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AN INTEGRATED APPROACH TO ELABORATE 3-D GEOLOGICAL AND GEOTECHNICAL MODELS: A CASE STUDY FROM THE DAUNIA SUB-APENNINE (APULIA, SOUTHERN ITALY)

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EXTENDED ABSTRACT

Il Subappennino Dauno è un'area geografica situata nel settore a NW della Puglia (Italia sud-orientale) e rappresenta le propaggini più orientali dell'Appennino meridionale. Dal punto di vista geologico, esso è costituito da formazioni strutturalmente complesse, eterogenee ed intensamente tettonizzate (*flysch*). L'intero territorio è fortemente propenso al dissesto da frana, condizione che si verifica soprattutto in concomitanza di piogge intense e di eventi sismici, ma anche in connessione a pratiche agricole e altre attività antropiche. Il Subappennino Dauno è sismicamente attivo, essendo stato storicamente interessato da terremoti distruttivi, con effetti fino al X grado MCS. L'instabilità sismo-indotta dei versanti rappresenta, quindi, una concreta problematica di questo territorio, con eventi franosi distruttivi caratterizzati da una marcata eterogeneità dei cinematismi di collasso: frane superficiali, colate, frane complesse, frane coalescenti e scivolamenti roto-traslazionali con frequente dinamica retrogressiva.

Lo studio dei fenomeni franosi sismo-indotti è molto complesso e per le analisi di stabilità vengono, generalmente, adoperati metodi dinamici, attraverso approcci semplificati o avanzati, lasciando spazio all'uso di metodi pseudo-statici solo nei casi in cui i caratteri morfologici, il modello geologico di sito e il modello geotecnico corrispondente risultano poco articolati.

In questo lavoro viene proposto un approccio integrato per l'elaborazione di modelli geologici e geotecnici di dettaglio di un'area campione del Subappennino Dauno, situata tra i comuni di Bovino e Rocchetta Sant'Antonio. L'area costituisce la porzione Sud delle propaggini orientali del Subappennino Dauno, dove affiorano le unità geologiche più esterne del dominio della catena appenninica, rappresentate dalle unità tettoniche cretacico-mioceniche e da quelle plioceniche, le cosiddette wedge-top units, cui seguono verso l'alto, nella zona più ad Est, le unità plio-pleistoceniche di avanfossa ed i depositi quaternari di origine continentale. Ne consegue la necessità di elaborare modelli geologici e geotecnici di dettaglio, rappresentativi anche di porzioni di territorio piuttosto limitate (<1 km^2), indispensabili per la scelta del metodo di analisi di stabilità dei versanti.

A titolo di esempio, in questo lavoro viene presentato un caso di studio nei dintorni di Deliceto, per il quale il modello geologico in 3-D, costituito da materiali arenacei limoso-argillosi di superficie (Conglomerati ed Arenarie di Castello Schiavo) poggianti su limi argillosi e marne di origine torbiditica in facies di flysch (*Flysch* di Faeto), è stato ottenuto a seguito di rilievi geologici e geomorfologici in situ, di dati di perforazioni a carotaggio continuo e di correlazioni stratigrafiche tra sezioni geologiche bidimensionali. Una serie di prove di laboratorio geotecnico ha consentito di ricavare un modello geotecnico 3-D di dettaglio, infatti oltre alla parametrizzazione fisica e alla classificazione di queste unità, sono state eseguite prove di taglio diretto (CD), di colonna risonante (RC), di taglio torsionale ciclico (CTS) e triassiali standard e cicliche (TXC).

In particolare, la parametrizzazione dinamica ha riguardato solo l'unità geotecnica limoso argillosa del Flysch di Faeto, in quanto costituita da materiali fortemente suscettibili a fatica geotecnica, conseguente a sollecitazioni cicliche e sede delle superfici potenziali di rottura più profonde. Le prove CTS hanno consentito di valutare la risposta dei terreni in termini di modulo di taglio (G) e di rapporto di smorzamento (D) per livelli deformativi torsionali medio-bassi (da 10^{-4} % a 10^{-1} %), mentre le prove TXC sono state utilizzate per caratterizzare in campo dinamico il comportamento tenso-deformativo dei materiali ad alti livelli di deformazione assiale (fino al 20%), determinare la resistenza ultima in campo dinamico e analizzare il comportamento post-ciclico. Entrambi i test sono stati effettuati in condizioni di drenaggio impedito, così come accade in natura a terreni saturi sottoposti a sollecitazioni cicliche indotte da un terremoto, adottando una frequenza di sollecitazione simile a quella sismica locale.

Le curve parametriche relative ai campioni indisturbati e poco disturbati non hanno mostrato differenze sostanziali, sebbene queste aumentino all'aumentare del livello di deformazione. Infatti, per i campioni indisturbati e per quelli poco disturbati è stato rilevato rispettivamente un incremento del rapporto di smorzamento (D) tra 2.9% e 19.9% e tra 2.8% e 22.9% nonché un decremento del modulo di taglio (G) mediamente pari a 77.3% e 83.9%. Infine, il comportamento post-ciclico, espresso in termini di coesione non drenata (c_u), è stato caratterizzato da un decremento compreso nell'intervallo 21.9%-24.8% e 23.9%-36.1% rispettivamente per i campioni indisturbati e poco disturbati.

ABSTRACT

In the Daunia Sub-Apennine (Apulia, southern Italy) slope instability processes due to rainfalls and earthquakes are widespread and cause significant damage to buildings and other structures, and, in some cases, loss of life. A detailed slope stability assessment requires information on the predisposing and triggering factors, and a good knowledge of the geological and environmental conditions as well. As concerns seismic-induced landslides, conventional methods used for slope stability analysis can be divided in: i) force-based pseudo-static methods, ii) displacement-based methods, and iii) stress-strain methods. Detailed representations of geological and geotechnical units as well as static and dynamic geotechnical characterization of materials have to be considered for the correct choice of the method for slope stability analysis, since these are fundamental for slope behaviour prediction and modelling.

