Italian Journal of Engineering Geology and Environment
www.ijege.uniroma1.it

ENGINEERING-GEOLOGICAL MODELLING AS A TOOL FOR ARCHAEOLOGICAL SITE PRESERVATION STRATEGIES

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EXTENDED ABSTRACT

L'Italia occupa il primo posto in Europa per rischio alluvioni e frane ed è tra i primi, assieme ai paesi balcanici, per quanto riguarda il rischio sismico. Il Bel Paese è anche noto come detentore del primato mondiale per numero di siti UNESCO e di beni archeologici. Diffusi sono i casi nei quali patrimoni di questo tipo sono collocati in aree ad elevato rischio geo-idrologico, che non favorisce la loro preservazione e, in molti casi, ne inficia finanche la fruibilità turistica.

Il presente studio descrive alcuni dei primi risultati scaturiti dalle attività del gruppo di lavoro dell'Università Sapienza di Roma nel sito dell'isola di Ventotene, seconda per dimensione nelle isole Pontine, ubicate circa cinquanta chilometri a largo delle coste del Golfo di Gaeta. Quest'ultima ospita uno degli otto casi di studio pilota del progetto europeo "H2020 TRIQUETRA", finalizzato allo sviluppo di un approccio di mitigazione dei rischi naturali legati al clima, che colpiscono beni archeologici di diversa tipologia. Questo studio mette, pertanto, a fuoco l'area del promontorio di Punta Eolo dove sono conservati i resti archeologici della "Villa Giulia", un complesso architettonico romano, che nel I sec. d.C. ospitò diverse donne della famiglia imperiale, condannate all'esilio nell'isola per reati vari. Le falesie che costeggiano il promontorio sono suscettibili all'innesco di fenomeni franosi in roccia che minacciano la preservazione del complesso archeologico e che, nel recente passato, hanno provocato il collasso di strutture di accesso e approvvigionamento idrico della Villa.

Da un punto di vista geologico, le due isole di Ventotene e Santo Stefano rappresentano la testimonianza del fianco sud-orientale di un antico apparato vulcanico formatosi nel corso dell'ultimo milione di anni. Il substrato dell'isola è composto da lave basaltiche associate allo stadio di attività vulcanica effusiva. Queste sono sormontate da una spessa successione di prodotti piroclastici connessi alla fase di collasso calderico, di cui il membro più giovane, noto come "Tufo di Parata Grande", costituisce l'unità litostratigrafica dominante dell'isola.

Viene di seguito presentato il primo modello geologico-tecnico realizzato per il sito di Punta Eolo. Concettualizzato mediante l'integrazione di diversi tipi di tecniche di investigazione, tale strumento si configura come mezzo di analisi preliminare del rischio geologico che affligge il sito archeologico di Villa Giulia. Attraverso un rilievo di terreno ad alta risoluzione, sono stati individuati gli elementi geologici e geomorfologici più rilevanti per la caratterizzazione di sito, e classificate cinque unità geologico-tecniche. Parallelamente, è stato condotto un rilievo geomeccanico estensivo finalizzato alla caratterizzazione dello stato di fratturazione dell'unità di basamento tufaceo, grazie al quale sono stati individuati numerosi blocchi parietali lungo il ciglio della falesia costiera, disgiunti dallo stabile plateau tufaceo. Le osservazioni di sito sono state integrate per mezzo di un rilievo fotogrammetrico effettuato tramite drone e mediante un rilievo batimetrico condotto lungo la costa occidentale del promontorio.

Al fine di vincolare gli spessori delle diverse unità geologico-tecniche è stata progettata una campagna geofisica consistita nella registrazione di misure singole di rumore sismico ambientale (HVNSR) distribuite nell'area di studio. I risultati descrivono la concentrazione di una frequenza di risonanza (f0) di 3 Hz in tutti quanti i punti di misura e, solo in alcuni, di un secondo picco in frequenza di maggiore intensità tra i 9 e 19 Hz. Il picco a più bassa frequenza è associabile alla risonanza del banco di tufi, vincolando il contatto tufi-lave a circa 60 m di profondità dal piano-campagna. Il secondo picco in frequenza è rinvenibile nelle stazioni condotte al di sopra dei depositi superficiali, ed è descrittivo della risonanza di coperture di spessore compreso tra i 4 e i 9 m.

A valle del presente studio viene proposta una cartografia tematica corredata da tre sezioni geologico-tecniche e una riproduzione tridimensionale del modello geologico-tecnico. La redazione di quest'ultimo conferma come i processi di crollo e ribaltamento in roccia che lambiscono il promontorio siano gli elementi di maggiore pericolosità per la preservazione del patrimonio archeologico di Villa Giulia, configurandosi come fattori di rischio geologico dominanti nell'area.

IJEGE, Special Issue 1 (2024): 115-126, DOI: 10.4408/IJEGE.2024-01.S-13
E-ISSN 2035-5688 | ISSN 1825-6635 / ©Author(s)

ABSTRACT

Traditionally, cultural heritage (CH) site conservation strategies have mostly focused on the employment of procedures to protect archaeological exhibits from weathering processes. However, CH-sites are often located in areas affected by geological hazards, which can threaten the conservation of the site itself. For these cases, engineering-geological modelling is an essential tool to design conservation strategies for geohazards management in the framework of CH-site preservation. The research here proposed is focused on the Punta Eolo promontory at Ventotene island (Italy) where the remnant of the roman "Villa Giulia" emperor palace is hosted.

