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

ANALYSIS OF THE LOCAL SEISMIC RESPONSE IN THE STROVOLOS MUNICIPALITY (NICOSIA DISTRICT, CYPRUS)

Roberto IANNUCCI[(*,**)], Benedetta ANTONIELLI[(*,**)], Marcello CORADINI[(***)], Vassilios KARASTATHIS[(****)], Charilaos MANIATAKIS[(*****)], Salvatore MARTINO[(*,**)], Lorenzo MESSINA[(*)], Evangelos MOUZAKIOTIS[(****)], Antonella PACIELLO[(******)], Stefano RIVELLINO[(*,**)], Charalampos SAROGLOU[(*****)] & Francesca BOZZANO[(*,**)]

(*)Sapienza University of Rome - Department of Earth Sciences - P.le Aldo Moro, 5 - 00185 Rome (Italy)
(**)Sapienza University of Rome - CERI, Research Centre for Geological Risk - P.le Aldo Moro, 5 - 00185 Rome (Italy)
(***) Space System Solution (S3) Ltd - Lord Byron str, 36 - Nicosia Tower Centre, Floor 7, - 1096 Nicosia (Cyprus)
(****)NOA - National Observatory of Athens - Institute of Geodynamics - Thissio P.O. Box 20048 - 18110 Athens (Greece)
(*****)NTUA - National Technical University of Athens - Iroon Polytechniou str - 15780 Athens (Greece)
(******)ENEA - Italian National Agency for New Technologies and Sustainable Economic Development - Via Anguillarese, 301 - 00123 Rome (Italy)
Corresponding author: roberto.iannucci@uniroma1.it

EXTENDED ABSTRACT

I terremoti sono uno dei principali rischi naturali del nostro Pianeta, causando ogni anno ingenti perdite alle comunità locali e severi danni a strutture, infrastrutture ed attività antropiche. L'Europa, e in particolare l'area Mediterranea, rappresenta una regione storicamente caratterizzata da un'alta frequenza di terremoti, i quali hanno causato danni ad edifici e centinaia di vittime come durante la sequenza sismica che ha colpito l'Italia Centrale nel 2016-2017, durante la quale sono stati osservati effetti devastanti legati ad una combinazione di effetti locali di amplificazione del moto sismico e una considerevole vulnerabilità dell'edificato.

Negli ultimi decenni l'analisi della risposta sismica locale e gli studi di microzonazione sismica si sono sempre più diffusi quali strumenti fondamentali per la valutazione e la mitigazione del rischio sismico delle aree urbane nonché per la salvaguardia di siti di particolare interesse per il loro patrimonio archeologico e architettonico. In questo lavoro, svolto nell'ambito del progetto H2020-RISE "STABLE - Structural stABLity risk assEsment", è stata eseguita un'analisi della risposta sismica locale, integrando dati geologici, geotecnici, geofisici e di modellazione numerica. L'area investigata ricade nel comune di Strovolos, situato nella parte centrale dell'isola di Cipro, all'interno del distretto di Nicosia, in un'area interessata da una pericolosità sismica regionale medio-alta come testimoniato da frequenti e forti terremoti registrati in passato.

L'area di studio è ubicata nella piana di Mesaoria bordata dalle due catene montuose principali di Cipro, i Troodos nella parte sud-occidentale costituiti da rocce di crosta oceanica (Cretacico superiore) e i Kyrenia nella parte settentrionale formati prevalentemente da calcari ben stratificati (Permiano) e marginalmente da rocce ignee e metamorfiche. In particolare, l'abitato di Stovolos è localizzato nell'area di affioramento della successione sedimentaria del Circum Troodos che deriva dall'erosione dei litotipi appartenenti alle suddette catene montuose; in particolare è, edificato sui depositi alluvionali quaternari che giacciono sulla Formazione di Nicosia (Plio-Pleistocene), costituita da marne e marne siltose sovraconsolidate (spessore massimo di circa 250 m), sovrapposta alle marne calcaree mioceniche della sottostante Formazione di Lefkcara.

