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GIS-BASED PERMANENT DISPLACEMENT MAPS FOR URBAN PLANNING OF UNSTABLE SEISMIC TERRITORIES: A CASE STUDY IN DAUNIA APENNINE (APULIA, ITALY)

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EXTENDED ABSTRACT

I fenomeni franosi sismoindotti coinvolgono, a volte con conseguenze piuttosto dannose, aree parecchio diffuse su scala mondiale. Per questa ragione tali contesti territoriali andrebbero costantemente monitorati in accordo a quanto previsto dalle vigenti normative ed alle procedure tecniche in materia di prevenzione dei rischio.

Gli approcci di studio finalizzati alla valutazione della suscettibilità da frana, anche in aree sismiche, sono di vario tipo: euristico (Pellicani *et alii*, 2014), multi-temporale (Andriani *et alii*, 2015), multi-step (Parise *et alii*, 2012), probabilistico (Del Gaudio *et alii*, 2012) e deterministico (Cotecchia *et alii*, 2009). Quest'ultimo rappresenta la procedura più dettagliata e conseguentemente più affidabile nella valutazione del rischio, poiché si basa sul concetto di modellazione geologica. Ricostruire il modello naturale di un'area è sempre una procedura molto difficile, soprattutto in contesti geologici strutturalmente complessi e litologicamente eterogenei come quello di catena montuosa di cui fa parte il territorio preso come riferimento. L'inquadramento territoriale tiene conto dei caratteri litologici, morfostrutturali, sismici, idrogeologici a cui si affianca la caratterizzazione fisico-meccanica dei materiali. Il livello di approfondimento della modellazione varia in funzione di diversi fattori (estensione dell'area di studio, tipologia di indagine da condurre, disponibilità economica, possibilità di poter condurre particolari tipi di test in situ ed in laboratorio, etc.); tuttavia si considera che più ristretta è l'area di indagine maggiore risulterebbe il dettaglio della modellazione.

Nel presente lavoro è stato condotto uno studio con approccio deterministico finalizzato alla stima di possibili spostamenti permanenti indotti in condizioni sismiche sul territorio di Deliceto (FG), il quale si colloca in zona sismica sulle propaggini montuose più orientali del Subappennino Dauno. L'abitato di Deliceto e le aree limitrofe manifestano alcuni fenomeni franosi classificati come scivolamenti superficiali diffusi, frane rototraslazionali e complesse (Carta Idrogeomorfologica della Puglia, www.sit.puglia.it e Inventario dei Fenomeni Franosi Italiani, www.ispra.it); potrebbero verificarsi anche fenomeni da crollo in corrispondenza dei versanti acclivi e rocciosi che bordano il centro storico.

Il territorio ricade nella Zona Sismica 925 del territorio italiano (ZS925) (Database of Individual Seismogenic Sources 3.2.0, http://diss.rm.ingv.it/), è caratterizzato da valori storici di magnitudo momento massima (M_w) pari a 6.6 (Database Macrosismico Italiano, 2011) e mostra valori di accelerazione al suolo massima, stimata su un tempo di ritorno di 475 anni (NTC, 2008), pari a 0.2 g (Mappa di Pericolosità Sismica, 2004).

L'analisi dinamica e la conseguente stima degli spostamenti indotti è stata condotta tenendo conto del metodo di Newmark (1965) per la stima dell'accelerazione critica al suolo, intesa come valore di soglia per il possibile innesco di fenomeni deformativi, ed applicando la relazione sperimentale di Ambraseys & Menu (1988), tenendo conto dei coefficienti di regressione proposti da Jibson (2007), per la determinazione degli spostamenti al suolo.

Prendendo in considerazione i caratteri litologici, quelli geomorfologici in riferimento al Modello Digitale del Terreno (DTM) con dettaglio di 5 m, i principali parametri fisico-meccanici dei materiali affioranti e le condizioni idrogeologiche, sono state redatte carte tematiche con ed in assenza di falda idrica, sia inerenti ai fattori di sicurezza sia agli spostamenti permanenti indotti.

I risultati, sintetizzati nelle carte tematiche, mostrano che gli spostamenti maggiori si manifestano lungo i versanti caratterizzati dall'affioramento della Formazione del Flysch di Faeto e sono generalmente compresi tra 0 e 10 cm; solo in casi sporadici, laddove affiora la facies lapidea del flysch, gli spostamenti possono essere compresi tra 10 e 100 cm.

La finalità del lavoro è stata sia quella di adoperare un approccio di studio, l'analisi dinamica di versante, mai adottato finora negli studi di suscettibilità da frana sismoindotta in Daunia, sia di produrre carte tematiche che quantificassero le possibili conseguenze di un sisma in termini di spostamenti indotti al suolo e fossero uno strumento utile per una corretta pianificazione del territorio.

ABSTRACT

Earthquake induced landslides (EIL) represent coseismic effects that heavily affect seismic territories worldwide and must be taken into account in urban planning according to national laws and technical provisions. Inventories of earthquake-triggered landslides and and geotechnical characterization of soils involved into mass movements are commonly prescribed to predict EIL with increasing details as the scale of the study increases. EIL hazard is assessed through several different methods. At urban scale, the deterministic approach of the Newmark's sliding rigid block method is commonly employed to draw EIL hazard maps by calculating permanent displacements triggered by seismic events. Thematic maps built within ArcGis environment have been combined to draw hazard maps through the raster calculator tool (ARCMAPTM 2010). In this paper the Newmark's method is applied to the case study of Deliceto town, located in Daunia Apennine (Apulia, Southern Italy). This territory is characterized by frequent and widespread landslide phenomena triggered by seasonal rainfalls and strong earthquakes, such as the 23rd November 1980 Irpinia earthquake. In particular, Deliceto is affected by the highest seismic level within Daunia territory corresponding to the expected peak ground acceleration (PGA) equal to 0.20 g. The outcomes of the present study suggest that the highest permanent displacements are expected along steep slopes made up of an alternation of limestones and marly clays belonging to the Flysch Faeto Fm.

Keywords: *earthquake, landslides, Daunia, permanent displacements, structurally complex formation, Newmark's rigid block analysis, urban planning.*

INTRODUCTION

Hydrogeological and seismic hazard assessment on Italian territory has been recently regulated by the Italian Law n. 100/2012. This law states that the regional civil protection offices are responsible for devising and actuating securety procedures in the aftermath of flood, landslide and earthquake phenomena, through the evacuation maps drawn by municipal offices. To this end, local administrations have to perform hazard studies at urban scale in order to draw hazard maps.

To map landslide susceptibility and hazard many different approaches have been applied in several scientific studies according to the specific characters of the territories (Fell *et alii*, 2008). In this paper, the authors focus on the hilly district of Daunia Apennine within Apulia (Southern Italy), that is highly exposed to landslide phenomena. It is a crossroad of strategic infrastructures and windfarms so that for Apulia this area is exposed to natural hazard and risks that must be assessed and mitigated. Several studies have been accomplished within the Daunia territory for supporting the planning activity on both Regional and Municipal scale, from 1:25000 to 1:50000 (Cotecchia *et alii*, 2009; Del Gaudio *et alii*, 2012; Parise *et alii*, 2012; Pellicani & Spilotro, 2013; Pellicani *et alii*, 2014; Andriani et alii, 2015; Pisano *et alii*, 2016). Landslide susceptibility maps in Daunia have been drawn through two main approaches, one heuristic, the other deterministic. The heuristic methods give a qualitative assessment of the landslide-prone areas by combining predisposing hydrogeomorphological, lithological and physical properties through weighing factors, chosen on expert judgement basis. Some of the experiences in applying the Stevenson heuristic method (1977) have been collected by Pellicani *et alii* (2014). In addition, Andriani *et alii* (2015) proposed a complex multi-criteria and multi-steps heuristic approach to susceptibility applied to the whole Torrente La Catola catchment area, mapped with a scale of 1:35000.