Detailed engineering-geological surveying has been carried out at Punta Eolo. In particular, engineering-geological investigations have been coupled with remote investigation of the area of interest. Thanks to the engineering-geological surveys, a detailed engineering-geological map was drafted, also highlighting the geomechanical setting of the Parata Grande Tuff formation (hereinafter, PGT). The presence of a superficial deposit, mainly composed of archaeological material overlaying a tuffaceous unit, was evidenced. To bound this layer's thickness more effectively, 52 single-station seismic noise measurements were carried out. Seismic ambient noise measurements show significant horizontal-to-vertical spectral ratio (HVSR) resonance peaks at 3 Hz, a variable secondary peak ranging from 9 to 19 14 Hz, respectively related with the contact between the PGT and the underlying lavas and the superficial deposits and PGT units. The measurements conducted at the edge of the promontory show evidence of polarization of the particle motion potentially related to the vibrational behavior of the unstable rock blocks that bound all the site.

A 3D model of the cliff, reconstructed by drone photogrammetry technique, allowed to perform the rock mass joints surveying along the not-accessible cliff faces, as well as to visualize the superficial deposits thickness all around the perimeter of the promontory. Additionally, a 3D geological model was made using the RockWorks 16 program to facilitate a more direct visualization of site-specific features. The engineering-geological model here presented enables the development of an efficient conservation strategy for the Villa Giulia archeological site, as a critical tool for mitigating geological risks. Furthermore, future archaeological excavation will be driven by the reconstructed geological model of Punta Eolo.

***Keywords**: engineering geological modelling, slope stability, coastal cliff*

INTRODUCTION

The small archipelago of Ventotene and Santo Stefano islands is characterized by attractive and varied aspects, intended both from a naturalistic and a historical point of view. From the late 1st century BCE onwards, in fact, Ventotene became a place of forced exile for several women of the imperial family. The most relevant case is the one of the Emperor Augusto's daughter Iulia Maior who was exiled in the island from the 2 BCE to the 3 BCE. The place where all the exiles spent their time was represented by a regal imperial palace renamed as "Villa Giulia", located in the northernmost side of the area known as "Punta Eolo''. Nowadays the preservation of Villa Giulia, which represents one of the most attractive cultural heritage (CH) sites of Ventotene Island, is threatened by numerous collapses of the sea cliff that bounds its borders.

The nowadays progress of modern geological risk mitigation strategies for CH-sites is a more topical and developing issue than ever before (Themistocleus *et alii*, 2018; Beni *et alii*, 2023), especially with regard to landslide risk (Vlcko *et alii*, 2009; Spizzichino *et alii*, 2013; Keskin & Polat, 2022). Many of the CH-sites are located in coastal areas affected by landslides conditioned by predisposing, preparatory and triggering factors (*sensu* Gunzburger *et alii*, 2005). For rocky cliffs, such factors influence the coastal retreat rate and are related with the *i*) marine forcing (*i.e.*, sea waves action), *ii*) continental forcings (which encompasses weather and hydraulic conditions) and *iii*) cliff setting (Prémaillon *et alii*, 2018).

Several researches which have been carried out on the study of coastal retreat processes (*e.g.* Dixon & Bromhead, 1991; Della Seta *et alii*, 2013; Alberti *et alii*, 2022; Marmoni *et alii*, 2023) are rooted on the conceptualization of an engineering-geological model (EGM). EGM is an approximation of the geological conditions, at varying scales, created for the purpose of solving an engineering problem (Parry *et alii*, 2014), and it serves as a fundamental tool for any kind of engineering-geological analysis. EGM conceptualization has nowadays reached a very high level of accuracy, incorporating various types of investigation techniques into its development. In this framework, a significant example is provided by Iannucci *et alii* (2020), who developed an EGM of the Għajn Ħadid Tower (Malta) using passive seismic techniques to investigate the slope stability of the cliff, or by Meisina *et alii* (2022) who conceptualized an EGM of the subsoil for the investigation of a liquefaction site using a 3D approach of analysis.

The present study provides a detailed EGM of the Punta Eolo locality where the CH-site of Villa Giulia is located. Multi-approach techniques were applied to conceptualize the EGM of the Punta Eolo promontory. In particular, a conventional engineering-geological survey was firstly carried out to characterize the accessible geological and geomorphological outcrops. The aforementioned observations were then refined using geophysical measurements and a drone-based survey, which included determining the thicknesses of the engineering-geological units and the geomechanical features of the promontory.

The engineering-geological map here presented is a pivotal tool for mitigating the geological risks that are threatening the CH site. Furthermore, the planning of future archaeological excavation campaigns may be driven by the reconstructed EGM of Punta Eolo.

ARCHAEOLOGICAL SETTING OF VILLA GIULIA

The island of Ventotene (the ancient Pandataria), part of the Pontine archipelago, has been inhabited since the Neolithic period. This early occupation is likely linked to the lithic industry and the commercial trade of obsidian sourced from near Palmarola (Della Ratta & Rinaldi, 1992; Zarattini, 2004). During the Mid-Bronze Age, established settlements emerged primarily to the north of the area between Cala Rossano and Parata Grande (Buchner, 1946; Zarattini *et alii*, 2013). However, evidence of frequentation during the Archaic and Republican periods is solely derived from shipwrecks and underwater findings (Gianfrotta, 1986; Zarattini *et alii*, 2013).

After the mid of the 1st century BCE the work of Varro on Roman agriculture attests to the cultivation of a particular type of vineyard on the island. Approximately in the same years, the promontory of Punta Eolo was selected – likely by Agrippa or another member of the imperial family – for the construction of a villa dedicated to otium, the so-called "Villa Giulia". This luxurious maritime villa was characterized by multiple pavilions, including a residential sector, along with a balneum, arranged around a substantial apsidal garden (*viridarium*) (henceforth referred to as the "residential area") (for the most recent reconstruction of the residential part of the villa, see De Stefano, 2023). This ensemble reached its culmination to the north in a panoramic terrace overlooking the sea. The construction of the villa also led to the creation of a sophisticated system of rainwater collection tanks and aqueduct canals that from the central area of the island fed the imperial residence and the nearby artificial port (De Rossi, 2019).