The purpose of this paper was to present a methodological approach for elaborating detailed 3-D geological and geotechnical models for areas very heterogeneous in terms of geological and soil properties. In the southern portion of the eastern Daunia Sub-Apennine, the outermost formations of the chain domain crop out. These are represented by the Cretaceous-Miocene and Pliocene wedge-top basin units, followed upwards, in the easternmost portion, by the Plio-Pleistocene foredeep units and by Quaternary filling deposits. A high susceptibility to slope failures for the area is testified by the large number of slope movements consisting in mud flows, roto-translational and composite landslides, and soil slips. Field variability of the slope movements from site to site for mechanisms, velocity, depth of rupture surfaces and volume of materials involved is due to the presence of structurally complex formations, characterised by very poor mechanical properties and high variability of their lithological and structural features. The construction of geological and geotechnical models able to represent realistic information is conditioned by the efficacy of the methods used for assessing the spatial lithofacies distribution and parametrization.

The case study of Deliceto is here presented, where the 3-D geological model was built based on the results of stratigraphic correlations between core logs and 2-D geological sections. In-situ surveys were performed by means of classical geological and geomorphological methods, and continuous coring boreholes. Silty-clayey sandstone materials (Conglomerates and Sandstones of Castello Schiavo) crop out along the slopes and rest on clayey silts and marls of turbidite origin (Flysch di Faeto). The Flysch di Faeto Fm. is a structurally complex geological unit which consists of three main lithofacies: 1) silty clays; 2) silty marly clays 3) marls and shales. A series of geotechnical laboratory tests, carried out in accordance with international standards for the static and dynamic characterization of materials, made it possible to obtain a detailed 3-D geotechnical model. In particular, resonant column (RC), cyclic torsional shear (CTS) and standard and cyclic triaxial (TXC) tests were performed on the silty clayey geotechnical unit of the Flysch di Faeto Fm., because it is highly susceptible to geotechnical fatigue resulting from cyclic stresses. The results of the laboratory tests confirmed a variable post-cyclic degradation in the range 40-80% and 12-36%, respectively for the secant shear modulus (G) and the undrained cohesion (cu) associated with an increase between 2.92% and 19.90% for the damping ratio (D), demonstrating the heterogeneity of the material in terms of geological and geotechnical characteristics.

Keywords: *Daunia Sub-Apennine, landslide, geological model, geotechnical parametrization, dynamic cyclic test*

INTRODUCTION

The Daunia Sub-Apennine (Apulia, southern Italy) is geologically made up of highly tectonized flysch units, intensely affected by a variety of landslide types that occur, in most cases, on a seasonal basis, mainly in relation to intense rainfall and/or man-made activities, and, subordinately, to seismic events. Many efforts have been carried out in recent years toward identification of rainfall thresholds for triggering shallow landsliding in Daunia (Vennari *et alii*, 2013; Loiacono *et alii*, 2014), following an approach applied also to the whole Italian territory (Rossi *et alii*, 2012; Brunetti *et alii*, 2014). The role of land use changes in the development of shallow landslides in Daunia, with particular reference to implementation of peculiar agricultural practices, has also been the object of several contributions (Wasowski *et alii*, 2010; Pisano *et alii*, 2017). Apart from rainfall and man-made actions, however, the Daunia Sub-Apennine is definitely affected by diffuse seismicity, also in relation to activities of nearby seismo-genetic areas such as the Southern Apennines to the west, and the Gargano Promontory to the east (INGV, 2015), and therefore it is worth to be studied as concerns the relationships existing between earthquakes as triggering factors and the observed landsliding processes. From landslide inventory at the regional scale, it is apparent that about 90% of the gravitational instability phenomena registered in Apulia are concentrated in the Daunia Sub-Apennines (Parise, 2003; Trigila *et alii*, 2013; Zumpano *et alii*, 2020). This is strictly related to presence in this area of structurally complex formations (Esu, 1977; Calcaterra *et alii*, 2008), showing physical-mechanical properties highly prone to development of landslide processes, both as first-time slides and re-activations of older phenomena.

The most common slope failure mechanisms belong to the categories of shallow landslides and flow-type phenomena such as soil slips, soil slumps and mudflows (Iovine *et alii*, 1996; Parise *et alii*, 2012). In particular, flow-type movements cause serious and recurrent damage to the road network and to other infrastructures as well, strongly contributing to depopulation of the towns in Daunia and the surrounding territories (Chiocchio *et alii*, 1997; Iovine & Parise, 2002; Pisano *et alii*, 2016; Zumpano *et alii*, 2018; De Caro *et alii*, 2020). According to the Cruden & Varnes classification (1996) these movements can be described as typically having moderate velocity (5 10^{-6}- $5 \cdot 10^{-4}$ m/s); nevertheless, on the occasion of the most significant rainstorm, phases of acceleration may be recorded, leading to high velocity (> 1.8 m/hr), generally confined into pre-existing channels, but also occurring on open slopes. Multi-source mudslides and complex rotational slumps evolving into flows are very frequent, and often represent the largest and longest phenomena (Parise *et alii*, 2012). They are closely related to presence at the outcrop of extensive clayey and silty clayey deposits, and show wide extent (from some to hundreds of square kilometers) in relation to their depth. Typically, they present multi-level differential deformation within the moving material, with possibility of rapid evolution of the morphological features during the instability processes (according to the model presented for flow-like phenomena by Fleming & Johnson, 1989). Another type of slope failure regards the rotational failures in stiff clays, especially in the easternmost part of Daunia (Amorosi *et alii*, 2003; Santaloia *et alii*, 2004; Cotecchia *et alii*, 2015).

In complex geological settings affected by gravitational instability, scientific studies and in situ evidences suggest that the landslide susceptibility assessment is problematic and require the adoption and use of multi-disciplinary approaches, ideally involving remote sensing techniques, geological, geomorphological and geotechnical in situ surveys, statistical data analysis, GIS-supported spatial analysis and physically-based modeling (Cotecchia *et alii*, 2009, 2010; Calò *et alii*, 2012; Del Gaudio *et alii*, 2012; Trigila *et alii*, 2013; Pellicani *et alii*, 2014; Andriani *et alii*, 2015; Di Martire *et alii*, 2017; Diprizio *et alii*, 2017; Guerriero *et alii*, 2019; Sepe *et alii*, 2019; Wasowski & Pisano, 2020). The landslide mechanisms, in fact, are variable in relation to the boundary conditions and complex interplay between internal and external factors, as earlier defined by Terzaghi (1950).