Another quantitative hazard assessment approach contemplates a probabilistic landslide hazard analysis that provide hazard curves and maps, considering temporal probabilistic distributions of triggering parameters (rainfall cumulates, seismic peak ground accelerations, Arias Intensity of the seismic signal, AI) combined to predisposing factors (Lari *et alii*, 2014). Del Gaudio *et alii* (2012), in particular, elaborated a seismic hazard map based on the permanent displacements induced by a seismic shaking scenario, adopting the Jibson's formula (1993). These Authors investigated a portion of Daunia Apennine belonging to the official Italian geological cartography at scale of 1:50000.

Deterministic approaches have also been used to draw landslide hazard maps (Vessia *et alii*, 2013, 2017). These approaches are based on analytical expressions in which experimental measurements of physical, mechanical and hydraulic parameters as well as detailed descriptions of hydro-geomorphological characters are needed to realize hazard maps at municipal scale (1:10000) in terms of safety factor. Using this method, Cotecchia *et alii* (2009) investigated the case study of Celenza Valfortore (located in the Daunia territory), disregarding the seismic shaking component.

With regard to the seismically-induced slope instability, several Authors developed worldwide local and regional scale studies based on the calculation of permanent displacements through the simplified Newmark rigid sliding block model (e.g. Franklin & Chang, 1977; Franklin & Chang, 1977; Sarma, 1980; Ambraseys & Menu, 1988; Yegian *et alii*, 1991; Jibson *et alii*, 1998; Jibson, 1993, 2007; Ambraseys & Srbulov, 1995; Luzi & Pergalani, 1996; Romeo, 2000; Bray & Travasarou, 2007; Hsieh & Lee, 2011;Vessia *et alii*, 2013 among others). This latter is the most used deterministic approach in seismic areas to draw GIS-based maps of unstable slopes.

This study contributes to the evaluation of earthquake-induced landslide hazard at the Deliceto urban centre, located in the South-Eastern sector of Daunia Apennine. Seismically-induced landslide maps of the Deliceto centre have been drawn using the deterministic approach, following the experiences hereby outlined. Safety factors and seismic-shaking-induced-permanent displacement maps have also been drawn. The working scale of this seismic hazard study is 1:8000.

In the following, the first part of this study deals with the geological setting and hydro-geomorphologic characterization of the investigated site within Daunia. The second part examines the principal characters of the historical seismicity in Deliceto and the geotechnical properties of the lithotypes involved into the past and future landslide occurrence. The last part describes the deterministic method used in this study and, finally, a discussion about uses and applications of deterministic hazard maps to planning and civil protection purposes is presented.

GEOLOGICAL OUTLINES OF DAUNIA

Daunia is located within the North-Eastern margin of the Southern Apennines (Patacca & Scandone, 2007). It is characterized by gentle hills and low mountains, only locally exceeding 1000 m above sea level. The geological setting of Daunia is closely related to the the evolution of the Apennine fold-and-thrust belt, developed from the Late Cretaceous to Early Pleistocene at the subduction-collisional boundary between the European and the westward-subducted Adriatic-African plates (Malinverno & Ryan, 1986; Doglioni, 1991).

The Southern Apennines consist of a series of tectonically deformed turbiditic formations of pre-Pliocene age. In particular, the outer sector of this chain is made up of three tectono-stratigraphic formations related to the Daunia tectonic unit unconformably overlain by Pliocene wedge-top deposits.

The Daunia tectonic unit comprises from the top to the bottom, silty clays and grey marls of the Toppo Capuana Fm.(Tortonian-Lower Messinian) gradually passing downward to alternating calcareous and marly turbiditic deposits belonging to the Flysch di Faeto Fm. (Upper Burdigalian- Serravallian) separated by a tectonic contact from the Flysch Rosso Fm. (Cretaceous-Lower Miocene), whose outcroppings are the most widespread in Daunia Apennines. It consists of a succession of clays and polychrome claystones with calcilutites and turbiditic calcirudites (Andriani *et alii*, 2015; Pieri *et alii*, 2011).

THE CASE STUDY OF DELICETO URBAN AREA

Geological features

The study area belongs to the sheet n. 421 "Ascoli Satriano" of the Geological Map of Italy at the scale of 1:50000 (ISPRA 2011). Deliceto is located in the southeastern part of Daunia, surrounded by the Apennine chain on the West and by the Bradanic foredeep on the East, where the Daunia tectonic unit is partially covered by Lower-Middle Pliocene wedge-top deposits belonging to the Bovino Synthem (Fig. 1), composed of coarse grained sandstones and conglomerates of the Castello Schiavo unit (BVNa) and alternating silty clays and sandy intercalations of the Vallone Meridiano unit (BVNb).

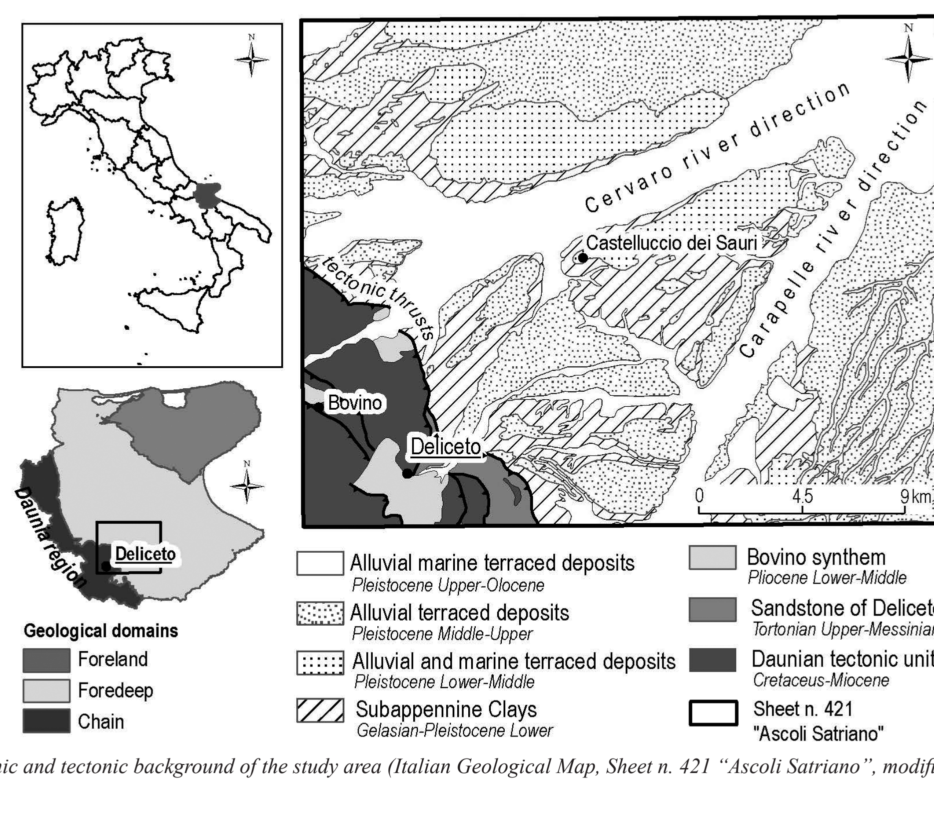

Fig. 1 - Stratigraphic and tectonic background of the study area (Italian Geological Map, Sheet n. 421 "Ascoli Satriano", modified by ISPRA 2011)