Originally designed for seasonal otium, the villa underwent a transformation into an exile residence for some of the most prominent women of the imperial family, a practice known as "relegatio in insulam". The first notable exile was Iulia, the daughter of Emperor Augustus, confined to the island by her father for five years, from 2 BCE. Subsequent women of the imperial family shared a similar fate in the 1st century CE (De Rossi & Medaglia, 2018). The shift in the villa's purpose - from a seasonal retreat to a permanent exile prison - involved an adaptation of structures and infrastructures, including the aqueduct and cisterns system, that from the central area of the island culminated in the southernmost sector of the complex (henceforth referred to the "service area") (De Rossi, 2019). The complex underwent at least 3/4 main building phases, discernible in both the architectural elements and the decorative system, prior to its abandonment in the Middle Imperial age (Medaglia, 2010; De Rossi & Medaglia, 2018; De Vos & Maurina, 2022).

However, the end of the villa did not lead to the abandonment of the island, as demonstrated by various late antique contexts. Between the Middle Ages and the Renaissance, the presence of ecclesiastical communities is documented, and in the mid-18th century CE the Bourbon dynasty initiated a plan to repopulate the site and carried out important quarrying activities right in the northern sector of the island where Punta Eolo is located.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

Ventotene and Santo Stefano represent the southeastern group of islands of the Pontine Archipelago. This latter is also composed by the islands of Ponza, Palmarola and Zannone and it is located about 50 km off the Gaeta coast. Approximately 2,800 m long and a maximum of 800 m wide, Ventotene has an area of 1.54 km^2 and it is distinguished by orography that gently slopes northwards from its highest point of Mt. Arco (139 m a.s.l.) (Figure 1a, b).

The island of Ventotene is located between the external margin of the continental platform and the Tyrrhenian abyssal plain (Zitellini *et alii*, 1984), at the hanging wall of the west-direct Apennines subduction zone, which is undergoing a tensional tectonics (Doglioni, 1991). In particular, Ventotene and S. Stefano represent the summit of a large stratovolcano built during the last 800k years, located on the southern edge of the Ventotene basin (Perrotta *et alii*, 1996), which had to reach a maximum height of 800 m (De Rita *et alii*, 1986 - Figure 1e). The eruptive center of the edifice was located 2-3 km off the western coast of Ventotene island (Metrich *et alii*, 1988; Perrotta *et alii*, 1996).

Nowadays, this sector hosts a sub-circular structure with a diameter of 3 km attributable to the caldera collapse of the volcanic apparatus (*Progetto MAGIC, Note a compendio del Foglio "Ventotene"*)

In the northern sector of the basin the Ventotene volcanic ridge (VR) is located, whose position is controlled by the interaction between a two major trending tectonic structures, respectively related with the eastern Ponza escarpment and a graben southwest of the Roccamonfina volcano, compatible with the extensional setting of the Tyrrhenian basin (Cuffaro *et alii*, 2016). The whole structure of the VR is the result of the aggregation of a series of volcanic edifices mainly eroded during the Quaternary glacial sea level lowstands (Cuffaro *et alii*, 2016). The volcanism responsible for the genesis of the Pontine Archipelago belongs to the potassic manifestation of the Roman Comagmatic Province (Metrich *et alii*, 1988; Conte *et alii*, 2020), that is extended from Northern Latium to the area of Naples and is characterized by a period of activity within the last 1 Myrs (Fornaseri, 1985).

The Ventotene island is composed by basaltic to trachytic lavas (0.80–0.48 Myrs; Metrich *et alii*, 1988) unconformably covered by pyroclastic products erupted in the time span 0.2 Myrs (Metrich *et alii*, 1988) to 41 kyrs (Alessio *et alii*, 1974) that