During the twentieth century, several methods for assessing the stability of slopes during earthquakes were developed (Jibson *et alii*, 1998; Parise & Jibson, 2000; Jibson, 2011 and references therein). They can be grouped into three categories, respectively based on: i) force-based pseudo-static analysis, ii) displacement-based analysis, and iii) stress-strain analysis. In particular, displacement-based analysis leads to an accurate estimate of slope displacements by modeling the dynamic response of landslide-prone slopes to seismic shaking in a more rigorous way (Jibson, 2007; Vessia *et alii*, 2013, 2017). By means of this more sophisticated analysis permanent co-seismic landslide displacements can be evaluated according to three methods: i) rigid-block, ii) decoupled, and iii) coupled.

Generally, dynamic methods are mostly used in complex geological settings, giving way for the use of pseudo-static methods only in cases in which ground models, in terms of morphological, geological and geotechnical features, are not very articulated, and the soils involved are not simultaneously affected by significant increases of interstitial pressures and significant decreases of shear strength in response to cyclic stresses. The reliability of the methods used, whether pseudo-static or dynamic, therefore remains strongly conditioned by the evaluation of the seismic actions, respectively expressed in terms of seismic coefficient and design accelerogram, and the elaboration of detailed geological and geotechnical models supported by field and laboratory data.

In this paper, we present a methodological approach for elaborating detailed 3-D geological and geotechnical models for areas very heterogeneous in terms of geological and soil properties. The southern portion of the eastern Daunia Sub-Apennine was selected because it is characterized by complex tectonic setting, articulated stratigraphic sequence, diffuse seismicity and high susceptibility to different types of slope failures. In particular, we refer to a case study in the surroundings of Deliceto in order to validate the approach proposed. The 3-D geological and geotechnical models were built based on topographic data, in-situ surveys, borehole stratigraphy, integrated by the results of soil tests, carried out in accordance with the international standards for the static and dynamic characterization of soils.

GEOLOGY, GEOMORPHOLOGY AND SEISMICITY

The Daunia Sub-Apennine is characterized by hilly landscapes, rarely above 1,000 m a.s.l., and present a geological setting which may be described as a duplex system of Mesozoic-Tertiary carbonates, overlain by a thick pile of platform- and basin-derived rootlet nappes (Dazzaro *et alii*, 1988; Scandone *et alii*, 2003 and references therein).

In particular, the outer sector of the Southern Apennines is made up of the Daunia tectonic unit formations of pre-Pliocene age, unconformably overlain by Pliocene wedge-top deposits. The Daunia tectonic unit comprises, from the bottom to the top, reddish thin-bedded clays and silts, interbedded with black bituminous layers, yellow cherts, calcarenites and calcilutites of the Flysch Rosso Fm. (Cretaceous–Early Burdigalian), conformably overlain by the Flysch di Faeto Fm. (Langhian–Serravallian), consisting of beds and banks of calcarenites, calcirudites, calcilutites, calcareous marls and marly clays, in turn conformably overlain by thick-bedded, dark gray, marls and marly clay of the Toppo Capuana Fm. (Late Tortonian–Early Messinian) (Spalluto *et alii*, 2021, and references therein).

In the study area, 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).

The instrumental and historical analysis of the seismicity suggests that Daunia, together with South-Eastern Molise, is characterized by isolated seismic events of moderate-high intensity, higher than 6 IMCS (Intensity scale of Mercalli-Cancani-Sieberg), and by long and inactive inter-event intervals. In particular, the town of Deliceto falls within the seismogenetic zone ZS925, as shown by the Italian Seismogenic Zonation ZS9, where the highest expected earthquake moment magnitude is 6.6 M_w (INGV, 2015).

METHODOLOGY

Within the area of interest, we elaborated 3-D geological and geotechnical models for a small study site (<1 km^2) in the surroundings of the town of Deliceto. The study site belongs to the southern portion of the eastern Daunia Sub-Apennine, highly heterogeneous in terms of geological and soil properties and characterized by a complex tectonic setting. These features determine a great variability of landslide types, due to complex interrelationships between predisposing and triggering factors, and to boundary conditions as well. In particular, we focused on a slope, located south of the inhabited center at Vico Fontanelle locality, highly prone to landslides, potentially triggered by both

