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Assessment of seismic slope stability at different scales in Molise Region (Southern Italy)

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ABSTRACT: The Molise Region (Central-Southern Italy) is an area characterized by a high susceptibility for rotational and translation landslides and by the presence of several active seismogenic sources. In this study, the well-known approach for the prediction of seismic displacements of slopes proposed by Newmark is applied at this specific area to obtain a level II zonation of the district. To work at large scale level, we carried out some hypotheses: infinite slope, limit cases for water table and seismic motion characterized through the assessment of PGA at surface following the maximum historical earthquake criterion. We adopted appropriate empirical relationships to predict induced displacements. The results in terms of forecasted seismic displacements were compared for a specific case study of an unstable slope in the village of Roccavivara (CB). There, rigorous Newmark analysis (level III), successfully support the large-scale approach.

1 INTRODUCTION

In Italy, several post-earthquake field studies reported evidence of the triggering of earthquake-induced landslides. For instance, the Central Italy seismic sequence in 2016 activated hundreds of occurrences, mainly rockfalls (Martino et al. 2017, Franke et al. 2018). The relevance of these phenomena in the country was documented in the C.E.D.I.T. Catalogue (Martino et al., 2014). The common occurrence of slope movement after earthquakes in Italy is due to the joint presence of relevant active seismogenic sources and areas characterized by high susceptibility to the landslide. It appears that any complete study aimed at evaluating the seismic risk of a given area must necessarily include the assessment of slope performance.

Early studies on the topic date back to the work of Keefer & Wilson (1989), who identify, through empirical correlations, the types of landslides more susceptible to be activated in case of a seismic event. Using the classification by Varnes (1978), the recognized categories, in order of susceptibility, are: category (1) topples and falls; category (2) slides; and, category (3) flows.

The literature on the topic identifies four progressive levels of analysis, according to the scale of investigation and the complexity of the methodologies used (ISSMGE 1999, MS Working Group 2008, Santucci de Magistris et al 2014, Silvestri et al. 2016). The first two levels are those typically relevant to zonation of territory, the last two refer to the assessment of the stability of a single slope. In this paper, updated approaches for Levels II and III on a relevant case study are shown. The former is developed within GIS (Geographical Information System), combining topographic, geological and geotechnical data with estimates of the expected ground shaking following a "scenario event" (Romeo 2000). The results can be compared with a test site (level III), pointing out the possibility to expand the scale of the studies to that of the single slope. In this paper, the area selected to perform slope stability analyses is the Molise Region, (Central-Southern Italy) within the Southern Apennines, which is characterized by medium-high seismicity and high landslides susceptibility. Furthermore, it is one of the Italian areas stricken by relevant earthquakes in the last decade (2002 and 2018), suffering damages in building heritage as well as in the physical environment.

2 METHODOLOGY

In literature, most Level II methods proposed for seismic slope stability assessment refer to rational displacement-based methods. At a territorial scale, they can be implemented through GIS, by combining seismological, topographic, geological and geotechnical data, as for instance suggested by the HAZUS (NIBS 2004) guidelines. The different approaches usually define the seismic hazard by synthetic ground motion parameters, refer to the infinite slope model for the stability analysis and adopt empirical relationships to predict earthquake-induced displacements. In Italy, these approaches were adopted for assessing the overall regional susceptibility (Luzi & Pergalani 2001, Forte et al. 2013), and in several cases addressed to evaluate the seismic performance of some strategic infrastructures (Biondi et al. 2005, Silvestri et al. 2006, d'Onofrio et al. 2013, Forte et al. 2015).