In the Deliceto area the structurally complex Flysch di Faeto Fm. (FAE) represents the geological basement of the South-Eastern sector of the Daunian chain domain. As shown in Fig. 2, FAE crops out in the Eastern portion of the Deliceto urban area, whereas it can be found at shallow depth elsewhere (about 3-5 meters under the ground level), overlain by conglomerates, sand and clay soils. Both the calcareous and clayey-marly facies of the Flysch di Faeto Fm. here crop out: the calcareous facies shows better mechanical properties than the clayey-marly and accordingly steeper slopes (Fig. 2). The slopes show a chaotic setting with steep dipping and bent layers. The facies of the rocky calcareous portion shows a color varying from white to grey, and it is interbedded by greenish marly clay layers that vary from 10 to 60 centimeters in thickness (Fig. 3). Furthermore, grain-supported conglomerates alternate with coarse-grained arenaceous deposits (BVNa) and alternate thin layers of sand and clay (BVNb) crop out respectively in the Western and in the Southern sectors of the study area. The BVNa unit is arranged in layers varying from a few decimeter to about a

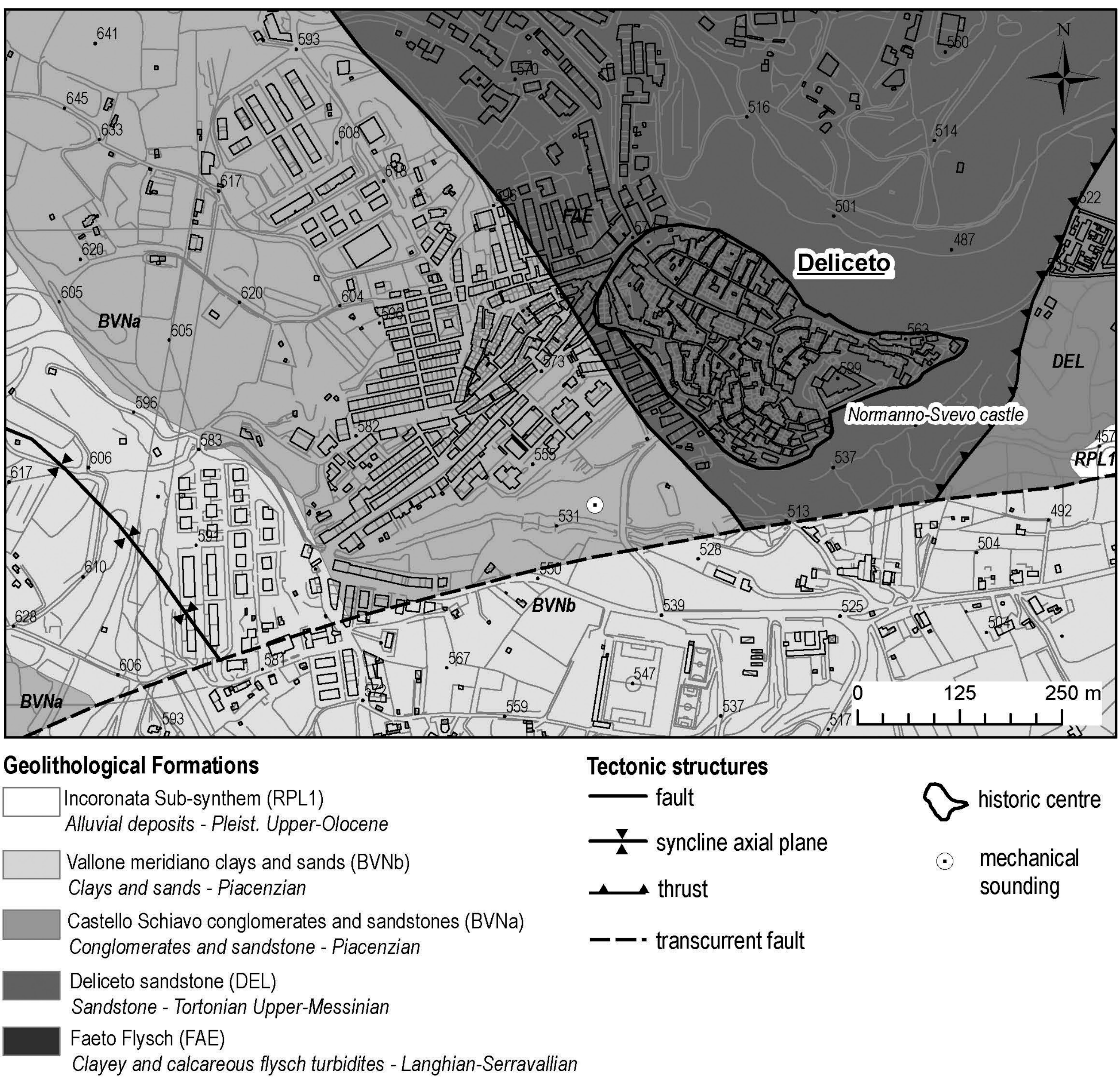

Fig. 2 - Schematic geo-lithological map of the Deliceto urban area (Geological Sheet n. 421 "Ascoli Satriano", modified after ISPRA 2011)