Una valutazione della pericolosità sismica di base per diversi periodi di ritorno (50, 475 e 2000 anni), è stata eseguita mediante un approccio combinato probabilistico e deterministico. Successivamente è stata eseguita la ricostruzione del modello geologico-tecnico di sottosuolo, utilizzando dati di indagini pregresse, quali *log* di perforazioni e risultati di prove geotecniche, e il rilievo geologico specifico di campo. Sono state inoltre effettuate misure di rumore ambientale sismico a stazione singola volte ad identificare le frequenze fondamentali di sito e, pertanto, preliminarmente le aree interessate da possibili effetti di amplificazione locale del moto sismico.

La modellazione geologico-tecnica ha permesso di individuare 2 differenti zone nel Comune di Strovolos, con relative colonne sismostratigrafiche, che differiscono per spessore e tipologia di depositi alluvionali: i) STR-Z1, avente nella parte superiore i depositi alluvionali attuali del Fiume Pedieos, e ii) STR-Z2, avente nella parte superiore depositi alluvionali quaternari più antichi. In entrambi i casi la successione di depositi poggia sulle Marne di Nicosia, membro marnoso della Formazione di Nicosia. Le analisi effettuate sulle misure di rumore sismico ambientale restituiscono un picco HVSR a circa 0.4-0.5 Hz, testimonianza di un contrasto di impedenza sismica profondo, probabilmente relativo al contatto tra la Formazione di Nicosia e la Formazione di Lefkara. Questo risultato evidenzia l'assenza di un significativo contrasto di impedenza tra i diversi depositi alluvionali e le Marne di Nicosia e che, pertanto, l'intera successione stratigrafica agisce come strato risonante sovrastante la Formazione di Lefkara.

Infine, sono state eseguite simulazioni numeriche 1D con il codice *open source* Strata, utilizzando colonne sismostratigrafiche rappresentative del modello geologico-tecnico del sottosuolo, per quantificare la risposta sismica locale. Gli spettri di risposta elastica ottenuti, per ciascun periodo di ritorno analizzato, hanno mostrato un aumento non trascurabile del moto sismico di base, in particolare per STR-Z2 avente un maggiore spessore di depositi alluvionali, che potrebbe essere considerato per possibili interventi idonei a migliorare le prestazioni degli edifici in caso di scuotimento sismico nell'area di insediamento di Strovolos.

ABSTRACT

Local seismic response analysis and microzonation studies represent fundamental tools for assessment and mitigation of the seismic risk in urban areas and cultural heritage sites. In this work, in the framework of the H2020-RISE "STABLE - Structural stABLity risk assEsment" project, local seismic response analysis by an integrated approach was performed in Strovolos municipality located in the central part of the island of Cyprus, within the Nicosia District, built on the alluvial deposits of the Mesaoria plain and affected by medium-high regional seismic hazard.

An assessment of the basic seismic hazard for different return periods was, firstly, performed by a combined probabilistic and deterministic approach. Then, the reconstruction of the engineering geological model of the subsoil, using available borehole logs, geotechnical test results and specific geological field survey was carried out; seismic ambient noise measurements, aimed to preliminarily identify areas with possible local amplification, were carried out as well.

Finally, 1D numerical simulations, on seismostratigraphic columns representative of the engineering geological subsoil model, were performed through the software Strata to quantify the local seismic response of the site. The elastic response spectra obtained, for each analysed return period, showed a significant increase of the basic seismic motion which could be considered for possible interventions suitable to improve the buildings performance in the case of seismic shaking in the Strovolos settlement area.

Keywords: *engineering geological modelling, seismic ambient noise, seismic hazard, numerical modelling*

INTRODUCTION

Earthquakes represent one of the major natural hazards worldwide, causing yearly significant losses to local communities and inducing severe damages on buildings and human activities (Badal *et alii*, 2005). Europe, and particularly the Mediterranean area, represents a region historically characterised by an high occurrence of earthquakes (Grünthal *et alii*, 2013; Stucchi *et alii*, 2013), that can induce severe damages on buildings and hundreds of casualties, as occurred in Central Italy during the 2016-2017 seismic sequence (Stewart *et alii*, 2018), where devastating effects were observed due to a combination of local seismic amplification effects (Sextos *et alii*, 2018) and a considerable seismic vulnerability of the involved settlements (Sorrentino *et alii*, 2019).