The procedure adopted in this paper follows the Newmark (1965) approach, which is particularly suitable for modeling Category 2 landslides, where the mobilizing volume is considered as a rigid-plastic block that experiences no internal deformation until the onset of the sliding. The triggering occurs when the acceleration overpasses the 'critical acceleration' threshold, a_c, which can be calculated from the assessment of the factor of safety (*FS*) from limit equilibrium analysis. For an infinite slope, *FS* can be expressed as:

$$FS = \frac{c'}{\gamma z sin\alpha} + \frac{tan\varphi'}{tan\alpha} - \frac{m\gamma_w tan\varphi'}{\gamma tan\alpha} \tag{1}$$

where: α is the angle of inclination of slope and slip plane; γ is the total unit weight of the soil; γ_w is the water unit weight; *c'*, φ' are effective cohesion and friction angle; $m = 1 - z_w/h$, varying between 0 and 1 for sliding mass respectively above or below the water table.

Hence, the critical acceleration a_c can be computed from the following expression:

$$a_c = (FS - 1)g \sin\alpha \tag{2}$$

where: FS is the static factor of safety; g is the gravity acceleration and α is the slope angle.

Permanent slope displacement, *u*, can be obtained using predictive relationships expressing the slope displacement as a probabilistic function of the critical acceleration and synthetic ground motion parameters; in most cases they consist uniquely of the peak surface acceleration (a_s), in some others, they also account for the frequency content and duration of the shaking.

In stability analysis based on a scenario earthquake, reference acceleration, a_r, can be evaluated by a Shakemap or simply adopting an appropriate Ground Motion Prediction Equation (GMPE), which can be corrected for different site conditions, in terms of stratigraphic (SS) and topographic amplification (ST) factors to obtain surface acceleration (a_s).

Following the approach by Ambraseys & Menu (1988), through extensive use of the Newmark dynamic analysis with seismic input motions recorded throughout the Italian territory, several authors proposed as many predictive relationships discussed and compared by Silvestri & d'Onofrio (2014). The following relationship:

$$\log u = 2.768 - 3.637\frac{a_c}{a_s} \tag{3}$$

suggested by Ausilio et al. (2007), was selected for this study for a conservative estimate of an upper bound displacement.

At level III, dynamic simplified analysis for the assessment of slope displacement, *u*, can be obtained by double integrating the difference between an accelerogram and a_c until the relative velocity becomes zero. To determine the critical acceleration, conventional stability analyses based on the Limit Equilibrium Methods (LEM) were performed to compute the static safety factor of the slope by using the commercial Geoslope software. As pertains the ground motion, a set of 8 recorded accelerograms were selected through the REXEL software (Iervolino et al. 2010). This tool permits to choose recorded time-histories of acceleration, whose average spectrum is compatible in broad period ranges, with the reference spectra of the EC8 (2003). It ensures that individual records in the returned combinations have a spectral shape as much similar as possible to that of the target spectrum. REXEL also permits to account for the site amplification assigning the soil class and topographic category. The research of the dataset was guided by the most likely M - R (Magnitude and Distance) pairs given by the INGV disaggregation study (http://esse1-gis.mi.ingv.it/s1_en.php), which give the pairs that mostly contribute to the seismic hazard of the area.

3 APPLICATION OF LEVEL II ZONATION TO THE TEST AREA

Molise region (around 4500 km^2) is located in the Southern Apennines and falls between several seismogenic areas, namely the Apennine axial zone, the Abruzzo-Molise corridor and the Apulia-Gargano foreland, which correspond respectively to the well-identified 927, 923 and 924 SSZs (seismogenic source zone) by ZS9 (Meletti et al. 2008). Those seismogenic structures generated several destructive earthquakes with felt intensities up to IX MCS in Molise. The most recent occurred in 2002 and 2018, but high magnitude earthquakes (M_w 6.5-7) occurred in historical times and strongly affected the Region, as summarized in Table 1.

