows that a simple study of pluviometric data cannot give clarity about the genesis of the landslide. In fact, the surveys carried out after the event showed an aquifer probably fed exceptionally from the occurred 2010 rainfalls. Further evaluations show that the vulnerability of the site, in this case, was not attributable to the vegetation covering absence; the observation of the orto-photos before the event in fact, shows to the important presence of vegetation.

So it can be supposed that the conditions of instability, originating from heavy rains, may have been favored by the presence of a previous landslide on the slope, which is evident in the geological map of the Messina province: these elements, in fact, could denote a predisposition to the geomorphological instability of the area.

2.2 *Geotechnical and geological aspects*

The area is characterized by these different geological elements (Figure 5):

1. *Tardorogene* coverings unit (*Reitano flysch: alternation of micaceous sandstones, of yellowish or gray - brown color, with intercalations of grayish or greenish marly clays* (*Ma* and Ma_s in the geological map));
2. *Sicilide* complex (*upper scaly clays* unit: *marly clays and gray-blackish clayey marl with decimetric levels of gray marly limestone and grayish calcarenite* (*Cc* and *Cq* in the geological

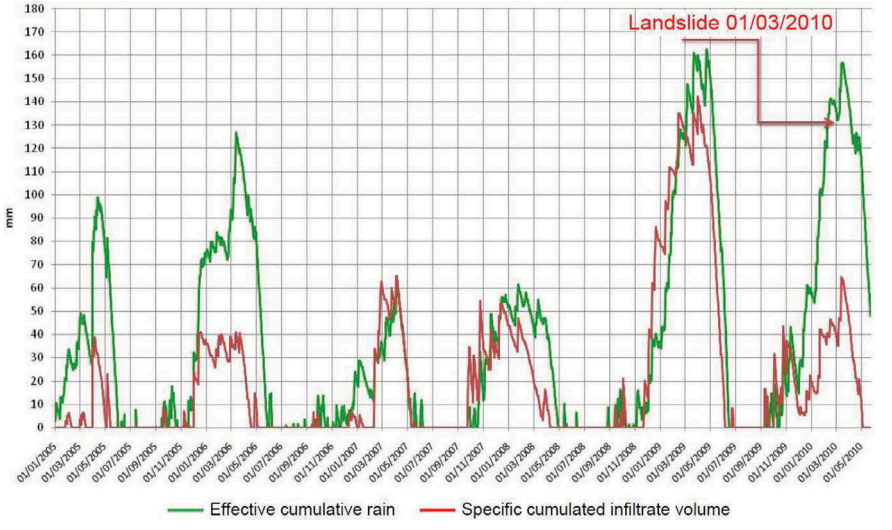

Figure 3. Effective cumulative rain and Specific cumulated infiltrate volume trends by pluviometric station data n. 1.

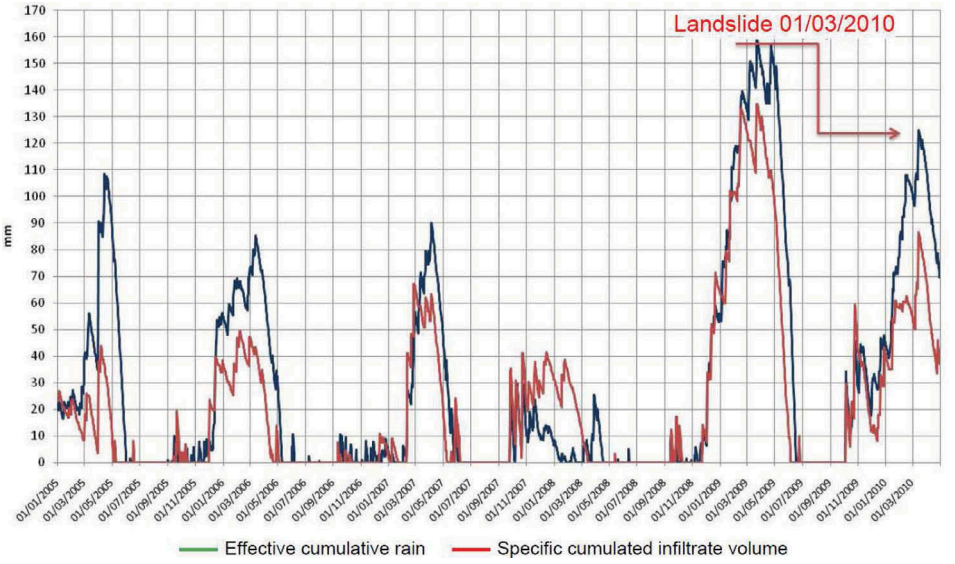

Figure 4. Effective cumulative rain and Specific cumulated infiltrate volume trends by pluviometric station data n. 2.

map); *Salici Mount – Castelli Mount* unit: numidic flysch, *blackish shafts* (*OM* in the geological map) *passing, upwards, to an alternation of brown clays and yellowish quartzarenites with local marly limestone and marl*);

3. *Panormide* complex (numidic flysch, *alternation of siliceous argillites and quartzarenites or quartzosyltites,* (*Omi* in the geological map)).