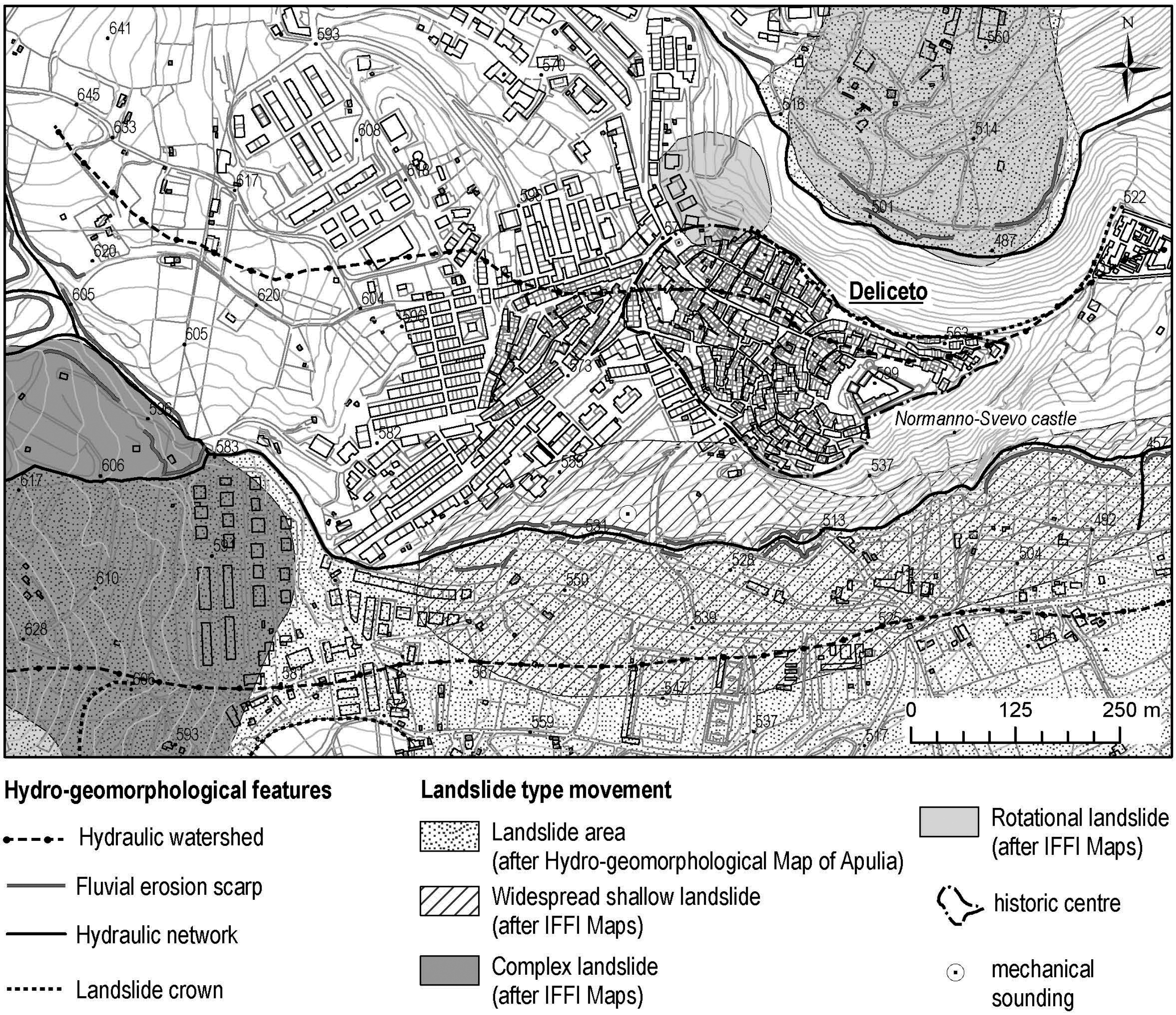

Fig. 3 - Hydrogeomorphological map of the Deliceto district (modified after Hydrogeomorphological Map of Apulia Region, www.sit.puglia.it and IFFI Maps, www.ispra.it)

meter in thickness. They are made up of calcareous and siliciclastic rounded pebbles (Fig. 4). The facies characters suggest that BVNa belongs to a transition environment dated to Pliocene (Piacentian). The BVNb unit, dated to Piacenthian, in particular is made up of silt clays interbedded with thin grey sandy layers that are strongly cemented. Their thicknesses vary from tens of centimeters to a few meters. Finally, in a small portion of the Eastern part of the study area Upper Miocene low cemented sands alternate with conglomerates and grey-white silty clay levels belonging to the Deliceto sandstones unit (DEL) are covered by alluvial deposits of the Incoronata Subsynthem (RPL1) (Fig. 2). The last consists mainly of Upper Pleistocene- Holocene sandy silty clays alternate with silty sands and lenticular sandy gravels with polygenic clasts (Ciaranfi *et alii*, 2011).

HYDROGEOMORPHOLOGICAL SKETCH

The historical center of Deliceto village is settled on a calcareous hill, ranging between 550 and 620 m a.s.l. The highest portion of this hill is located alongside an East-West watershed that crosses the new dwelling neighbourhood up to the old centre of Deliceto, where the ancient Normanno-Svevo castle was built, at a height of about 600 m (Fig. 3). Moreover, the territory of Deliceto is characterized by the presence of a widespread hydraulic network and some seasonal suspended aquifers of

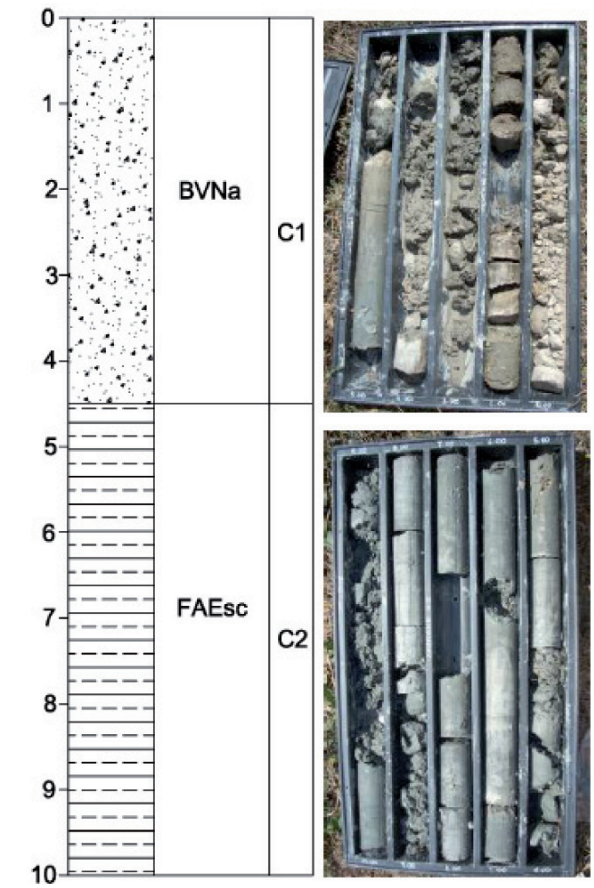

Fig. 4 - Stratigraphic sketch of the first 10 m depth at Fontanelle site in Deliceto urban area (see Fig. 2, the trace of the mechanical sounding)

limited extension confined within the first few meters depth, fed by seasonal rainfalls.

Two main channels, situated respectively in the N and in the S sides of the urban area along an approximately E-W direction, collect water from flash floods and/or rains in the autumn and winter months above all; the precipitation regime, together with local topography, soil texture and low groundwater storage capacity account for large variations in flow rate. These channels flow into a tributary of the Carapellotto creek (Fig. 4). The water system of channels represents a morphological boundary for the slopes of the Deliceto urban settlement, flowing downstream from these slopes.

The oldest part of Deliceto is set on the calcareous facies of FAE, which is tectonized and heavily fractured. Even though these carbonate rock masses can be considered relatively stable, infrequent and isolated events of collapses and toppling landslides occurred more likely in the case of rocky slopes greater than 45°. The steep slopes mostly located beneath the old town of Deliceto and range from 30° to 70°. On the contrary, low slope gradient land surfaces (less than 30%) are observable towards the existing urban area gradually giving way to the flat areas located in the South-East side of the map (Fig. 3), mainly due to the change in lithology.

The landscape of the study area is characterized by several landslides, reported in the official landslide inventory maps or IFFI maps (the Italian Inventory of Landslide; www.ispra.it) and in the hydrogeomorphological map of the Apulia Region (www.sit.puglia.it). These two maps were merged to produce the map in Fig. 3. Two principal rotational slides are evidenced in the Northern part of the urban area within the calcareous FAE. In addition, shallow landslides are shown (Fig. 3) beneath the ancient center of Deliceto. Here, the clayey-sandy facies of BVNb, involved in the sliding phenomena, crops out. In particular, widespread sliding mass movements are generated at the boundary surface between BVNb and the clayey-sandy facies of FAE. Finally, complex landslide phenomena are evidenced in the Western sector of the map within the BVNb unit. All the slope movements described above were stabilized soon after the failures by human interventions, such as slope profiling, reforestation, reinforced walls installation to minimize future reactivations triggered by both seismic events and heavy rainfalls.