Figure 1a and Table 2 summarized the geological setting of the Molise Region. The oldest rocks are Carbonate units (C; Mesozoic-Tertiary) cropping out in the south-western part of the Region, while Flysch deposits (Tertiary) represent the most widespread formation. It can be distinguishable into several geolithological Complexes, from the most clay-rich (VC, MC, MS) to marly calcareous (MCa) and arenaceous-conglomeratic (SC). Along the coast, the upper member of the Plio–Pleistocene terraced deposits (also included in the SC) lie on the Grey–Bluish Clays (GBC; Plio–Pleistocene). The most recent deposits are Alluvial Complexes (Holocene) split into a Coarse (CA) and a Fine Alluvial (FA) and Landslides Deposits (LD), delimited only when

Table 1. Main historical earthquakes affecting Molise region.

Epicentral area	Date	I_0	M_w
Boiano	05/12/1456	XI	7.0
Gargano	30/07/1627	X-XI	6.9
Sannio	05/06/1688	X-XI	6.8
Boiano	26/07/1805	X	6.6
S. Giuliano di Puglia	31/10/2002	VIII-IX	5.7
Montecilfone	16/08/2018	VII	5.1

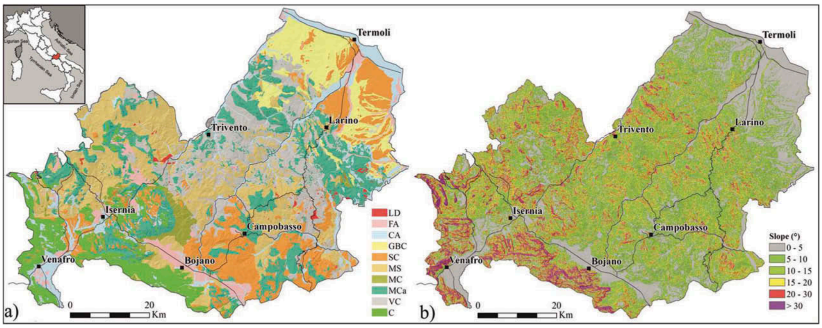

Figure 1. Molise region study area a) Geolithological setting b) Slope angle map 50 x 50 m.

Table 2. Geolithological Complexes and their mechanical characterization

ID	Geolithological Complex	γ kN/m^3	φ' (°)	c' kPa	s_u kPa	m (-)	EC8 soil class*
LD	Landslides	19.5	18.0	-	-	1.0	D
FA-CA	Fine and Coarse Alluvial	20.8	21.0	14.0	-	0.8	B
GBC	Grey-Bluish Clays	20.8	-	-	54	1.0	C
SC	Sandstones and Conglomerates	19.8	23.7	16.7	-	0.5	B
MS	Marly Sandstones	20.4	22.0	21.6	-	0.5	B
MC	Marly Clays	20.9	-	-	90	0.8	B
MCa	Marly Carbonates	19.9	22.2	18.4	-	0.5	B
VC	Variegated Clays	20.4	-	-	117	1.0	B
C	Carbonates	-	-	-	-	-	A

* Soil classes come from a V_{S30} map of Molise by Forte et al. (2017).

present on 1:100,000 maps. The morphological setting is characterized by steep mountains in the SW, which pass to more gentle slope Eastwards, with several inner plains, as the slope angle map in Figure 1b shows. It is calculated from a DEM, with cells 50 x 50 m wide.

The procedure described for the assessment of slope stability in seismic conditions was not applied for the Carbonate complexes, being mainly affected by Category 1 landslides. Furthermore, areas characterized by slope angle less than 5° were neglected from the analysis, in order to reduce the computation time. Hence, around 25% of the Region was not suitable for the application of the procedure. Table 2 also reports the physical, mechanical and seismic parameters attributed to the lithological complexes from the synthesis of a dataset constituted by 1682 stratigraphic logs, 297 downhole measurements, 1013 identification tests, 482 direct shear tests and 388 unconsolidated undrained strength tests on undisturbed soil samples. The depths of the slip surface for each complex was based on the stratigraphic limit between the weathered cover and the intact soil mass and did not result deeper than 15 m b.g.l. The groundwater table depth was assigned through hydrogeological assumptions. For the clayey complexes, the undrained shear strength (s_u) was preferred over to the effective shear strength.