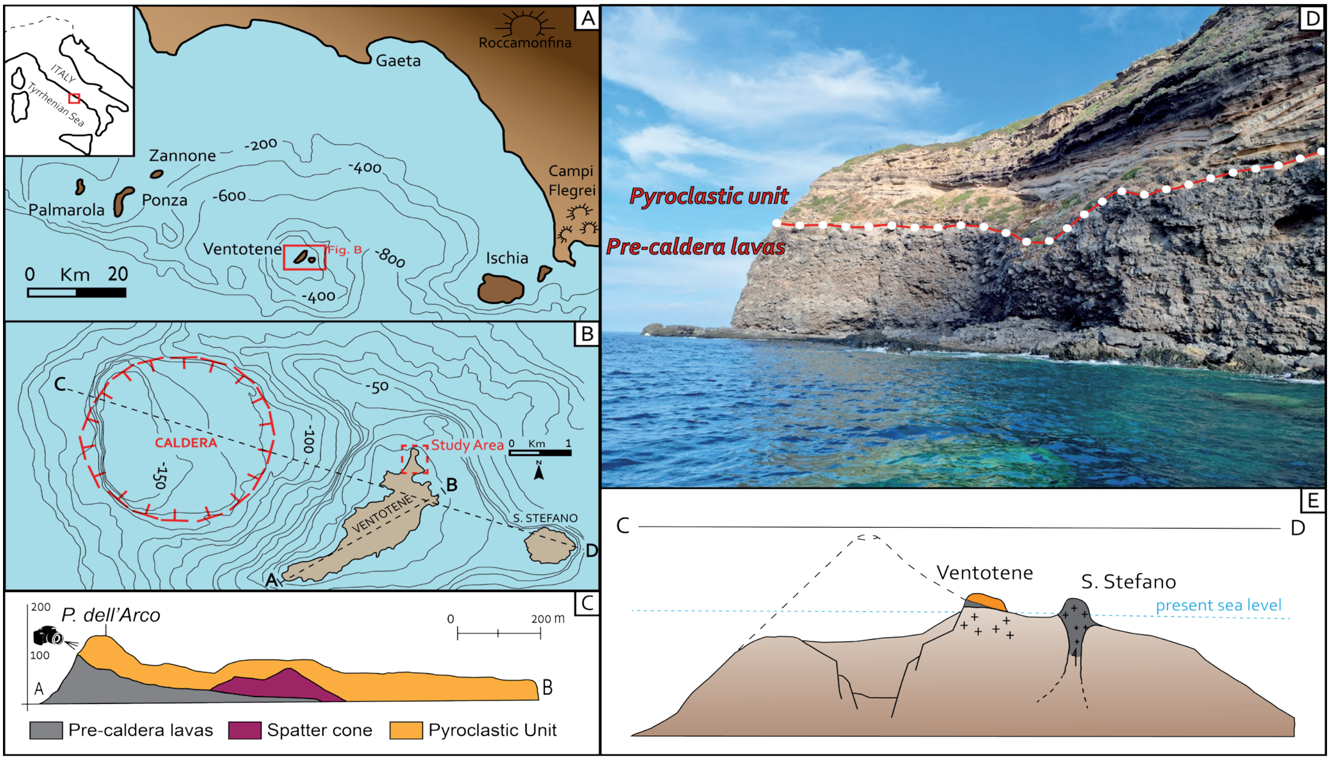

Fig. 1 - A) Geographic location of the Pontine archipelago and B) of the Ventotene and Santo Stefano islands; C) schematic cross section of the Ventotene island; D) photo of the contact between the pre-caldera lavas and the pyroclastic unit taken in Punta dell'Arco locality (refer to the image D for the location); E) schematic cross section of the ancient stratovolcano structure, and the actual caldera system with Ventotene and Santo Stefano islands [mod. after Metrich *et alii (1988) and* Perrotta *et alii (1996)]*

nowadays form a tuff plateau slightly dipping toward NE (Figure 1c, d). Perrotta *et alii* (1996) differentiated the volcanic deposits present in Ventotene into 27 members: 3 are related to lava flows and dome genesis, whereas the others 24 are composed of pyroclastic deposits, except one that consists of a scoria cone. The youngest member is represented by the so-called "Parata Grande Tuff" (PGT) and it predominantly crops out in the northernmost sector of the island.

PGT is composed of four main sub-members:

- Massive member (M), represented by a sequence of grain-supported deposits, well sorted pumice fall deposits and a massive ash bed;
- Coarse-tail graded member (CTG), characterized by an increase in lithic content, organized in single beds, with a spread presence of lithic blocks up to 1 m;
- Inverse graded member (IG), represented by planar and poorly sorted deposits with an inverse gradation;
- Sand-wave member (SW), organized in layers with dunes and cross-stratification, alternating with massive beds

These deposits are well exposed at Punta Eolo locality, situated in the northernmost sector of the island.

Among the aforementioned 27 members, the PGT unit is the only outcropping succession whose features are similar to those of the deposits related to a caldera collapse (Perrotta *et alii*, 1996). In the north-central sector of the island the stratigraphic succession is completed by the presence of cross-bedded sands and aeolian deposits (Di Fiore *et alii*, 2015).

Seismicity is low in the study area, with a maximum MCS intensity of VI associated with the Molise Earthquake on July 27, 1805 (Guidoboni *et alii*, 2019); the same is true for tsunamis, for which no historical records exist (Favali *et alii*, 2004). In accordance with the Italian seismic hazard model (Stucchi *et alii*, 2011), the local peak ground horizontal acceleration (PGA) corresponding to return times of 475 and 2475 years are equal to 0.066 g and 0.080 g.

The dominant morphogenetic control on the landforms in the Ventotene is represented by the sea, and secondly by the gravity-induced processes, including landslides and subsidence. The coastal profile is discontinuous, with a few pocket beaches (*e.g.*, Cala Nave, Cala Rossano) interrupting the linear continuity of persistent sea cliffs (*sensu* Martino & Mazzanti, 2014) Many landslides struck the boundaries of the island, depicting a predominant process in terms of coastal retreat and geological risk in general (Bosco *et alii*, 2013; Caso *et alii*, 2015; Ruberti *et alii*, 2020). It is sadly well-known, for example, the case of the Cala Rossano landslide that in 2010 killed two people. According to Hungr *et alii* (2014), the majority of the landslides documented in Ventotene are small to medium rock-falls and topples. Less frequent but larger are irregular rock slides such as the one of Cala Bosco, which threatens the preservation of the island's monumental cemetery. Also the Punta Eolo promontory cliffs (that reach heights variable from 5 to 15 m) are continuously hit by sea-waves and strong wind gusts that play a preparatory and triggering role for the activation of rock-topples and -falls.

ENGINEERING-GEOLOGICAL MODELLING

Methodology

A detailed engineering-geological survey was performed to *i*) recognize and map the engineering-geological units and the landforms cropping out in the study area, and *ii*) characterize the spatial distribution and the geomechanical features of the joints dissecting the PGT formation. The in situ observations have been also supported by remote analyses. In particular, a drone photogrammetric survey was performed at Punta Eolo to process a 1 cm resolute 3D topographic model and Digital Surface Model (DSM) of the area. The geomorphological landforms surveying was implemented in a GIS environment and, above all, the contacts between the engineering-geological units were mapped. The remote analysis allowed to implement the resolution of the joint's distribution analysis. It has been possible also to detail the underwater topography of the western sea stretch thanks to bathymetric survey with a resolution of 10 cm, and to an underwater video inspection.