SEISMIC CHARACTERS AND SEISMICALLY INDUCED LANDSLIDES

The Daunia Apennine sector is the portion of the Apulia region characterized by the compressive tectonics of the Southern portion of the Apennine chain where several large tectonic thrusts moved from North-West to South-East during the Plio-Pleistocenic ages (Dazzaro *et alii*, 1988). Daunia belongs to the highly deformed transition area between the most advanced frontal thrusts of the Apennine chain and the westernmost part of the foredeep. The instrumental and historical analysis of the seismicity suggests that Daunia, located near the South Eastern sector of the Apennine chain , is characterized by isolated seismic events of moderate-high intensity higher than 6 IMCS (Intensity scale of Mercalli-Cancani-Sieberg) and long and inactive inter-event intervals. Deliceto falls within the seismogenic zone called ZS925 as shown by the Italian Seismogenic Zonation ZS9 (Database of Individual Seismogenic Sources 3.2.0, http://diss.rm.ingv.it/) enforced by the Decree PCM n. 3274 (2003). In ZS925 the highest expected earthquake moment magnitude is 6.6 Mw. According to the historical seismicity at Deliceto, Table 1 lists eight major earthquakes felt since 1851 that caused at this site intensity $I_{MCS} \geq 6$ (DBM11 2011). Furthermore, at Deliceto the Italian seismic reference hazard map (MPS04) (NTC 2008) shows the highest PGA value in the Daunia territory, that is 0.2 g corresponding to a return period of 475 years.

In Daunia, a few documents reported ground failures induced by earthquakes. The most of these poor references refer to the strong seismic events centered in the Subapennine area like the 1456, 1805, 1930, and 1980 earthquakes, or in the Gargano foreland area, like the 1627 X–XI degree event (Del Gaudio

Intensity at the site I(MCS)	YearMonthDayHourMinute	Epicentre site	Epicentre Intensity Io	Moment Magnitude Mw
7	1851 08 14 13:20	Basilicata	10	6.38 ±0.17
6-7	1857 12 16 21:15	Basilicata	11	7.03 ±0.08
6	1910 06 07 02:04	Irpinia-Basilicata	8	5.73 ±0.09
6-7	1927 12 27 08:49	Deliceto	5-6	4.51 ±0.34
8	1930 07 23 00:08	Irpinia	10	6.62 ±0.09
6-7	1948 08 18 21:12	Northern Apulia	7-8	5.64 ±0.21
7	1962 08 21 18:19	Irpinia	9	6.13 ±0.10
7	1980 11 23 18:34	Irpinia-Basilicata	10	6.89 ±0.09

Tab. 1 - Historical seismic events that affected the Deliceto site with a seismic intensity I (MCS) ≥6 (emidius.mi.ingv.it/DBMI11/)

Index property	C1	C2	C3	C4	C5
Lithology	BVNa	FAE	FAE	FAE	FAE
Depth (m)	1.3-4.5	7.3-7.5	12.7-12.9	17.5-17.7	23.6-23.8
Lithotype (according to AGI Classification)	Gravelly silt with clay and sand	Silt with clay	Silt with marly clay	Silt with marly clay	Silt with marly clay
Natural unit weight γ_n (kN/m^3)	20.44	21.12	21.59	21.46	21.78
Water content W (%)	15.52	16.90	13.08	13.67	8.88
Saturated unit weight γ_{sat} (kN/m^3)	21.39	21.50	22.21	21.67	22.46
Void ratio e	0.58	0.47	0.28	0.37	0.30
Saturation degree S_r (%)	0.72	0.91	0.74	0.91	0.70
Liquid Limit LL (%)	-	56.45	36.45	73.6	35.6
Plastic Limit PL (%)	-	23.02	17.87	21.76	18.17
Plasticity Index PI	-	33.43	18.58	51.84	17.43
Consistency Index IC	-	1.18	1.25	1.15	1.47

Tab. 2 - Index properties and Atterberg limits of FAE and BVNa performed on five samples along the S1 borehole

et alii, 2009 and references herein). Del Gaudio *et alii* (2012) applied to an area of Daunia, belonging to the sheet n.407 "San Bartolomeo in Galdo" of the New Italian Geological Map (1:50000 scale) a procedure for the assessment of seismic hazard impact on slope stability adopting Arias intensity (I_a) as seismic shaking parameter and critical acceleration, a_c, as parameter representing slope resistance to failures to seismic shaking.

Deliceto is located nearby the preceding two centers (a few kilometers from each of them) and likely involved into those types of earthquake-induced phenomena, such as earthflows and sliding mechanisms. Nonetheless, the wet conditions when Irpinia earthquake occurred might have contributed to the seasonal reactivation of the instability phenomena that are described in Hydrogeomorphological Sketch section.

MECHANICAL PROPERTIES OF THE OUTCROPPING UNITS

The geological formations cropping out at Deliceto urban area are grouped into five litho-technical units as shown in Table 4. They were characterized by their unit weights, friction angles and effective cohesions to perform GIS-based static and dynamic stability analyses. In addition, Tables 2, 3 and 4 show index properties and mechanical parameters of the lithotechnical units met along the borehole S1 placed at the South of the urban center (Fig. 2, mechanical sounding). The listed values are directly measured by the writing authors at Deliceto through 4 Atterberg limits, 5 index properties, 3 direct shear tests, 4 triaxial cyclic tests, 4 torsional cyclic tests and geomechanical relieves. At this site, FAE is the commonest geological unit, that can be met both on the surface and in depth. It is characterized by two lithological facies corresponding to two different geomechanical behavior: the rocky calcareous FAErc and the silty-clayey one FAEsc. This latter shows a marly facies from 12 up to 24 m depth. The FAE rocky calcareous facies crops out diffusely whereas its clayey facies can be found at shallow depth, at about 5 meter, under DEL, BVNa and BVNb surficial deposits. Due to its structural complexity and heterogeneity the FAE unit shows variable physical and mechanical properties even at short distance. Nevertheless, both the rocky and the silty-clayey facies are involved in shallow landslides. Field evidences show toppling and fall kinetics for the rocky facies and sliding movements within the silty-clayey one. Some index properties of FAEsc and BVNa were measured through five samples taken from the continuous coring of 30 meter depth (Tab. 3): C1 sample is representative of BVNa from 2 to 5 meter depth; at depths greater than 5 meter FAEsc is sampled (C2-C5). The silty-clayey facies is constantly wet due to the autumn and winter rainfall regimes combined with the intense fissuring. It is confirmed by the values of the natural and saturated unit weights of C2 sample and its water content. This unit shows the plasticity index varying from 18 to 52 (C2-C5). The plastic behaviour of the FAEsc is confirmed by an X-ray diffractometric analysis performed on 3 samples from the S1 borehole at depths between 6 and 10 meters. These analyses show the presence of illite and vermiculite minerals that provide with the plastic behaviour of the clayey fraction.

Furthermore, shear tests were performed on four specimens cut from undisturbed samples. The measures of friction angles and effective cohesions show that BVNa can be described as a silty-gravelly soil with clay and sands, characterized by a $\phi'_{peak} = 30°$ and $c' = 17$ kN/m^2. Conversely, FAEsc investigated through C2, C3 and C5 samples show increasing mechanical strength values with depth passing from silty-clayey to marly-clayey. No critical state values for ϕ and c' were measured for the purpose of this study. In fact, the stability analyses based on permanent displacement calculations were carried out on stable soils where seismic events are supposed to trigger mass movements along new sliding surfaces (no reactivated landslides are considered).