Figure 2 shows the distribution of the critical acceleration, a_c, resulting from the application of Eqs. 1 and 2 throughout the whole test area.

This map is representative of a 'landslide susceptibility map in seismic conditions' (i.e. earthquake-independent) for the case study. The evaluation of the permanent displacements requires the selection and the representation of the seismic input. For this case, a scenario-based approach was followed, by the selection of the earthquake characterized by the worst combination of Magnitude-Distance for the study area, i.e. the event of July 26th, 1805 (Mw 6.62 ± 0.11). This event was the strongest earthquake, which affected the Molise Region, after

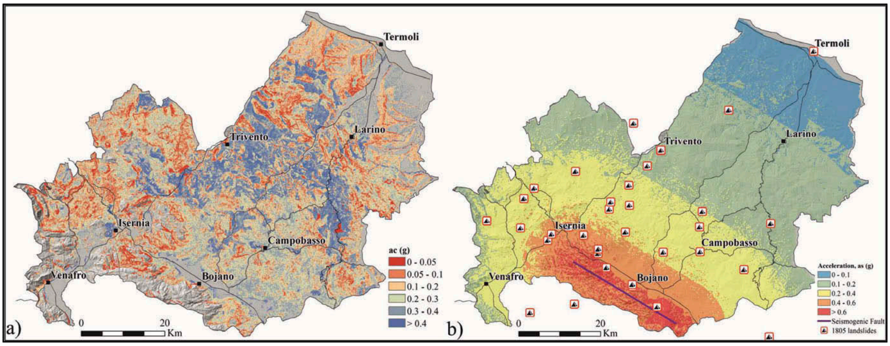

Figure 2. a) a_c distribution map for the study area. b) a_s distribution map following the GMPE by Bindi et al. (2011) amplified.

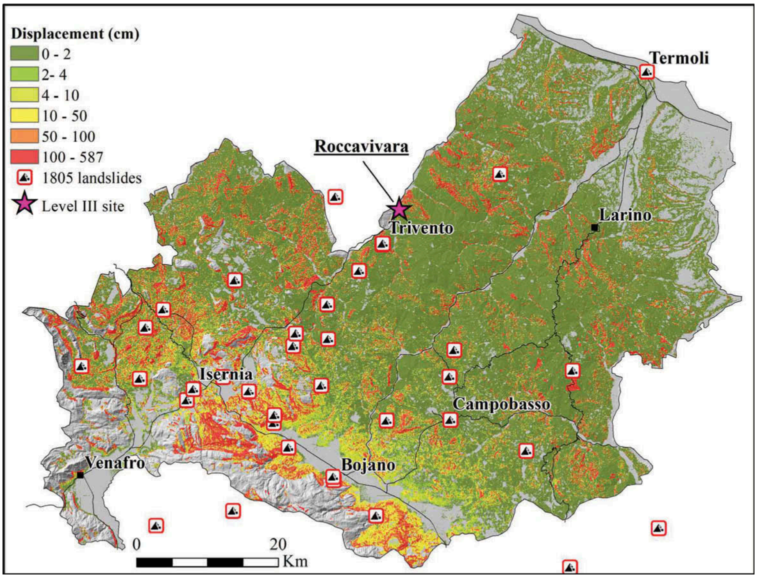

Figure 3. Seismic displacement map for Molise Region.