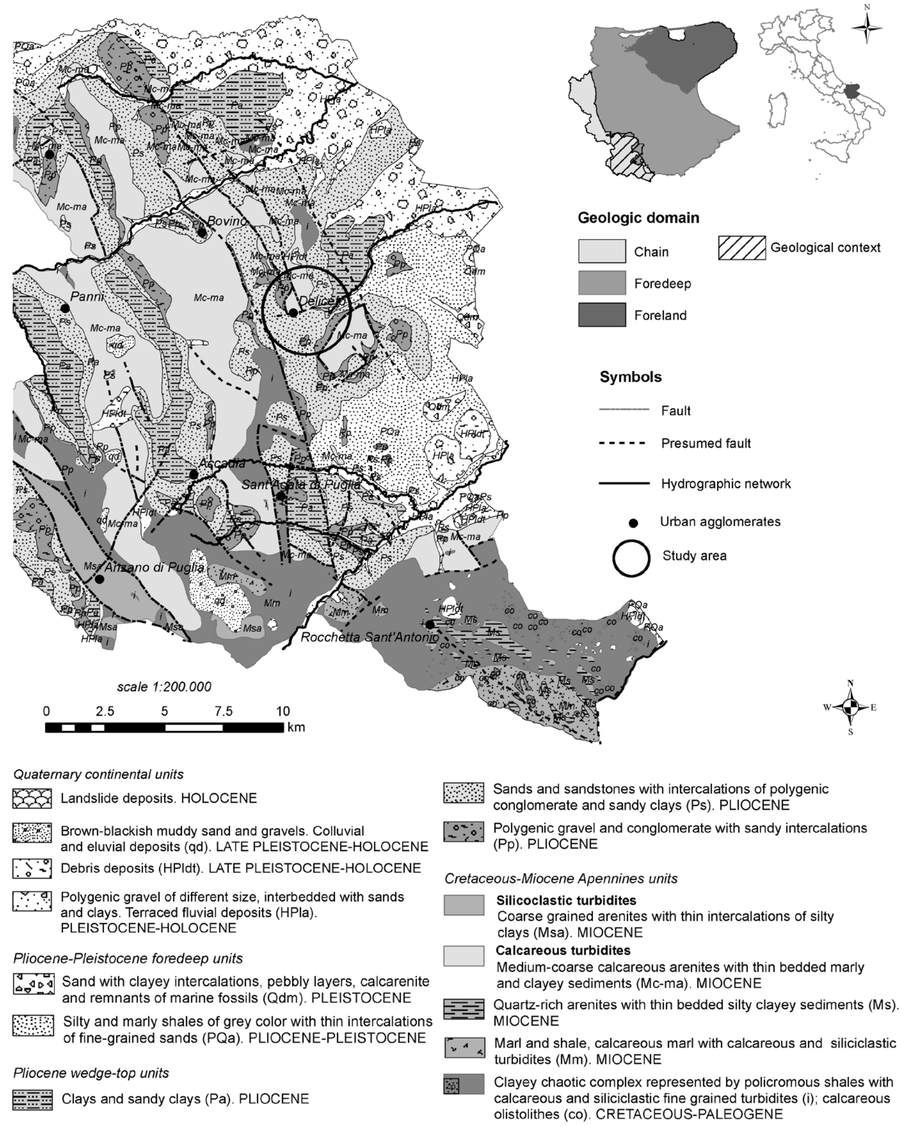

Fig. 1 - Geological setting of the eastern Daunia Sub-Apennine (after Geological Map of Italy, modified)

seismic and rainfall events.

Boreholes drilled in the study site for reconstruction of the subsurface stratigraphy and core sampling have proved the vertical extent of marly clays and marls with silty-sandy intercalations of the Flysch di Faeto Fm. (Langhian-Serravallian), tectonically overlain by shelf and transitional deposits belonging to the Bovino Synthem (Piacenzian). These are medium-coarse grained sands alternated with conglomerates (BVNa), and silty clays and poorly cemented grey sands (BVNb) (Fig. 2), these latter cropping out only in the southern sector, in tectonic contact with the former.

A comparison between the 8 m resolution digital terrain model (DTM) freely available at the cartographic regional website (SIT-Puglia website, http://www.sit.puglia.it) and the 3-D point cloud obtained by terrestrial laser scanning (TLS) with an accuracy of 1 cm, allowed to produce a detailed 3-D topographic map. The 2-D lithological map was generated based on conventional geological in-situ surveys and three 30-m boreholes with high core recovery and 80-100 m spacing. The 3-D geological model was obtained by integrating the 3-D topographic map, the 2-D lithological map and three 2-D lithological cross sections obtained through correlations between core logs and extensive fieldwork. The 3-D geotechnical model was based on the geological model and the soil test results, carried out in accordance with the international standards for static and dynamic characterization of soils.

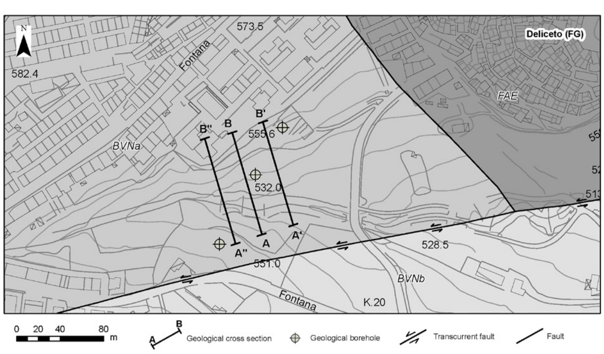

Fig. 2 - Lithological map of the study site. Key: BVNb, Vallone Meridiano clays and sands (Piacenzian); BVNa, Castello Schiavo sandstones and conglomerates (Piacenzian); FAE, marly clays and marls with sandy intercalations of the Flysch di Faeto Fm. (Langhian-Serravallian)

Geological model

Spatial data and physical properties of materials (e.g., index properties and unit weights) were collected from the above-mentioned in situ survey and laboratory investigations and used to create the 3-D geological model shown in Fig. 3. It consists of three litho-stratigraphic units, from the ground surface to below: i) Castello Schiavo sandstones and conglomerates (BVNa); ii) marly clays and silty clays of the Flysch di Faeto Fm. (FAEc); iii) marls

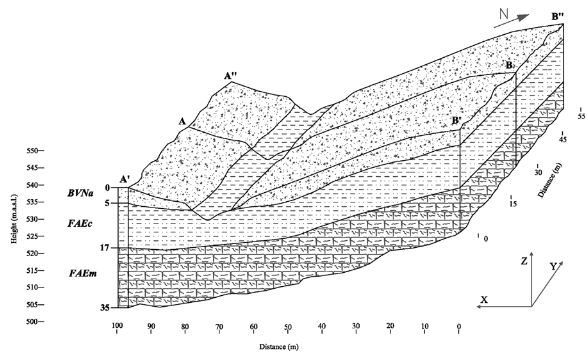

Fig. 3 - Geological model of the study site: Castello Schiavo sandstones and conglomerates (BVNa), marly clays and silty clays of the Flysch di Faeto Fm. (FAEc), clayey marls and shales of the Flysch di Faeto Fm. (FAEm)

and shales with silty-sandy intercalations of the Flysch di Faeto Fm. (FAEm). The BVNa unit presents a maximum thickness of 5 meters and consists of carbonate silty sands alternated with lenses of polygenic grain-supported conglomerates with well-rounded carbonate and siliciclastic gravels. In particular, the FAEc unit presents a mainly marly clay facies, with subordinate clay and silty-clay facies. Total thickness of this unit is about 12 meters. The FAEm unit is composed by greenish clayey marls and shales.