A geomechanical characterization of the tuffs outcropping in the area was carried out according to ISRM (2007) standard, to evaluate the rock mass jointing distribution and conditions. Several scan lines were performed along the borders of the cliff where the tuffs are exposed and easily observable.

Seismic ambient noise measurements were performed in single-station configuration in 52 sites covering the Punta Eolo promontory. SL06 24-bit digitizers with built-in SS20 three-component velocimeters (2.0 Hz eigenfrequency) by SARA Electronic Instruments (Perugia, Italy) were used recording for 30 min with a sampling frequency of 200 Hz. At each measurement point, the horizontal-to-vertical noise spectral ratio (HVNSR) function was computed using the methodology proposed by Nogoshi & Igarashi (1970, 1971) and Nakamura (1989). This method was used to determine the fundamental frequency (f0) of sites with a stratigraphy with a significant impedance contrast, typically soft soil overlying stiff bedrock (Bour *et alii*, 1998; Haghshenas *et alii*, 2008).

Geopsy software (www.geopsy.org) was used for the analysis. Each recording was segmented into 40-second non-overlapping windows, in the frequency range between 1 and 20 Hz and using a 5% cosine taper. The fast Fourier transform (FFT) was calculated

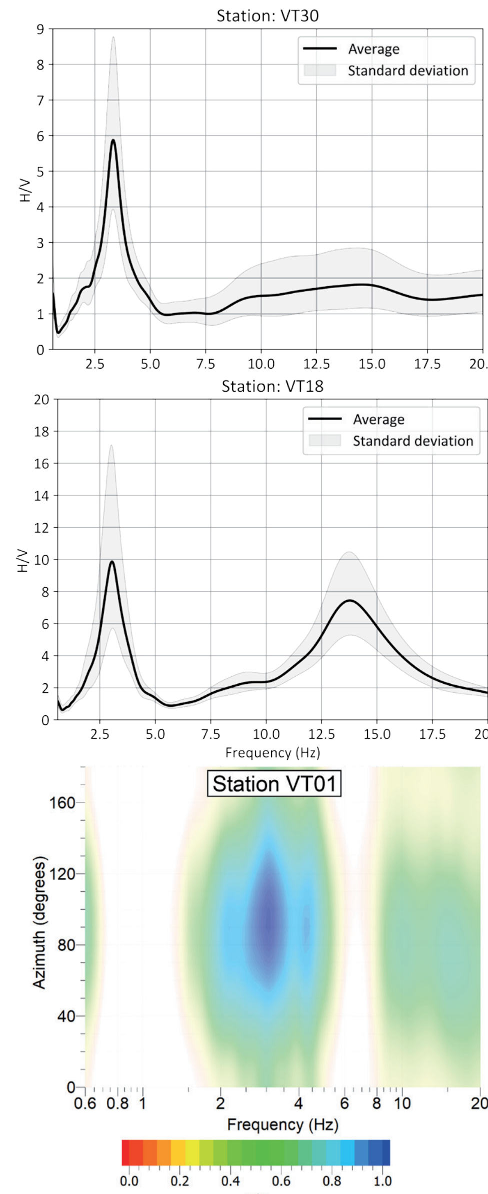

Fig. 2 - VT30, VT18 and VT01 single seismic measurement stations, respectively representative of the single and double HVNSR peaks and the HVNSR azimuthal polarization (for the station's location please refer to the Annex I)

for each window's three components (North-South, East-West, and Up-Down). The resulting FFT spectra were smoothed with the Konno & Ohmachi function (1998), and the average of the single-window spectra and H/V ratio was then obtained. An analysis of the statistical distribution of ratio between the horizontal and vertical particle vibration (H/V rotate) has also been carried out.

A seismostratigraphic profile derived by a MASW (Multichannel Analysis of Surface Waves) investigation carried out in the Punta

Eolo area, integrated the HVNSR analyses, evidencing a Vs=310 m/s associated with shallow deposits and a Vs=740 m/s related with PGT formation.

To systemize the geological characteristics of the study area and to offer insights into the spatial distribution, relationships, and complexity of subsurface structures. a 3D engineering-geological model of Punta Eolo was realized. Given the absence of borehole data, the construction of the 3D solid model was based on the reconstruction of 108 "synthetic boreholes" (SB) distributed into the promontory area. These latter have inherited the stratigraphic information derived from the in situ surveys and from the other approach of analysis used for the geological characterization of the engineering-geological units outcropping at Punta Eolo. The modeling process was executed using RockWorks 16 software (RockWare Geoscientific Software Consulting Training, OH, USA). This software employs advanced modeling methods within a georeferenced environment to generate three-dimensional models of the subsurface. In this specific case, the interpolation algorithm employed was Inverse Distance Weighted (IDW). The 3D model's mesh is composed of elements known as voxels, extending vertically from -80 m to 34 m above sea level. The voxel grid is discretized at intervals of 2 m along the X and Y axes and 0.5 m in the Z direction, resulting in a total of 141 nodes for X, 201 nodes for Y, and 229 nodes for Z (Ciampi *et alii*, 2022).

RESULTS

The detailed engineering-geological survey and the remote analyses allowed to highlight the stratigraphy of the units outcropping in the Punta Eolo promontory and the geomorphological features of the study area.