the 1456 earthquake. The reference ground motion distribution was predicted through the GMPE by Bindi et al. (2011). The reference acceleration, a_r, was corrected into the peak surface value, as, by multiplying it for the stratigraphic and topographic amplification factors, SS and ST. The former was obtained assuming the soil class types assigned to each Complex from a V_{S30} map (see Table 2). The V_{S30} map was obtained assuming as reference value, the median of the distribution of V_{S30} calculated on DH tests falling within each geolithological complex. The well-recognized decrease of amplification with ground motion amplitude was expressed by a power law decreasing with a_r through empirical relationships (Landolfi et al. 2011, Tropeano et al. 2018). The value of the topographic amplification factor, ST, was computed as a function of the average curvature of the DEM, as suggested by Silvestri et al. (2016). Indeed, theoretical studies in literature (e.g. Sanchez-Sesma 1990) suggest associating ST to the slope curvature, accounting for amplification of seismic waves due to focusing on ridges, as well as for their attenuation in canyons. By combining the critical acceleration map (Figure 2a) with the ground motion distributions (Figure 2b), the corresponding expected displacement could be calculated with Eq. 3. In Figure 3, the distribution of the displacement is shown. Following Silvestri & d'Onofrio (2014), the adopted ranges may correspond to the Limit States specified by the Italian Building Code.

4 LEVEL III ANALYSIS

A level III analysis for slope stability was carried out in order to compare and verify the results obtained in the level II study. The studied landslide is located in the village of Roccavivara in the neighboring of Trivento (CB) and can be classified as earthslide, according to the Cruden & Varnes (1996), see location in Figure 3. It is a typical instability phenomenon, widespread and seasonally occurring in Molise. The slide involved nearly 36.600 m^3 of soil, which affected and displaced the regional neighboring roadway. It developed within the Variegated Clays Complex (VC), made of clays and silty-marly clays, in tectonic contact with the Marly Carbonate Complex (MCa), constituted by cherty calcarenites with thick gray marls intercalations. The landslide is located at the height of 220-240 m a.s.l. upstream of a river terrace, which consists primarily of coarse alluvial deposits (CA) of the Trigno River. The geological and geotechnical characterization was based on 5 stratigraphic boreholes, 1 piezometer, 1 CH

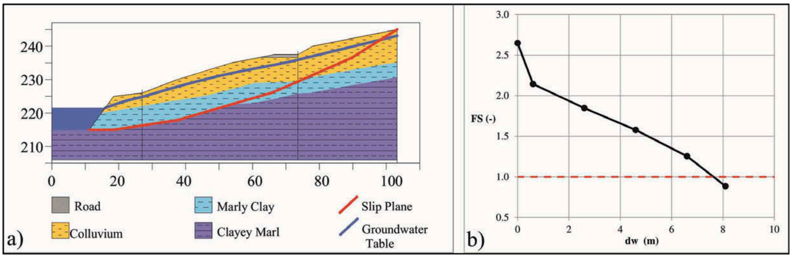

Figure 4. a) Geological cross-section for Roccavivara earthslide; b) Variation of the Factor of safety (FS) with the height of the groundwater table (dw). *FS*= 1, when the water table is 8.1 m above the slip surface.

test and the collection and testing of 6 undisturbed soil samples. The testing program consisted of physical identification, unconfined compression strength tests, and direct shear tests. The geological cross-section shown in Figure 4 displays three recognized layers, i.e. the bedrock made of grey stiff clayey marls, overlaid by a weathered cover of about 3-4 m thick of marly clays with a high water content, which, in turn is capped by a reddish-brown reworked colluvium. The strength parameters in terms of φ' and c' resulted 25° and 18 kPa for the shallower layer and 27° and 18 kPa for the weathered cover.

Back-analysis carried out on this phenomenon identified the raising of the groundwater table as triggering factor. The variation of the *FS* with the position of the groundwater table, shown in Figure 4b, reaches the limit equilibrium (*FS*= 1), when the water table is at ground level.

The assessment of the slope stability in seismic condition was performed through the well-established Newmark analysis. A critical acceleration (a_c) of 0.07g was calculated with the Eq. (2) for pre-failure condition, i.e. groundwater height at 6.3 m (*FS*= 1.3). This groundwater level agrees with the measurements in the piezometer. Furthermore, this assumption is consistent with the scenario modeled in the II level analysis.