Geotechnical properties

Soil core samples were collected and subjected to geotechnical laboratory tests according to the ASTM standards for physical properties and for static and dynamic characterization of soils. In particular, physically based parameters and values of direct shear strength from the Casagrande apparatus method were obtained for all samples (Fig. 4). Resonant column (RC), cyclic torsional shear (CTS), and standard and cyclic triaxial tests (TXC) were performed only on the silty clays of the Flysch di Faeto Fm., because these are highly susceptible to geotechnical fatigue resulting from cyclic stresses. In fact, most of the surface ruptures develop and propagate through the slope in correspondence of silty clays and marly clays of the Flysch di Faeto Fm. Four geotechnical units were identified, as shown in Tab. 1 where their

Geotechnical unit	BVNa Unit 1	FAEsc Unit 2	FAEcm Unit 3	FAEm Unit 4
Depth (m)	1-5	5-9	9-17	>17
Classification (USCS–ASTM D2487-17)	SW	CH	CH	CL
Saturated unit weight γ_{sat} (kN/m^3)	21	22	22	22
Clay fraction (%)	15	52	55	20
Index Plasticity Index PI (%)	/	48	40	18
Activity	/	0.9	0.7	0.8
Effective Cohesion c' (kPa)	15	35	75	95
Peak friction angle φ'_p (°)	30	26	25	34
Residual friction angle φ'_r (°)	10	9	9	14

Tab. 1 - Basic physical and mechanical properties of the geotechnical units obtained on undisturbed specimens (mean values)

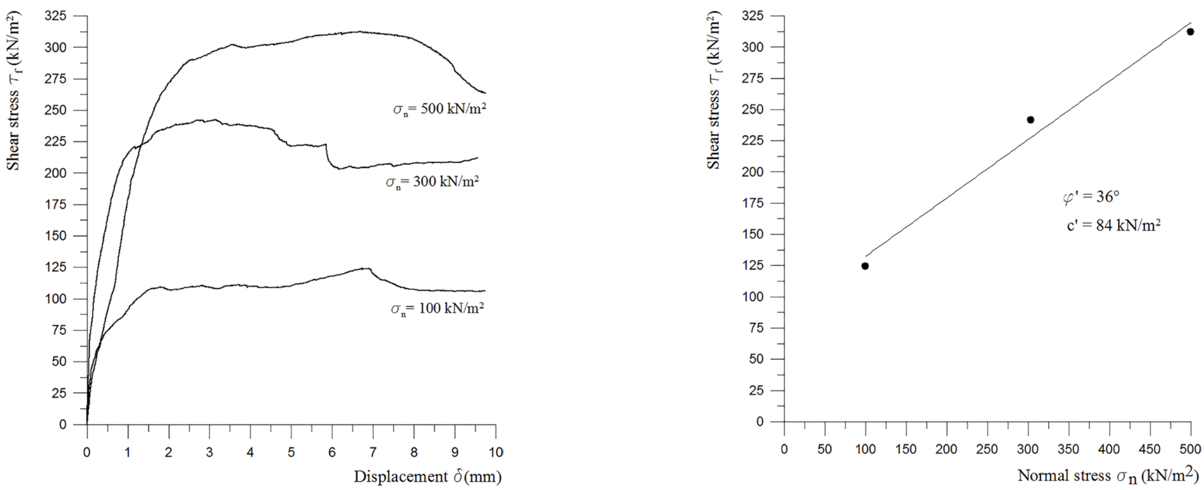

Fig. 4 - Shear stress vs. displacement (left) and shear stress vs. normal stress (right) graphs for a direct shear test carried out on three samples of clayey marls and shales of the Flysch di Faeto Fm. (FAEm) at different normal pressure

index properties and basic mechanical parameters are listed.

Soil parameters were obtained using undisturbed or low disturbed samples collected with Shelby tube samplers. Low disturbance was due to the operative difficulties associated with sample extrusion and with specimen preparation and assembly in the testing apparatus, due to high heterogeneity of the materials.

Resonant Column (RC) and Cyclic Torsional Shear (CTS) tests were performed according to Standard Test Method for Modulus and Damping of Soils by Fixed-Based Resonant Column Devices (ASTM D 4015-15). The RC and CTS tests are used to measure the resonant frequency (f_0), the shear modulus ratio (G/G0), and the damping ratio (D), which are function of torsional strain level (γ%) in the range between 10^{-4} % and 10^{-1} %. The RC column test is performed applying a harmonic torsional excitation to the top of the specimen by an electromagnetic loading system. The harmonic load was applied with a constant amplitude over a range of frequencies, and strain response curves were obtained. The resonant frequency (f_0) corresponds to the peak value of the torsional strain (Fig. 5).

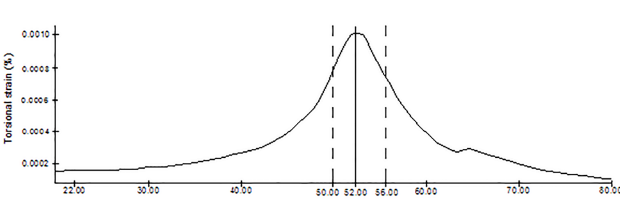

Fig. 5 - Resonant frequency curve for a sample of marly clays and silty clays of the Flysch di Faeto Fm. (FAEsc)

Figure 5 shows the peak value of the resonant frequency, which is equal to 52 Hz, related to 0.0010% maximum torsional strain for a specimen of FAEsc (Unit 2 in Tab. 1). In the CTS test the shear strain level was increased step-by-step, and the shear modulus and damping ratio were measured. To provide evidence for the dynamic behaviour of Unit 2 and for highlighting any behavioral anomalies related to disturbing factors, in Fig. 6 are shown two shear modulus degradation and damping ratio curves by combined resonant column and cyclic loading torsional shear tests (RCTS) on one undisturbed and one low disturbed specimens. The findings of the analysis for eight samples (four undisturbed and four low disturbed) show an increase in the damping ratio (D) between 2.9% and 19.9% for undisturbed samples, and between 2.8% and 22.9% for low disturbed samples. Correspondingly, an average decrease of 77.3% and 83.9% was registered for the shear modulus (G), for undisturbed and low disturbed samples, respectively.