A detailed geotechnical survey campaign (Figure 5) have been performed (Ferraro et al. 2015; Castelli et al. 2016a; Ferraro et al. 2018) based on these in situ and laboratory tests:

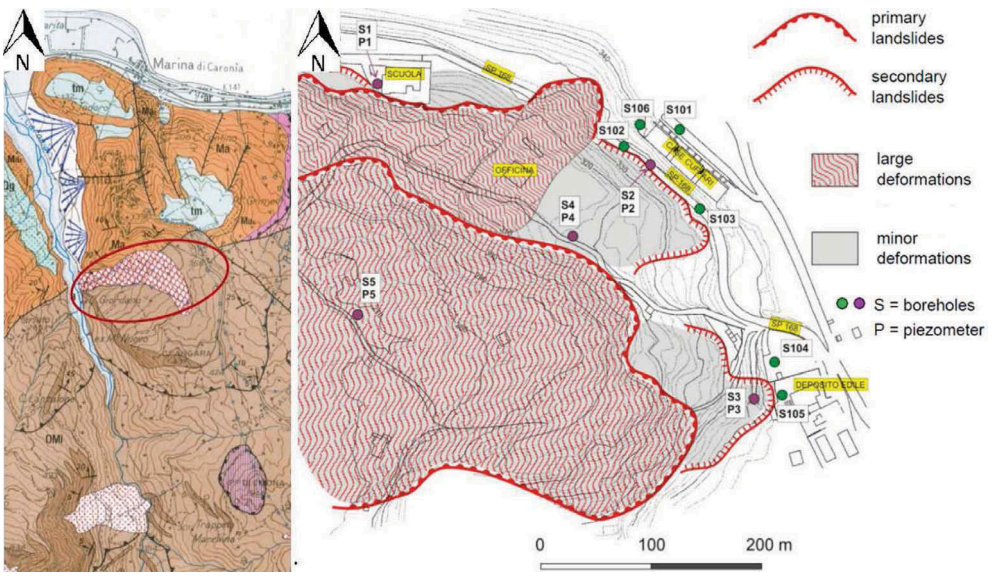

Figure 5. Geological map (left) and in situ test survey program (right).

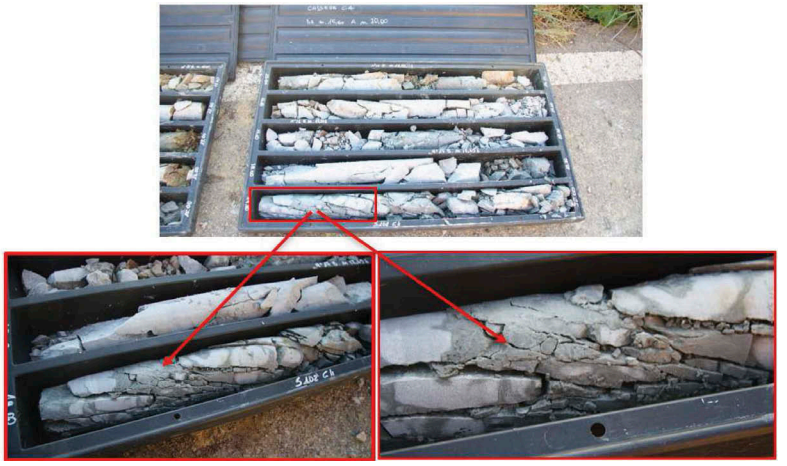

Figure 6. Drill core box related to the S102 borehole.

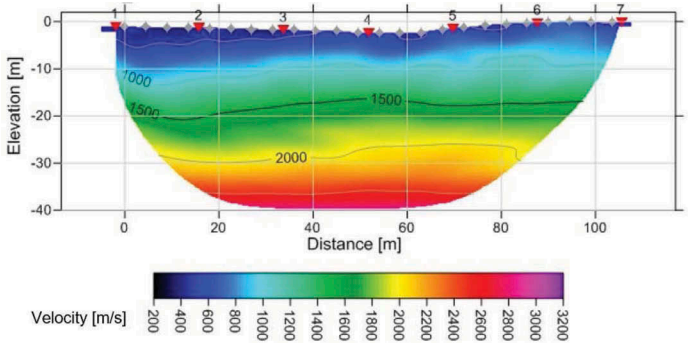

Figure 7. Seismic tomography TS06 wave velocity color-map.

n. 5 core drilling boreholes, depths between 30 and 50 meters, with piezometers;
n. 5 core destruction boreholes, depths between 30 and 50 meters, with piezometers;
n. 7 seismic tomography;
n. 2 MASW tests;
n. 3 down-hole tests;
inclinometer measurements;
piezometric measurements;
laboratory tests.