A total of five engineering-geological units have been recognized (Figure 3; Annex I):

- Lavas Unit (LU). It is the basal unit above which all the stratigraphic succession is placed, and it is related with the pre-caldera volcanic activity of Ventotene stratovolcano. This engineering-geological unit does not crop out in the study area, but it has been recognized and considered thanks to the geophysical results (Calabrian-Chiabania).
- Tuffs Unit (TU). It is the dominant unit cropping out in the study area, and it bounds the perimeter of the Punta Eolo locality giving it the distinctive characteristic of rocky cliff promontory. TU is associated with PGT formation and, in particular, with its sand-wave member. Two differentiated sub-members have been recognized according to their stratigraphic features: a massive member (MTU) and a stratified one (STU) (Chibanian – Upper Pleistocene).
- Eolian Unit (EU). Composed by sands alternating with salt-encrusted horizons, this unit crops out dominantly in the northernmost sector of the promontory reaching maximum thicknesses of 50 cm (Olocene).
- Eluvial-Colluvial Unit (ECU). This member is represented by weathered material and by detrital deposits mainly transported by running waters and rill channels (Olocene).
- Anthropic Unit (AU), constituted both by the archaeological remains of the Villa Giulia complex and by the waste deposits of the different archaeological excavations carried out in the area (1st Century BCE - Actual).

Given the volcanic depositional nature of the TU, it has not been easily possible to recognize a dominant layering for this unit; the bedding (J0) was however associated with a SE-dipping orientation (120/07°). The spread presence of open joints parallel oriented to the coast was instead mapped and associated with the J1 (270/85°), J2 (005/85°) and J3 (090/85°) joint sets, respectively associated with the western, northern and eastern coastal stretches of the promontory. These sub-vertical joint sets are mainly associated with the progressive release of the rock mass caused by quarrying activities carried out at Punta Eolo promontory over the last several centuries.

The geophysical data represented by the HVNSR and MASW results served as a crucial tool to constrain the thicknesses of the identified engineering-geological units. Almost all the single seismic stations located on the TU show HVNSR curves characterized by a distinctive peak in a narrow frequency range close to 3Hz, followed by a sharp decrease of the spectral ratio. The 3Hz HVNSR peak can be related to the fundamental frequency (f0) due to the stratigraphic setting of the site, which depends on the contact between the TU and the underlying LU. A second HVNSR peak at frequencies ranging from 9 up to 19 Hz is detectable in many other stations (Figure 2). This is the case of the stations that have been installed above the superficial deposits that composed EO, ECU and AU. These secondary frequency peaks have been interpreted as evidence of the contact between the TU and the thin overlying deposits. Nevertheless, using these results alone, it was not possible to detail any overlaps of the deposits since they are all characterized by a similar seismic impedance. The variability of the secondary frequency, however, is related with the depth of the geological contact between the TU and the shallow deposits: the higher the frequency, the shallower the depth of contact. A preliminary evaluation of the fundamental frequency of a resonant layer (f0) can be obtained by the following relation:

$$f_0 = v_s / 4H$$

Where Vs is the S-wave velocity within the layer and H is its thickness. Thanks to the known primary and secondary HVNSR peaks and the Vs values derived from the MASW analysis, it has been possible to evaluate the thickness of the shallow deposits and of TU at correspondence of each single seismic station. In particular, Vs value of 310 m/s was