Cyclic triaxial unconsolidated undrained tests were performed on undisturbed and low disturbed specimens of Unit 2 according to ASTM D 5311-13 (2013) to simulate undrained field conditions during earthquake or other cyclic loading. The cyclic strength of a soil is a function of different factors, including the development of axial strain, magnitude of the applied cyclic stress, number of cycles of stress application, development of excess pore-water pressure, and state of effective stress. As expected, cyclic loading caused faster rupture than static loading and soil fatigue damages, thus implying the development of large plastic shear strains without localized structural failures. Figure 7 (*left*) shows an example of the hysteretic soil response in a load-controlled test. According to ASTM D2850-15 (2015), failure was taken to correspond to the deviator stress at the 15 % axial strain. A frequency cyclic loading of 0.1Hz was applied, due to evidences of low-frequency amplification at the site. The frequency spectra were obtained from the Fourier transform of the most critical accelerogram recorded at four seismic stations

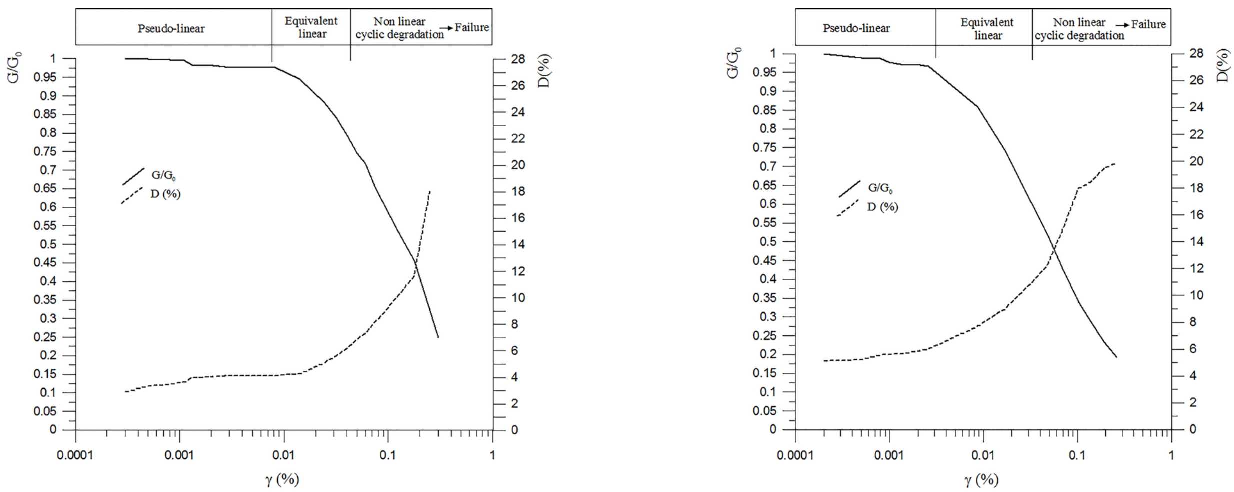

Fig. 6 - Shear modulus degradation and damping ratio curves measured by combined resonant column and cyclic loading torsional shear tests (RCTS) for undisturbed (left) and low-disturbed specimens (right) belonging to Unit 2

(Bisaccia, Ufita Valley, Ascoli Satriano and Ariano Irpino) in the surrounding of Deliceto, according to the seismic attenuation law by Sabetta & Pugliese (1996) for the Italian territory. An open-source software (SeisGram 2K) was used for the seismographic analysis, while the seismic data from the four stations were taken from the Database of Individual Seismogenic Sources (DISS) of the National Institute of Geophysics and Volcanology (INGV). Figure 8 shows the Fourier frequency spectrum of the most critical accelerogram associated to the seismic event of July 17, 1361 at the seismic station of Ascoli Satriano. The stability threshold for cyclic loading was about 500 N and undrained cohesion after cycling loading (c_u) resulted between 99.0 kPa (Fig. 7-*right*) and 115.0 kPa for low disturbed samples and between 116.5 kPa and 121.0 kPa for undisturbed samples. Accordingly, a strength degradation between 23.9% and 36.1% for low disturbed and between 21.9% and 24.8% for undisturbed samples was registered, by comparing the undrained cohesion after cycling loading (c_u) with that obtained by the static triaxial method in unconsolidated undrained conditions for undisturbed samples (mean value of cu is 155.5 kPa). The dynamic properties of Unit 2 are summarized in Tab. 2.

Dynamic mechanical properties	Undisturbed samples	Low-disturbed samples
Depth (m)	5-9	5-9
Initial shear modulus G_0 (MPa)	22.5-24.0	20.0-23.5
Final shear modulus G (MPa)	3.9-6.7	2.6-4.3
Initial damping ratio D_0 (%)	2.9-5.1	2.8-3.8
Final damping ratio D (%)	11.6-19.9	14.0-22.9
Post cyclic undrained cohesion c_{upc} (kPa)	116.5-121.0	99.0-118.0

Tab. 2 - Dynamic properties of the Unit 2

Geotechnical model

Based upon data from the geological model and in situ surveys, the geotechnical properties and laboratory behaviour