Boreholes (Figure 6) shows, in general, this stratigraphic profile: clayey detrital soil in the first 5-10 meters of depth, and then the numidic flysch. Seismic tomography (Figure 7) and MASW test show the thickness of the layers characterized by V_p<900 m/s.

3 NUMERICAL ANALYSES

3.1 *Geotechnical model*

A 2-D cross section has been realized by the Geoslope FEM codes Slope/W and Quake/W, in order to study the slope analysis stability and the local seismic response after the stabilisation

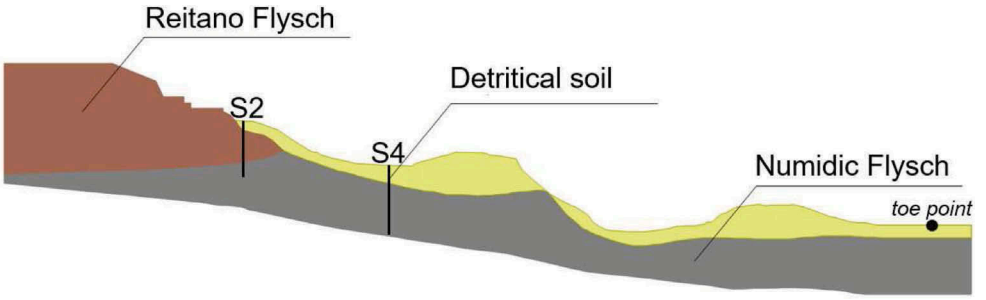

Figure 8. 2-D geotechnical model.

Table 1. Geotechnical parameters of soil.

Soil type	Vs_{mi}	Vp_{mi}	Vp/Vs	γ	ν	G_{max}	φ'	c'
	m/s	m/s		t/m^3		t/m^2	°	kPa
Debris soil	285	498,50	1,75	2,02	0,205	17446,25	23	6,90
Reitano Flysch	535	926,10	1,73	2,08	0,226	59956,70	28	19,90
Numidic Flysch	530	1442,00	2,72	2,03	0,250	57378,00	25	3,10
Bedrock	800	2.176,00	2,72	2,20	0,250	57378,00	30	0,00

work for the landslide risk mitigation, that was realized with micropiles bulkhead (diameter 0.30 m, depth 15.00 m) with 24.00 m length anchors on multiple rows.

The geotechnical soil model for the 2-D section (Figure 8) is characterized by the parameters shown in the Table 1, in terms of thickness of layer, average Vs_{mi} and Vp_{mi} of the layer, unit weight γ, Poisson's ratio ν, shear modulus G_{max}, friction angle φ' and cohesion c' (Cavallaro et al. 2006; Ferraro et al. 2009; Caruso et al. 2016). Moreover, in order to take into account the non-linearity behavior of the soil, the curves for the stiffness attenuation G/G_{max}-γ and for the damping ration evolution with strain evolution D-γ, have been utilized (Ferraro et al. 2016; Castelli et al. 2018a,b).

3.2 *Seismic response analysis*

In order to evaluate the slope seismic response trough a linear-equivalent approach, Quake/W code has been used. Thanks to this code it was possible to calculate the PGA at two points: the first point located at the top of the slope, behind the crest, the second at the toe of the slope. Seven different inputs were used, consisting of six synthetic seismograms related to the Messina and Reggio Calabria 1908 earthquake (Bottari et al. 1986; Tortorici et al. 1995; Amoruso et al. 2002); DISS Aspromonte Est; DISS Gioia Tauro; DISS Messina straits) and one related to the 1693 Catania scenario earthquake (Cavallaro et al. 2016a; Castelli et al. 2016b; Grasso & Maugeri, 2014). The seismograms were scaled to the PGA = 0.176 g provided by the italian code NTC2018 (Cavallaro et al. 2016b) for the site. The soil dynamic properties taken into account for the numerical analyses are described through the G/G_0-γ and D-γ curves related to similar materials of the same area (Cavallaro et al. 2018). As an example, only the results obtained through the DISS-Aspromonte seismogram are reported (Figure 9); it is also noted that using the 7 seismograms, similar results have been obtained. Numerical analysis through DISS-Aspromonte seismogram (input PGA 0.176g) shows at the toe of the slope a PGA equal to 0,257 g (Figure 10 left), while in S2 point, behind the crest of the slope, shows a PGA equal to 0,332 g (Figure 10 right). This result demonstrates the presence of a seismic topographical effect for the slope (Bard, 1982).