In recent decades, a large body of literature about local seismic response and seismic microzonation studies (e.g., ICMS Working Group, 2008; Gaudiosi *et alii*, 2014; Martino *et alii*, 2015; Macerola *et alii*, 2019; Moscatelli *et alii*, 2020; Pergalani *et alii*, 2020; Antonielli *et alii*, 2021; Varone *et alii*, 2021) evidenced how the evaluation of the seismic shaking expected in a given site can be reliably assessed using integrated approaches, based on engineering geological modelling, geophysical investigations and numerical modelling.

In the framework of cultural heritage protection, the H2020-RISE "STABLE - Structural stABLity risk assEsment" project (www.stable-project.eu; Serpetti *et alii*, 2020) aims at assessing the seismic action by a site-specific local seismic analysis and the vulnerability of selected historic buildings to evaluate the damages expected for the following historical centres of the Mediterranean area: Rieti (Italy), Nafplio (Greece) and Strovolos (Cyprus).

Strovolos is a municipality located in the central part of the island of Cyprus, within the Nicosia District, and built on the alluvial deposits of the Mesaoria plain. In the past, Cyprus was affected by several strong earthquakes that produced severe damages especially in the southern and western parts of the island (Ambraseys & Adams, 1993; Kalogeras *et alii*, 1999; Papazachos & Papaioannou, 1999; Papadimitriou & Karakostas, 2006), even if amplification effects of the seismic motion have to be accounted in the Nicosia District area due to the outcropping of recent alluvial deposits (Algermissen & Rogers, 2004).

In this study, the local seismic response analysis of the Strovolos municipality area was performed according to the following main analysis steps: i) assessment of the basic seismic hazard for different return periods (i.e., 50, 475 and 2000 years), ii) reconstruction of the engineering geological model of the subsoil, iii) execution of single-station seismic ambient noise measurements, iv) 1D numerical simulations to define the local seismic response of the site. Following a seismic vulnerability analysis of the buildings composing the Strovolos urban settlement, the acceleration time histories and elastic response spectra obtained for each return period by numerical simulations will be provided to evaluate the type of interventions suitable to improve the building performance in the case of future earthquakes.

GEOLOGICAL SETTING

The Nicosia District and the Strovolos Municipality area are located within the large Mesaoria basin that is bordered by the two main mountain ranges of Cyprus: the Troodos mountain range, developed on the south-west part of the island, and the Kyrenia mountain range, in the northern part (Fig. 1).

Four main stratigraphic successions compose the island of Cyprus (Fig. 1), thus indicating different depositional environments: the Troodos terrane, the Mamonia complex, the Kyrenia succession and the Circum Troodos succession.

The Troodos terrane outcrops on the Troodos mountain range

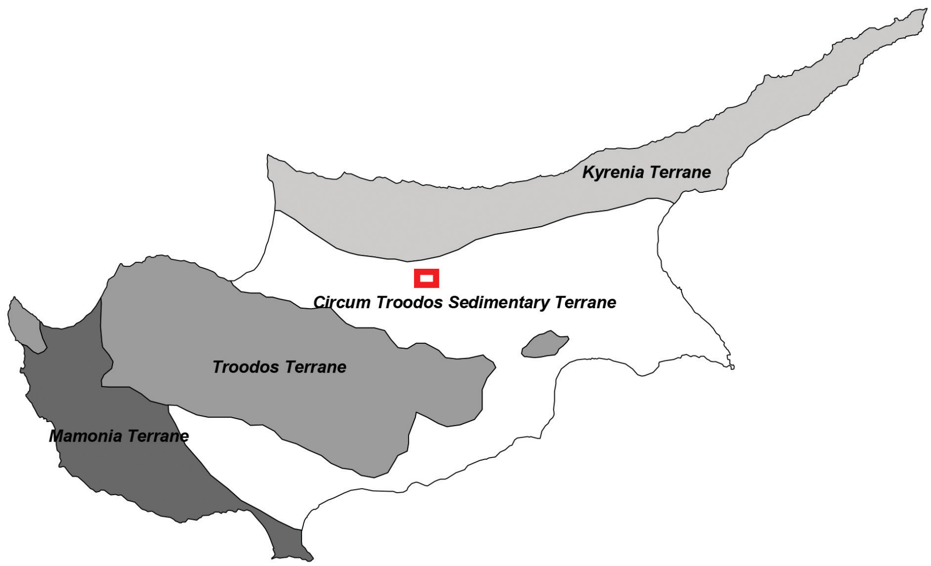

Fig. 1 - Geological sketch showing the four main stratigraphic successions composing the island of Cyprus (from Panayides *et alii, 2004); in the red frame the Strovolos Municipality*