Acceleration time histories were obtained through REXEL software, which extracted 8 recorded accelerograms from both the Italian Accelerometric Archive and the European Strong-Motion Database for normal fault earthquakes. The target spectrum was built on the "Collapse Limit State" for roadway, which possesses a nominal life of 50 years and is functional type III. PGA was referred to the amplified acceleration value (a_s) at Roccavivara from the shakemap in Figure 2b. Accelerograms extraction also accounted for the site condition (soil class B), topographic category (T1) and the Magnitude-Distance pairs mostly contributing to the seismic hazard. This latter came from the disaggregation study and resulted respectively between 4 and 7 for Magnitude and 0 - 40 km for the distance. The selected accelerograms are characterized by a bracketed duration between 25 and 90s and were recorded on several stations from the Greek earthquake of Kalamata (Mw 5.9) occurred on 13/09/1986; Irpinia earthquake (Mw 6.9) on 23/11/1980 its aftershocks (Mw 5.0) on 24/11/1980 and Umbria-Marche (Mw 6.0) on 26/09/1997.

Finally, Newmark displacements were computed by SLAMMER software (Jibson et al. 2013), scaling PGA of each accelerogram to the a_s of the shaking scenario for the analyzed earthslide. Results are shown in Figure 5a.

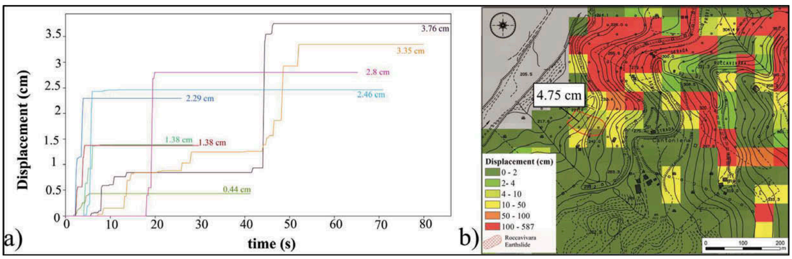

Figure 5. (a) Newmark displacements and (b) displacements from Level II method.

For the pre-failure conditions, the maximum value of 3.76 cm was obtained. This value was compared with the results of the level II analysis for Roccavivara earthslide. In this case, the landslide perimeter occupies four pixels (see Figure 5b), whose mean, weighted for the area of each pixel, resulting in a total value of 4.75 cm, which is well matched with the maximum value obtained from the rigorous Newmark analysis.

5 CONCLUSIONS

In analyzing the stability of a given area, the estimate of seismic displacements due to slope movement is a relevant parameter. The availability of a map showing the forecast of possible movement allows detecting areas that can be most likely affected by landslides and helps to manage the emergency after a strong-motion event. It helps also to plan the most appropriate mitigation works or strategies. In this research, despite the non-homogeneity of the parameters used for evaluating instability and the difference in the scale, a comparison between Level II and III was attempted. The results in terms of obtained displacements are in agreements. Level II analysis can provide a reliable close-up view on the variability of the earthquake-induced deformation phenomena, provided the geology is accurately described, the geotechnical database is enough robust and uniformly widespread along the whole territory, and the reference shake-map reliably simulated. It might be argued that such methods should be upgraded. For instance, a more comprehensive evaluation of the energy content of the expected reference seismic motions rather than of the peak ground acceleration only can be considered. Moreover, site effects can be evaluated with higher accuracy and it could be considered that Level II does not account for the multiphase soil nature, non-linear behaviour, and so on. Nevertheless, the variability of such factors can be reliably included only in Level III or in the most advanced level IV. The application of the proposed methodologies to different areas of the national territory would allow a significant advance towards more conscious management of the national territory characterized by a landslide risk and seismic risk among the highest in Europe.

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