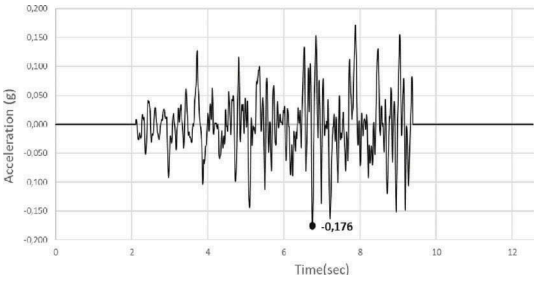

Figure 9. DISS Aspromonte input Seismogram.

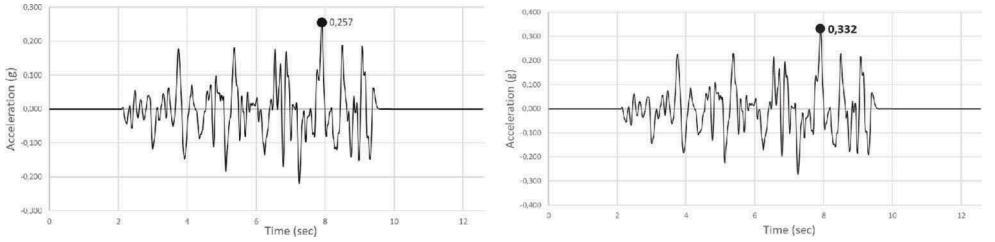

Figure 10. (left) response acceleration time history, at the toe of the slope; (right) S2 response acceleration time history, at the top of the slope.

3.3 *Slope response analysis*

The slope stability analysis was performed by the FEM code Slope/W-Geoslope under two cases: 1) slope in static conditions; 2) slope in dynamic conditions trough a pseudo-static method. Due to the importance of pore-water pressure in the stability analysis, SLOPE/W code has various ways of specifying the pore-water pressure conditions; in this case a piezometric line at the surface in the detritical soil and 3,00 meters deep in the Reitano Flysh have been considered. The Geoslope software suite allows the interoperability between the Quake/W and Slope/W codes, so the results obtained through the dynamic analysis by Quake/W have been considered for subsequent slope stability checks. The PGA used for numerical analyses was chosen equal to 0,332 g (the obtained value at point S2 located behind the crest of the slope). Stability analyses have been carried out (Cavallaro et al. 2008) into static and dynamic conditions both without intervention (Figure 11), while into dynamic conditions have been performed including intervention (Figure 12). The stability analyses carried out with different methods show F_S values sometimes lower than 1.0, because the slope, once the landslide process was finished, falls into metastable conditions. These F_S values are greater in

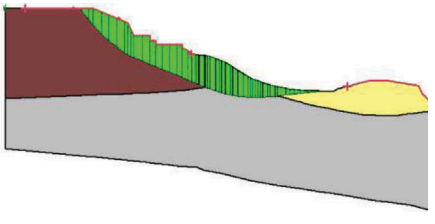

Figure 11. Slope stability analysis results in terms of safety factor (SF) for the static and dynamic conditions.

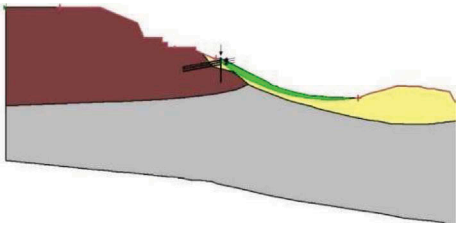

Figure 12. Slope stability analysis results in terms of safety factor (SF) for the dynamic conditions.

the case of static conditions without intervention than those of the dynamic conditions, while are always greater than 1.0 in the case of dynamic conditions with micropiles intervention (Table 2).

4 CONCLUSIONS

It has been shown the case study of a landslide which affected a slope located in the northern part of Sicily, characterized by a big landslide movement. The data, deriving from the geotechnical characterization, consisted in the execution of several in situ (boreholes, down-hole, MASW, electrical 2-D tomography, inclinometers, piezometers) and laboratory tests (Diaz-Segura, 2015). Numerical seismic response analyses were performed at two point, one at the top and one at the toe of the slope, which have been monitored in order to study the topographical amplification effects. Results show a 0,332 g maximum response acceleration at the crest of the slope and a 0,257 g maximum response acceleration at the toe of the slope. Detailed analyses on the topographical amplification effects for slopes are described by Bouckovalas and Kouretzis., 2002; Gazetas et al. 2002. Slope stability analyses were carried out into static and dynamic conditions. These analyses are crucial for the intervention works of the slopes because they allow to evaluate the rate of topographical amplification which could compromise the efficiency of a consolidation work located near the crest of the slope.

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