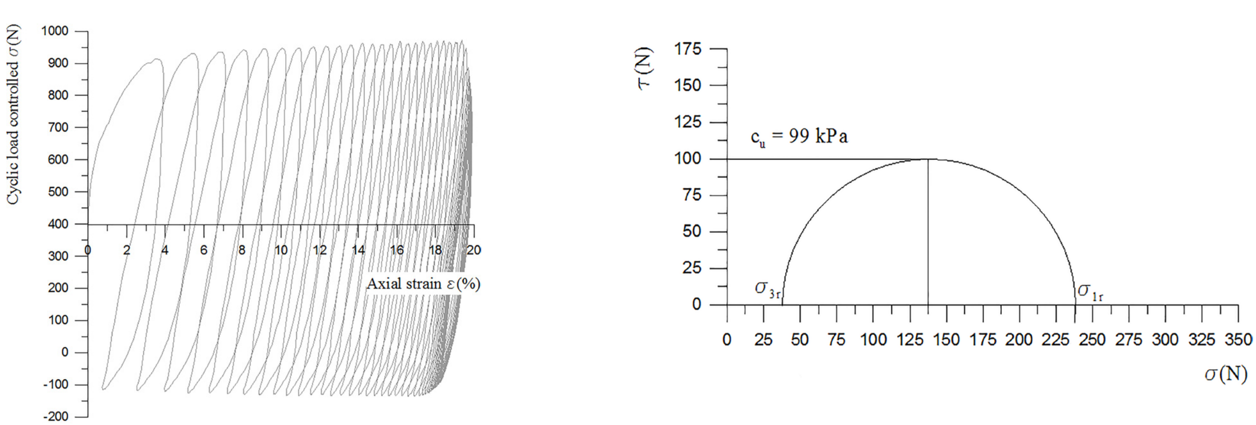

Fig. 7 - Cyclic stress-strain hysteresis loops (left) and post-cyclic undrained strength measured by triaxial cyclic tests (right) for a low disturbed specimen of Unit 2

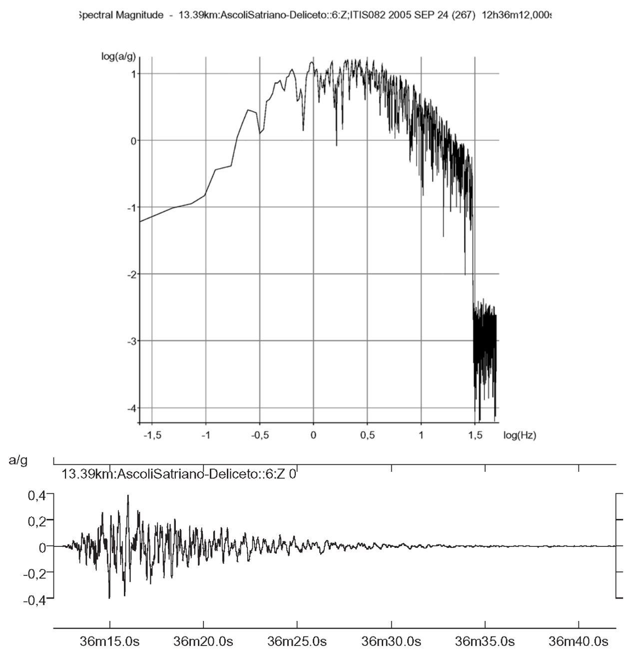

Fig. 8 - Fourier frequency spectrum (top) of the most critical accelerogram (bottom) associated to the seismic event of July 17, 1361 at the seismic station of Ascoli Satriano

of the materials allowed us to reconstruct the geotechnical model of the study site (Fig. 9). It consists of the following four geotechnical units, listed in downward order: Unit 1) loose to slightly cemented silty sands mixed with gravels belonging to the Castello Schiavo sandstones and conglomerates; Unit 2) silty clays of the Flysch di Faeto Fm.; Unit 3) marly clays of the Flysch di Faeto Fm.; Unit 4) clayey marls and shales of the Flysch di Faeto Fm.. All of them are heterogeneous units, due to presence of lenses of gravels and sands. In particular, the deepest unit (Unit 4) shows lithoid consistence.

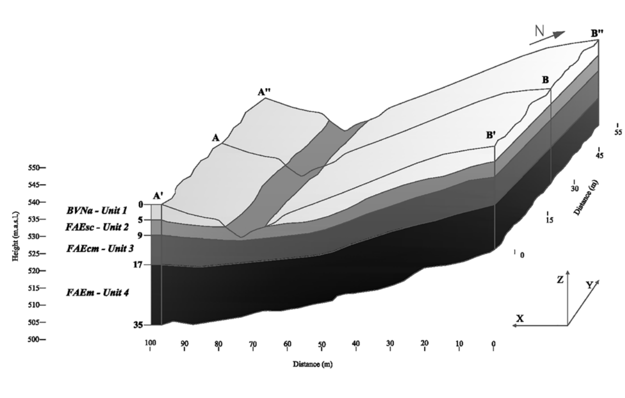

Fig. 9 - Geotechnical model of the study site: loose to slightly cemented silty sands mixed with gravels (Unit 1), silty clays (Unit 2), marly clays (Unit 3), clayey marls and shales (Unit 4)

DISCUSSION

When elaborating detailed geological and geotechnical models, it must be kept in mind the statement that models are typically built for a specific purpose, which in the present case is to provide a rational basis for the correct use of stability analysis procedures for slopes. The model can be further enriched by description of the most common failure types and mechanisms affecting the study area, which, in turn, may provide useful insights toward a better assessment of the likely slope movements and the comprehension of the geotechnical behaviour of the materials. This evaluation requires sound interpretation of the geological and geomorphological data, based on deep heuristic knowledge. The geological uncertainties can be limited if the data are accurate and precise, which constitutes the basis for any interpretation of the slope behaviour. Conversely, an evaluation of the most likely slope movements is dependent upon a detailed knowledge of the geotechnical properties of materials, and of their likely variations as well, in turn requiring specific campaigns of laboratory and in situ investigations.

At the study site, rotational slumps and shallow landslides were documented in the northern sector of the urban area and beneath the historical center of Deliceto, respectively. The shallow mechanisms are controlled by development of progressive shear failures within the clayey-sandy facies of the Vallone Meridiano clays and sands, while the rotational slides involve the Flysch di Faeto Fm. In general, widespread sliding mass movements are developed at the boundary between the cover deposits (BVNa, BVNb) and the underlying Flysch di Faeto, showing greater consistence. Composite landslides, sensu Cruden & Varnes (1996), starting as rotational slide and evolving into earth flows, were registered in the western sector (Fig. 2), close to buildings for residential use in a densely anthropized area. These involve the silty sandy mixed with gravel facies of the Castello Schiavo sandstones and conglomerates, and the silty clays of the Flysch di Faeto Fm. (FAEsc) (Fig. 10). In detail, rotational slides and composite movements involve the silty clays of the Flysch di Faeto Fm. (FAEsc) and, subordinately, the marly clays of the same formation (FAEcm), while the clayey marls and shales (FAEm) constitute the basement unit, at depth ranging between 17 and 20 m from the surface. In recent years, many instability phenomena were stabilized by human works through slope profiling, reforestation, and retaining walls to mitigate the risk related to likely reactivations (Fig. 11).