and is composed of Upper Cretaceous oceanic crust and mantle material that was obducted onto continental crust during the Cretaceous age (Gass & Masson-Smith, 1963). The succession is characterised by the following sequence of rocks, in ascending order: ultramafic complex, plutonic ultramafic and mafic rocks, sheeted dike complex, mafic volcanic sequence of mostly pillowed lava flows, iron- and manganese-rich hydrothermal sediments.

The Mamonia complex is composed of igneous, sedimentary and metamorphic rocks which have undergone intense deformation following a faulting in a transcurrent regime (Swarbrick, 1993) and outcrops mainly in western and southwestern parts of Cyprus and partially in the southeastern part of the island.

The Kyrenia succession is located in the northern part of the island and has a stratigraphic sequence characterised mainly by well-stratified allochthonous Permian limestones, and marginally by metamorphic and igneous rocks which have overrun above clastic and limestone sediments of late Cretaceous-Miocene age (Baroz, 1979).

The Circum Troodos succession outcrops in the central and south-western part of the island and it is characterised by a sequence of sedimentary rocks mainly resulting from the erosion related to the regional uplift of the two mountain ranges bordering the Mesaoria basin, i.e., the Troodos range to the south-west and the Kyrenia mountains to the north. The bottom of this sedimentary succession corresponds to the Kannaviou Formation, composed of volcano-clastic sandstones, silts and bentonic clays (Lord *et alii*, 2000). In southern Cyprus, the Kannaviou Formation is overlaid by the Lefkara Formation, which typically consists of pelagic marl and white chalk and the Pakhna Formation, a cream to buff-brown chalks and marls. During the late Miocene marine regression, i.e., the Messinian salinity crisis, the Kalavasos Formation was deposited in northern Cyprus (Necdet & Anil, 2006), consisting of gypsum and gypsiferous marls deposited in restricted and structurally controlled basins (Robertson *et alii*, 1995a; Harrison *et alii*, 2004).

The Nicosia Formation was deposited during the Pliocene and Pleistocene and includes several marine depositional facies. The Nicosia Formation is considered a time transgressive sequence of detrital derived largely from older units. It was deposited on the northern flank of the emerging Troodos Range and contains significant intraformational unconformities. The dominant facies is the Nicosia Marl Member (Tnm), which deposited during the Pliocene and is composed of greyish or yellowish marls. The Kephales Member (Pleistocene) is a marine delta facies and consists of a series of conglomerates and sandstone, while the Athalassa Member (Pleistocene) is composed of calcarenites interlayered with sandy marls.

The Nicosia area is divided between the Kyrenia terrane and the Circum Troodos sedimentary succession; in particular, the Strovolos urban settlement is built on the deposits of the latter.

SEISMIC HAZARD ASSESSMENT

Seismic hazard assessment for the region was carried out using a combined probabilistic and deterministic approach. The main goal was to estimate the expected peak ground acceleration (PGA) for specific return periods (50, 475 and 2000 years) using a probabilistic approach and then performing scenario based deterministic calculations in order to derive synthetic accelerograms that would correspond to such return periods. These synthetic waveforms implicitly take into account the local faults characteristics, thus providing greater validity to the seismic response analysis that will be carried out in a next step.