Specimen	Friction angle φ'_p (°)	Effective Cohesion c'_p (kPa)
C1	30	17
C2	25	25
C3	38	75
C5	35	133

Tab. 3 - Simple shear tests performed on four specimens from undisturbed samples

	Lithotechnical units	γ_n (kN/m^3)	γ_{sat} (kN/m^3)	ϕ'_p (°)	c'_p (kPa)
	FAErc - rocky calcareous	21	22	25	200
FAE	FAEsc - silty clay	21	22	25	75
	FAEmc – silty marly clay	22	22	38	133
BVNa	Sandstone and conglomerates	20	21	30	17
BVN_b	Clays and sands	19	20	23	20
DEL	Sandstones	20	21	28	50
RPL1	Alluvial deposits	18	19	30	0

Tab. 4 - Physical and mechanical properties of the lithotechnical units detected at Deliceto

According to the authors knowledge no dynamic laboratory tests were performed on FAEsc by past studies in the Daunia area and especially at Deliceto. These tests can be useful to investigate the elastic threshold of the shear strain γ_e of FAEsc under a cyclic loading induced by an earthquake. This knowledge is needed to assess the seismic degradation of FAEsc shear strength depending on its plasticity index. Accordingly, Fig. 5 shows four cyclic triaxial and torsional tests were performed to undertake a dynamic characterization of FAEsc. Two reconstituted and two undisturbed specimens were tested in order to investigate the influence of the inherent heterogeneity of this soil unit on the γ_e. As shown in Fig. 5a, γ_e is 10^{-3} for the reconstituted specimens and 10^{-2} for the undisturbed ones; thus, the undisturbed soil shows a larger elastic field of behavior than the reconstituted one. Furthermore, form the same plot, it is worth noticing that the degradation curves of the reconstituted specimens fall within the ones of the undisturbed soils. This is also true for damping curves. Fig. 5b shows the curves of C1* that is used as representative of cyclic response of FAEsc on average (linear and volumetric thresholds of shear strains are evidenced on the top of the plot).

The assessment of the FAErc strength properties were addressed through the Bieniawski rock mass classification (1976) based on the Rock Mass Rating (RMR) index. The RMR is evaluated on the basis of in field geostructural and geomechanical measurements and the strengths parameters in terms of friction angle and cohesion (Tab. 4). Samples of BVNb, DEL and RPL1 were taken from the outcrops, and laboratory classification and simple shear tests were carried out to obtain index properties and strength parameters as summarized in Table 4.

STABILITY ANALYSIS AND PERMANENT DISPLACEMENT MAPS AT DELICETO

The present study aims to calculate the static and dynamic slope stability of the hilly territory of the Deliceto urban area. To achieve this goal, two variables were calculated according to a deterministic approach:

- the Safety factor Fs of slopes that allows to assess slope stability under dry and wet conditions. This factor is obtained by applying the limit equilibrium method and calculating Fs as the ratio between resistance and acting forces;
- permanent displacements induced by seismic load calculated through the simplified method of Newmark's rigid sliding block.

Stabilization interventions were undertaken on all the landslides outlined by IFFI project in Fig. 3. The authors reconstructed a 5 meter DTM through the following steps: (1) the topographic map at 1:5000 edited by the Apulia Regional Territorial Office has been used; (2) then, a DTM has been drawn from the 3D analyst GIS tool (ARCMAP™, 2010). Furthermore, an on site geomorphological survey enabled the authors to take into account the stabilization interventions performed on unstable areas when calculating the safety factors and the permanent displacements maps. Finally the stability analyses assume that a planar infinite sliding mechanism can be activated along the slopes belonging to the area evidenced by Fig. 6 and Fig. 7 according to the equation:

$$Fs = \frac{c' + d[\gamma_{sat} - r_u \gamma_w] cos^2(\alpha) \tan(\varphi')}{\gamma_{sat} d \sin\alpha \cos\alpha} \qquad (1)$$

where *c'* is the effective cohesion, *d* is the vertical depth of the sliding surface, γ_{sat} is the saturated unit weight, γ_w is the water unit weight, α is the inclination of the slope, ϕ' is the effective friction angle and r_u is the ratio between the height of the water table, starting from the sliding surface, and the thickness of the unstable material. This ratio ranges between 0 and 1: 0 means that the water table is below the sliding surface whereas 1 means that water level corresponds to the maximum level of the unstable material, meaning that the material is completely submerged. In GIS-based analyses, physical, hydraulic and mechanical properties (shown in Tab. 4) were assigned to all the lithotypes whereas the inclinations of slopes were drawn from DTM. Accordingly, different thematic raster maps have been drawn from the geological shape file polygons: the internal friction angle, the water table depth and the cohesion. The inclination raster map has been directly derived from the DTM grid.

Moreover, Table 5 shows the input values of the parameters

Soil unit	Sliding surface depth (m)	r_u	γ_n (kN/m³) for dry conditions	γ_{sat} (kN/m³) for wet conditions	Soil strength along sliding surfaces	
					ϕ'_p (°)	c'_p (kPa)
FAErc	40	0	21	22	25	200
BVNa	5	0.8	20	21	25	75
BVN_b	5	0.8	19	20	23	20
DEL	5	0.6	20	21	25	75
RPL1	2	0.5	18	19	30	0

Tab. 5 - Input values for GIS-based permanent displacement calculations under dry and wet conditions

needed within Eqs. 1-2. In the present analyses, the sliding surfaces are assumed at the stratigraphic boundary between two different lithotypes, e.g, BVNb and FAEsc, BVNa and FAEsc, RPL1 and DEL. The corresponding shear strength of the sliding surface is assumed to be the peak effective values of the friction angles and cohesion related to the weakest soil layer. Accordingly, FAErc that doesn't slide is assumed to have a very deep sliding surface. On the contrary, BVNb moves at 5 meters depth alongside the stratigraphic boundary with FAEsc with its shear strength properties. BVNa is supposed to slide at depth of 5 meters where is set the boundary with FAEsc but the sliding surface strength properties are those of FAEsc, that is the weakest soil layer. This assumption is based on the past experiences on 1980 Irpinia earthquake induced slope instability (Del Gaudio *et alii*, 2012; Vessia *et alii*, 2017 and the references herein) where planar sliding movements were the commonest mechanisms in clayey soils. In Deliceto urban area, the landslide inventory related to rainfall induced landslides (reported in Fig. 3) shows a large portion of complex and shallow landslides and a limited small extension of rotational landslides. It is worthy