The most serious problem in modelling for slope stability analysis lies in the characterization of the structurally complex formations, in terms of geological and geotechnical features, and to the difficulty in recovering samples effectively representative of all materials involved. Structurally complex formations are highly anisotropic and characterized by heterogenous lithological and structural features, so that they cannot be confidently studied

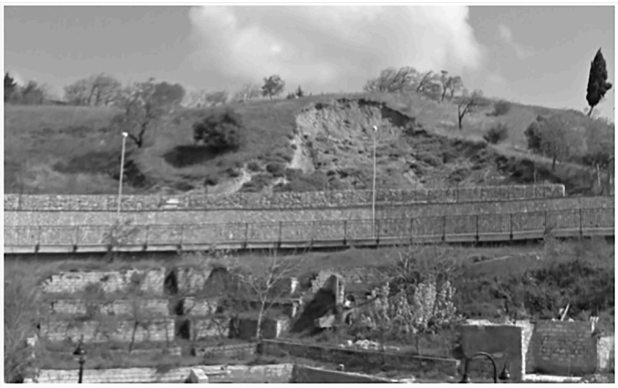

Fig. 10 - Rotational slide-earth flow involving the Flysch di Faeto Fm. in the western sector of the residential area of Deliceto

Fig. 11 - Gravity retaining wall on the western side of Papa Giovanni XXIII hill at Deliceto

and modelled with the classical approaches of soil mechanics (Croce, 1971). As a consequence, strength parameters measured by means of laboratory tests on intact samples are generally not applicable to field conditions, due to inherent heterogeneity of materials and/or presence of discontinuities (Esu, 1966). In detail, chaotic structures, presence of gravels, rock fragments and blocks (these latter characterizing Unit 4) make extremely problematic the collection of laboratory specimens. Nevertheless, in the last decades many researchers have proposed stochastic approaches for characterizing the spatial variability of geotechnical properties for structurally complex formations, or statistical analysis coupled with numerical simulation for assessing slope stability at variable ranges of factors of safety (Coli *et alii*, 2012; Chen & Zhang, 2014; Napoli *et alii*, 2018; Shepheard *et alii*, 2019; Ruggeri *et alii*, 2021). Statistical and stochastic approaches were not used in this study, due to unavailability of a large amount of data, needed for this type of analysis. Furthermore, in our case study the failure surfaces develop at the contacts between different lithological units or follow lithological changes along sharp or irregular boundaries within the same unit. Thus, starting from the geological model, the geotechnical units were identified as a result of the laboratory tests and of studies, interpretation and classification of slope movement types and processes. As regards the laboratory tests, for all the geotechnical units identified, both index properties and strength parameters vary widely with grading, degree of weathering, calcareous concretions and encrustations. Arithmetic mean values were obtained and used to identify the units, although the limited statistical sample makes relatively low the significance level of results. In particular, resonant column (RC), cyclic torsional shear (CTS) and standard and cyclic triaxial (TXC) tests were performed only on the silty clayey geotechnical unit of the Flysch di Faeto Fm. This choice was dictated by two main reasons: 1) Unit 2 is characterized by very poor mechanical properties, which variability is closely related to the grain-size of the samples; 2) in situ investigations suggested that Unit 1 and Unit 2 are more susceptible to failures processes, but the presence of large pebbles precludes any possibility of obtaining significant specimens for Unit 1.Furthermore, laboratory characterization of the silty clays of Unit 2 demonstrated that this material subjected to dynamic and cyclic stresses, in addition to assume non-linear behaviour, is highly susceptible to fatigue failure and pore pressure increase. In this particular case, aquifers were not found at depth lower than 20 meters during in situ investigations, but pore pressures in the near surface units certainly fluctuate in accordance with the annual rainfall regime.

In view of the above, performing in-situ tests, through combination of geophysical and geotechnical techniques, could be of great importance for investigating a larger volume, and for evaluating the spatial variability of the materials in their natural environment. This could potentially allow to obtain information about low-strain and large-strain response of the deposits, and to reduce the degree of uncertainty in the geological and geotechnical models.

CONCLUSIONS

The main conclusions obtained in this study, carried out on structurally complex formations in the Daunia Sub-Apennine, can be summarized as follows:

1) construction of geological and geotechnical models able to represent realistic information is conditioned by the efficacy of the methods chosen for the spatial distribution and parametrization of the lithofacies;

2) geological and geotechnical models must be built for a specific purpose, aimed at constituting a rational basis for solving specific geo-engineering problems;

3) structurally complex formations are highly anisotropic and characterized by inherent heterogeneity involving their geological and geotechnical features, even at the mesoscale;

4) the most serious problem in modelling for slope stability analysis lies in the ranking of units, which should be considered

homogeneous from the geological and geotechnical standpoints, also entailing the difficulty in recovering samples effectively representative of all materials involved;

5) statistical and stochastic approaches can provide valuable insights for assessing aleatory uncertainties related to the estimation of geotechnical parameters; however, the limited number of measurements and data suggest that important information could be obtained by means of direct and indirect observation, or be based upon experience founded on the application of multi-disciplinary approaches;

6) detailed studies on failure modes and mechanisms affecting an area can provide valuable information for constructing real-based geological and geotechnical models, and for assessing the most likely slope movements, based upon the behaviour of materials;

7) an uncertainty reduction process requires proper interpretation of the geological, geomorphological and geotechnical data which, in turn, derives from deep heuristic knowledge;

8) combining in-situ geophysical and geotechnical techniques allows to investigate larger volume and spatial variability of the materials in their natural environment, and to better validate the data obtained by mains of laboratory tests. In this way it is also possible to properly evaluate the low-strain and large-strain response of materials.

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