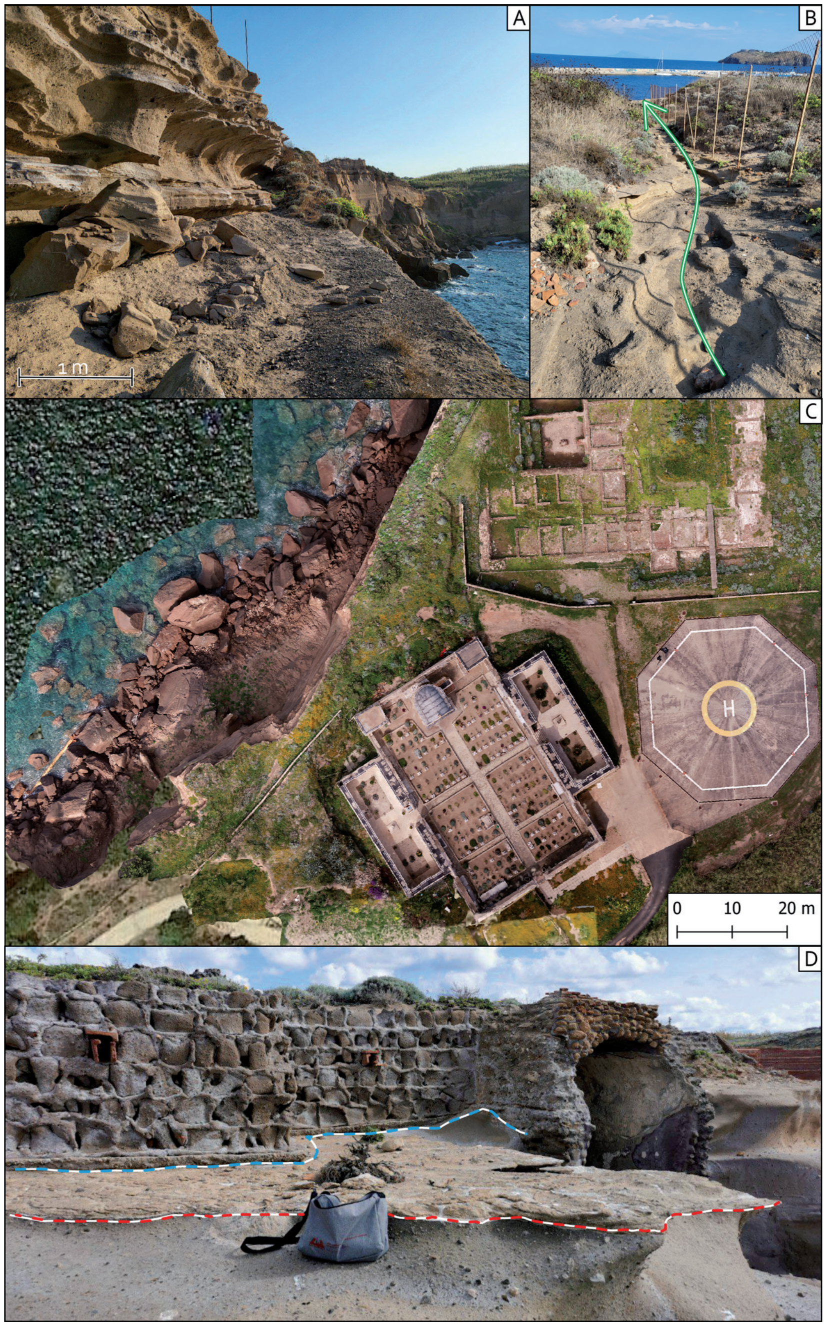

Fig. 3 - A) Tuffs Unit (TU); B) rill grafted on the Eluvial-Colluvial Unit (ECU); C) slope deposits accumulated below the western cliff of Punta Eolo; D) contact between TU and Eolian Unit (EO)(marked with the red dotted line), and between the EO and the archaeological remnants of the Villa Julia (marked with the blue dotted line)

associated with surface deposits, while 740 m/s was associated with the TU. According with these results, the primary peak at 3 Hz indicates a contact depth of approximately 60 m between LU and TU, whereas the secondary peaks show variable thicknesses of the shallow deposits ranging from 4 to 9 m. Finally, many of the HVNSR rotate results corresponding to the station located along the edge of the tuffaceous plateau show a polarization in terms of volumetric wave components (*i.e.*, P- and S - waves) orthogonally oriented respect the border direction of the cliff (Figure 2).

The aforementioned results have been used as input for the 3D engineering-geological model reconstruction.

In particular, the position of some of the synthetic boreholes (SB) was made to coincide with those of the single seismic measurements. For these cases, the SB inherited the stratigraphic information about the contact depth between the superficial deposits and the TU, and between the TU and LU. For the other SB the thickness of the superficial deposits has been assumed based on the in situ observations.

With regard to the geomorphological characterization of the site, the following morphogenetic landforms categories have been recognized and cataloged according to ISPRA (2018)(Annex I).

Gravity-induced slope landforms

The sea-bottom below the western cliff of the promontory hosts many rock blocks that testify an intense gravitational activity of this sector. The highest concentration of blocks is found south of the west coast, along a cliff portion connected with the Cala Bosco landslide system (Figure 3c). In general, the larger blocks (≈ 200 m^3) tend to be concentrated close to the cliff, then decrease in size moving offshore.

Joints distributed along the promontory perimeter isolate many rock-blocks, predisposing their activation in terms of falls and topples kinematics; the opening of the joints can reach in some cases the order of 20 cm. Isolation of blocks is also controlled by the numerous anthropic cuts related to the past quarry activities carried out in the promontory.

Anthropogenic landforms

The main anthropogenic geomorphological element is represented by the abundant cuts distributed along the coasts. Their height ranges from 1 to 5 m and, in general, quarry shelves are organized in three differentiated orders.

Runoff and running waters-related landforms

The drainage network characterizing the study area is controlled by the presence of the superficial deposits (*i.e.*, EU, ECU and AU). The overlapping of these erodible units above the bedrock basement (*i.e.*, TU) favors the development of rills (Figure 3b). In some cases, these landforms are able to cut the entire stratigraphic sequence of superficial deposits even affecting the TU itself.

Lito-structural landforms

Some WNW-ESE structural lineaments have been recognized. They are probably related with the structural set-up of the area that is controlled by the syn-caldera lithostratigraphic unit deposition system. The trend of these lineaments is curiously consistent with that of other structural elements reported for the island by Rossi & Medaglia (2016).

DISCUSSION

Based on a multi-approach analysis carried out in the study area, an engineering-geological model of the Punta Eolo promontory was conceptualized (Annex I). Furthermore, the 3D geological model (Figure 4) has served as a fundamental tool for visualizing stratigraphic information within the study area.

The PGT Formation, here presented as Tuff Unit (TU), is widely covered by the Eluvial-colluvial Unit (ECU). The surveyed field evidences testify that the remnant portion of the archaeological structures are founded directly on the bedrock or, at most, on the eolian deposits (*i.e.*, EO) (Figure 3; Figure 4). It is therefore plausible to assume that most of the thickness of the ECU was produced after the construction and the subsequent abandonment of Villa Giulia, that occurred around the end of the 1st century CE. EUC outcrops are concentrated along the borders of the topographic high of the promontory. This finding proves that the aforementioned ECU accumulation zones represent a very gentle slope talus that connects the upper part of the promontory with the lower one. This latter is nowadays represented by a flat platform generated by the past quarrying activities. The topographic difference existing between the southern section of the study area (*i.e.*, the service area) with the northern one (*i.e.*, the residential area) also favors a high ECU outcrops concentration and thickness.

Regarding the eolian deposits (*i.e.*, EU), they are mainly concentrated in the northernmost sector of the study area (Annex I). The thickness of this engineering-geological unit gradually decreases from East to West, ranging from 5 to 50 cm. This E-W oriented variation may be related to the depositional mode of an eolian deposit, that is controlled by the wind direction and tends to be organized in dunes. Dunes are characterized by a topset (*i.e.*, the face oriented against the wind), a foreset (*i.e.*, the face downwind oriented), and a maximum thickness that is located close to the foreset. In Ventotene the prevailing wind is from the West (Ruberti *et alii*, 2020), so it is plausible that in a free-field condition a sedimentary structure such as a wind-dune would be structured with a W-exposed topset, an E-exposed foreset and a maximum thickness located close to the East rather than the West.