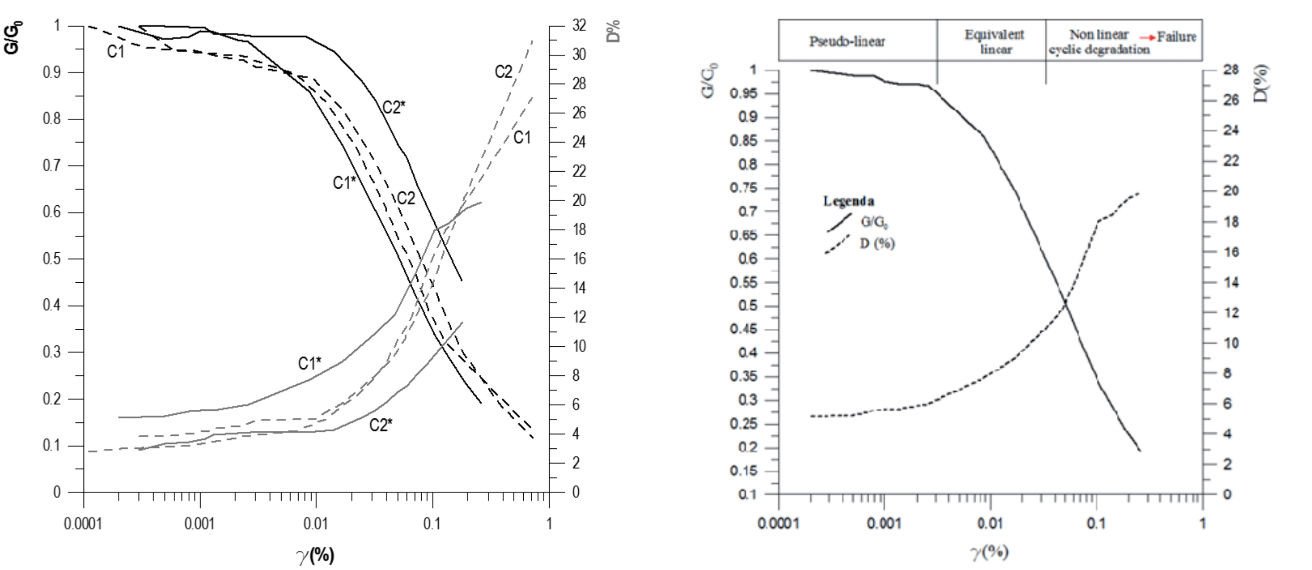

Fig. 5 - Shear modulus degradation curve and damping ratio curve measured by cyclic torsional shear tests: a) on two reconstituted (C1 and C2) and two undisturbed specimens (C1 and C2*); b) on C1* undisturbed specimen sampled at depth of 5.0 m from the ground level*

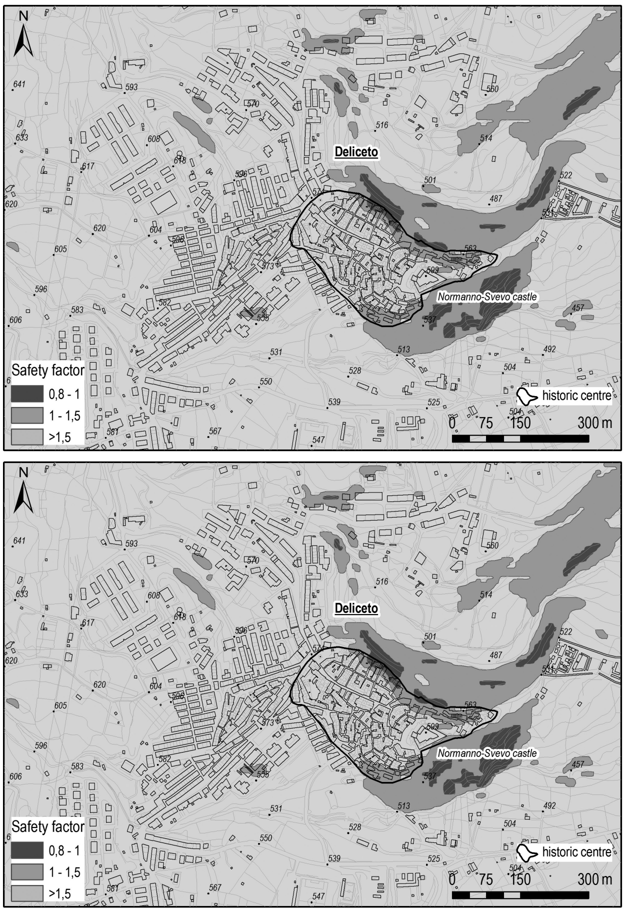

Fig. 6 - Safety factor maps: a) dry soil conditions; b) wet soil conditions

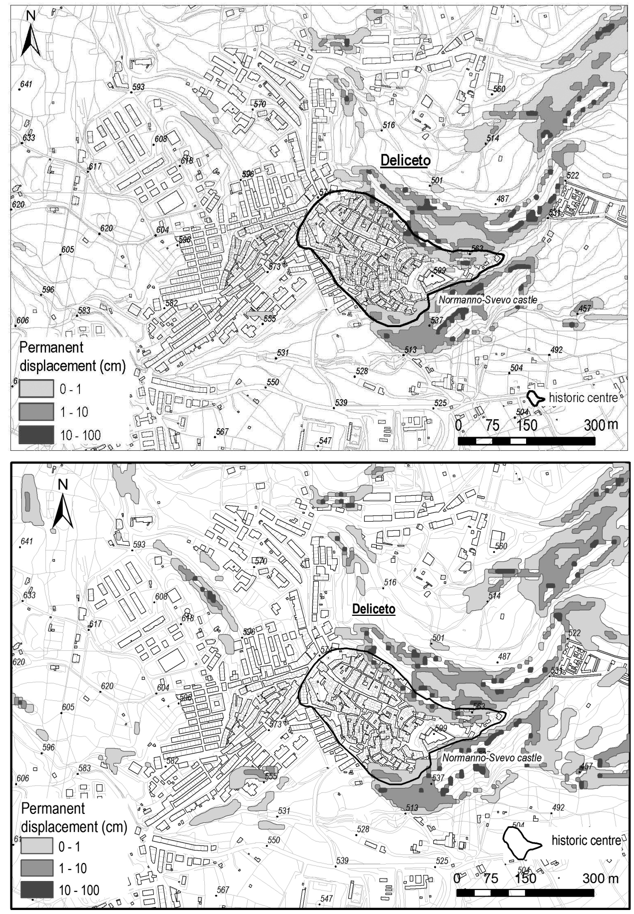

Fig. 7 - Permanent displacement maps: a) dry soil conditions; b) wet soil conditions

to be noted that seismic-induced landslides occur alongside commonly planar surfaces that have been weakened by both the water table oscillation and litho-stratigraphic discontinuities. In this case study, the groundwater system is made up of seasonal water storage that are placed in BVN units acting as aquifers overlying the FAEsc acting as aquiclude (Fig. 4). In this lithological setting, at Deliceto urban area, the lithological contact between BVNa and FAEsc is likely to be involved in seismically induced mass movements. The depth of this boundary varies between 3 and 5 m. The occurrence of sliding movements at between 3-5 m depth has been also numerically checked by Diprizio (2017).

Two Safety Factor maps were calculated and shown in Fig. 6a and 6b: they are related to dry and wet conditions to encompass the two representative conditions of the soil water content in summer and winter season. The depths of the sliding surfaces were assigned according to the values shown in Table 5: for FAErc, 40 m depth means that it is stable with respect to the sliding movements; FAEsc is placed at the sliding interface of BVNa and BVNb.

It is worth noticing that the two maps are not that different. The steep slopes are not affected by wet conditions because they are mainly made up of FAErc. On the other hand, the gentle slopes, affected by wet conditions, are not prone to slide. Therefore, from these maps based on the safety factors, one can point out that the areas affected by widespread and shallow landslides are generally stable, with a safety factor higher than 1.5.

The evaluation of permanent displacements induced by seismic events is then accomplished in the stable under static loading areas. This means that, provided with the safety factor maps, the permanent displacements were calculated starting from the evaluation of the critical acceleration of the study area through the following expression:

$$a_c(g) = \frac{(Fs-1)\tan\alpha}{1+\tan(\alpha)\tan(\varphi')}g \qquad (2)$$

where a_c is the critical acceleration calculated according to a pseudo-static approach, *Fs* is the static safety factor, α is the slope inclination, φ' is the friction angle of the sliding rigid block and *g* is the gravity acceleration. In this approach, the contribution to permanent displacements is obtained for those areas manifesting a safety factor above 1 (Fs>1.0). In order to calculate the permanent displacements, the Ambraseys & Menu (1988) equation was used:

$$\log(s) = C_{1b} + B_{1b} log\frac{a_c}{a_{max}} + A_{1b}\log\left(1 - \frac{a_c}{a_{max}}\right) \quad (3)$$

where a_c and a_{max} are the critical and maximum acceleration respectively, A_{1b}, B_{1b} e C_{1b} are the regression coefficients suggested by Jibson (2007).

In this study, as previously mentioned, the maximum acceleration is assumed to be equal to 0.2 g. Figs. 7a and 7b show the permanent displacement maps calculated for the case of dry and wet soil conditions.

From these maps, the strict relationship between slope inclinations and induced permanent displacements D is pointed out. However, large movements (D≥10 cm) are not too wide and seem to have an almost point character whereas movements of 1≤D≤10 cm involve larger areas within the FAEsc.

DISCUSSION AND CONCLUSIONS

The results of the deterministic study discussed above can be fruitfully compared with those of landslide hazard maps as defined by the Italian Law n. 100/2012 as planning tool within the Deliceto municipal territory. To this end, the IFFI and Hydrogeological maps of Apulia that were joined in Fig. 3 at the Deliceto urban area, were overlain by the static safety factor and the permanent displacement maps drawn in Figs. 8a and 8b. For this comparison, only wet soil conditions are used, in order to obtain the "worst case" maps. Starting from Figs. 8a,b, some useful advices can be proposed to improve the landslide stability maps of this area. Fig. 8a shows Fs values much higher than 1.3 inside the areas that can be considered as prone to be reactivated. In addition, the old landslides are stable under static loading, whereas areas close or made up of FAErc show a coefficient Fs<1. This condition is met especially where the slopes are steeper. These locations, of a rather limited size, must be monitored by the local authorities. Furthermore, Fig. 8b shows the seismic stability of the Deliceto urban area under the expected maximum peak ground acceleration of 0.2 g in wet soil conditions. In this case, the old mapped landslides show to be affected by small permanent displacements, ranging from 1 to 10 cm for limited portions falling within the perimeter of the landslide polygons. Conversely, the steep slopes located around the highest sector of the old town center show points that can suffer metric permanent displacements. In order to read the calculated permanent displacements in terms of the expected damage that are likely to cause, in Table 6 three different empirical scale of damage according to the international collected experiences are reported. As can be noted, earthquake-induced permanent displacements of slopes equal to 10 cm is always associated to restoring or limited damage, whereas a value of 10^2 cm is associated with severe damage that can cause structural failures in buildings and roads.

Damage scale	Legg & Slosson (1984) D (cm)	Idriss (1985) D (cm)	Silvestri *et alii* (2005) Damage scale	Silvestri *et alii* (2005) D (cm)
No damage	<0.5	<3	No damage	<2
Weak	0.5-5	15	Restoring	2-10
Strong	5-50	30	Out of order	10-50
Severe	50-500	90	Collapse	>50
Catastrofic	>500	300		

Tab. 6 - Empirical damage scales associated with GIS-based permanent displacements

Thus, the maps drawn in the present study can be a useful aid to local authorities when dealing with decisions concerning landslide monitoring activities, which are not only time consuming but also expensive. Finally, from the preceding discussion, one can assess that the deterministic approach to static and seismic hazard maps, especially at municipal scale, should be considered a compulsory support to planning activities. This approach can also be used to plan territorial monitoring activities needed to draft evacuation plans and to improve the safety of new building projects. To this end, dense investigation campaigns to perform in field and laboratory physical and mechanical characterizations are needed especially for gaining representative values of soil properties in structural complex and heterogeneous geological units, such as the Flysch di Faeto Fm.

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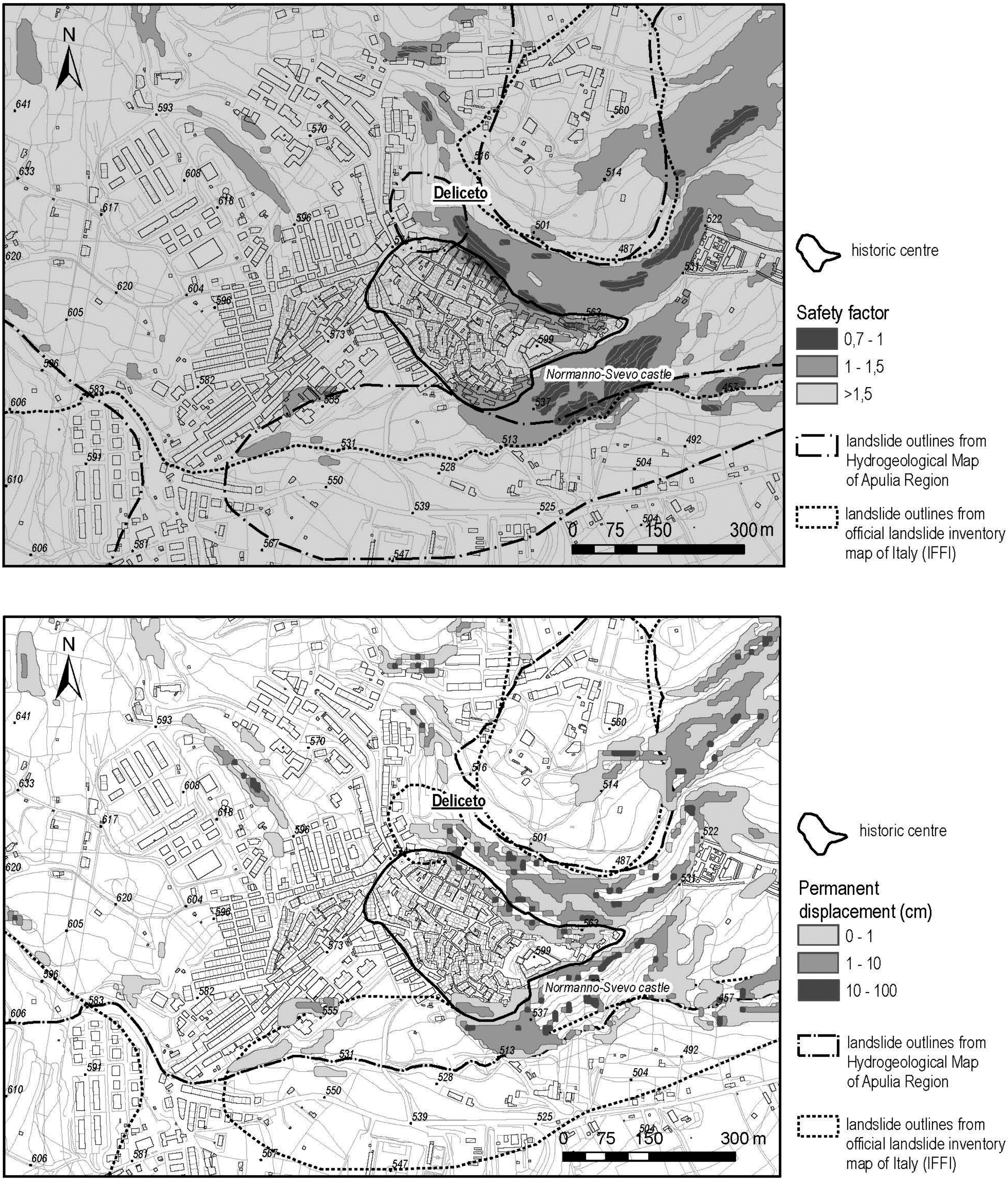

Fig. 8 - Contours of IFFI and Hydrogeomorphological landslide inventory within the Deliceto urban territory: a) static safety factor map related to wet soil conditions; b) permanent displacement map related to wet soil conditions

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