Even if the *in situ* identification of the tuffs layering is not easy, a E-SE dipping (120/7°) of the TU was recognized. This result is in accordance with the geometry of the Ventotene volcanic edifice: it was characterized by an eruptive center located to the West of the island area that is nowadays occupied by the collapsed volcanic caldera. The area today coincident with the island represents the E-SE volcanic flank. The layering of TU therefore reflects the stratigraphic structure of the volcanic edifice in its eastern part.

The extension of the Punta Eolo promontory had to be broader in the past. In fact, coastal retreat processes are very common in Ventotene island and the study area is no different in this respect. The architectural structure of the archaeological site suggests that the Roman residence must have been larger, especially in the residential area site. In particular, the access and service roads were probably located in the western sector if the complex, as well as the underground aqueduct structures fed the water supply of the imperial building (De Rossi, 2019). Nowadays none of such structures are preserved, suggesting that the coastline stretch on which they were founded collapsed. These data, after all, agree with the geomorphology of the promontory, characterized by numerous slope instability processes located along the western cliff.

Numerous of the joints belonging to the J1, J2 and J3 sets are able to isolate parietal rock-blocks and to predispose their future activation in terms of landslide process. The isolation of the blocks is many times made possible thanks to the presence of an anthropic cut that locally represents the slope face of the cliff. The HVNSR rotate results show a polarization in terms of volumetric waves component (*i.e.*, *P*- and *S*- waves) along azimuthal direction orthogonal to the edge of the blocks. This result proves a directivity of the particle motion inside the rock-block, testifying their isolated nature.

CONCLUSIONS

This study proposes the first high resolution engineering-geological model of Punta Eolo promontory in Ventotene island (Italy), where the important archaeological site of the Roman “Villa Giulia” is located. Special attention was devoted to *i*) map the contacts between the superficial deposits and the tuffaceous bedrock, and *ii*) detail the geomorphological setting of the promontory. Considering the absence of boreholes data, the geophysical survey represented an essential tool to bind the subsurface stratigraphy and to constrain the thicknesses of the engineering-geological units. In particular, the HVSNR results highlight a tuff’s thickness of about 60 m (below which lavas are located) and a superficial deposits thickness variable between 4 and 9 m.

The multiapproach of analysis allowed to recognize several parietal rock-blocks geometrically decoupled from the stable tuffaceous plateau, and for this reason susceptible to be gravitationally activated with a fall or topple kinematics.

In terms of geological risk analysis, the rocky landslides represent the dominant geological hazard; secondly, surface water runoff, organized in rills and gullies, stands for the second most important hazard for the preservation of the Roman ruins of Villa Giulia complex.

Future studies will be developed to carry out slope stability analyses of the sea-cliff. In this framework, the influence of the meteo-climatic conditions on the activation and evolution of rocky landslides will be investigated, with a special attention on the impact waves action on the cliff. Monitoring of the deformation process of a sector of the sea-cliff prone to landslide would represent an essential resource for these purposes.

ACKNOWLEDGMENTS

This research was financed by “Toolbox for assessing and mitigating Climate Change risks and natural hazards threatening cultural heritage - TRIQUETRA” project financed by the EU HE research and innovation program under GA No. 101094818 (Scientific Responsible for Sapienza University of Rome: S. Martino). Special thanks go to the Ventotene Municipality and M. Pagano of the Idrogeo s.r.l. Company for their assistance and for sharing technical information on the bathymetric survey as well as the geotechnical and geophysical survey conducted at Punta Eolo. The Authors would also wish to thank Federico Lavaroni and Antonio and Dario Santomauro for their collaboration in the field activities.

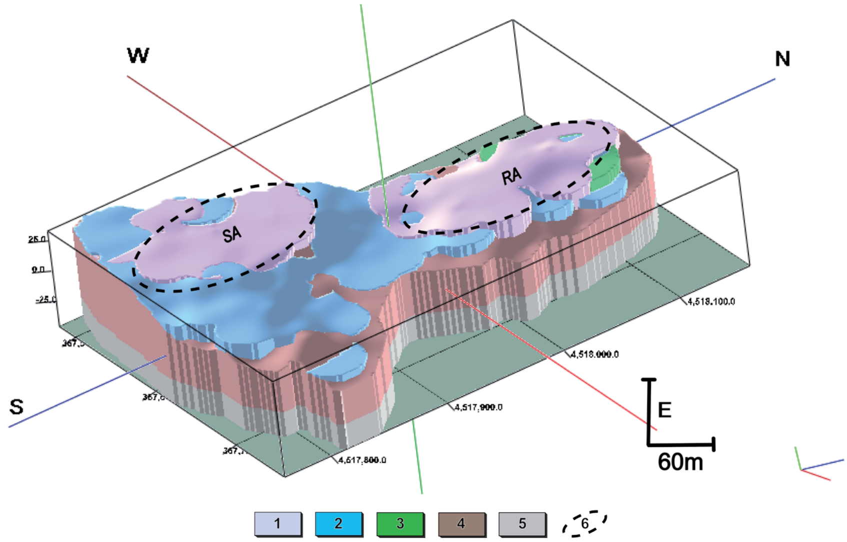

Fig. 4 - 3D model of the Punta Eolo area. Legend: (1) Anthropic Unit (AU); (2) Eluvial-Colluvial Unit (ECU); (3) Eolian Unit (EU); (4) Tuff Unit (TU) (MTU and STU members are paired); (5) Lavas Unit (LU); (6) Service archaeological area (SA) and residential archaeological area (RA)

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Received January 2024 - Accepted March 2024