In this study, a probabilistic seismic hazard assessment (PSHA) was performed based on the zonation scheme and the corresponding seismicity parameters proposed by Papaioannou (2001) and Cagnan & Tanircan (2010), which includes 4 shallow and one deep seismic zone in the region of Cyprus. A hybrid attenuation relationship was used, including the attenuation relationships by Segou & Voulgaris (2013), applicable to the broader Greek and Turkish region for magnitudes up to M 6.6 and the one proposed by Campbell & Bozorgnia (1994) for the Eastern Mediterranean region for higher magnitudes. For the study area of Strovolos in Nicosia, rock site conditions were assumed. The resulting PGA value for a return period of 475 years is 0.259 g, whereas for return periods of 50 and 2000 years the corresponding values are 0.094 and 0.379 g respectively.

As a next step, a deterministic seismic hazard assessment (DSHA) was performed in order to develop accelerograms that would correspond to the aforementioned PGA values and that would take into account the local active faults. At this aim we used the stochastic simulation of ground motion methodology (Boore, 1983), expanded for finite sources by Beresnev & Atkinson (1997) and modified in order to implement a dynamic corner frequency by Motazedian & Atkinson (2005). With this technique the acceleration spectra are simulated by combining information regarding the source, the path and the site effects. With respect to the source term, the characteristics of the local active faults were taken into account. In general, the most significant local tectonic structures that can be associated with seismic activity are showed in Fig. 2a. These are the Paphos Thrust, the Kannaviou Fault System, the Arakapas Fault Zone, the Larnaca Fault Zone, the Ovgos Fault Zone and the Trakhoni, Yerasa, Arkhangelos, Mia Milea, Odhou and Skali faults (more details are provided by Malpas & Xenophontos, 1999; Soulas, 2001; Algermissen & Rogers, 2004; Harrison *et alii*, 2004; GEOTER, 2005a, 2005b). The above-mentioned fault zones were implemented as planar fault surfaces with specific geometrical characteristics (Fig. 2b), discretized in a series of point sources. The synthetic time series for each fault case were obtained by convolving the individual time series of each point source. For the path effect, a geometrical spreading factor of 1/R was implemented with the anelastic attenuation model of Atkinson & Boore (1995) and the associated duration model. With regards to the site effect, the spectral attenuation coefficients for rock sites proposed by Klimis (1999) were used.

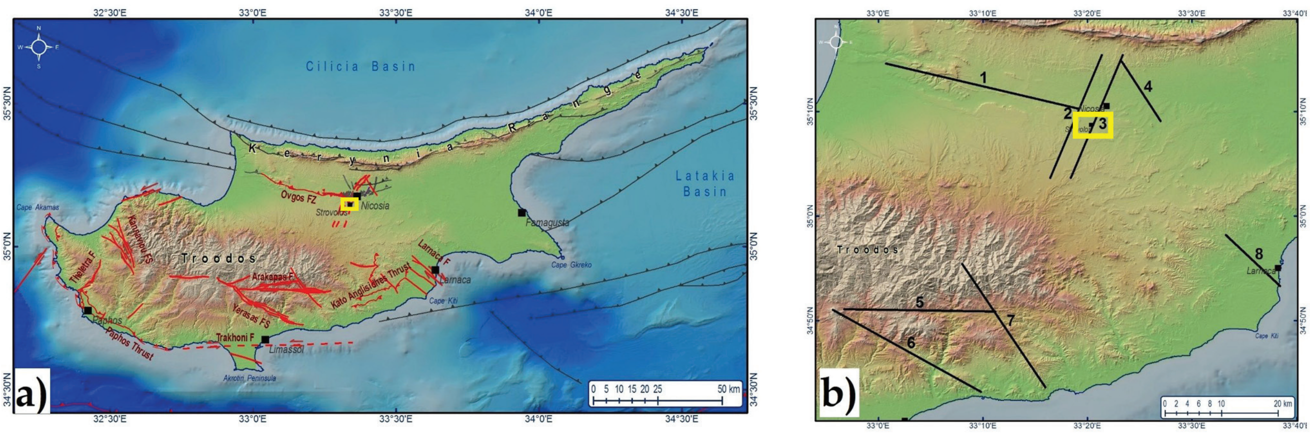

Fig. 2 - a) Active faults of Cyprus as presented in the manuscript (in red) and other tectonic structures (gray), b) seismic sources used in the stochastic simulations: 1) Ovgos fault zone, 2) Arkhangelos fault, 3) Skali fault, 4) Mia Milea fault, 5) Arakapas FZ, 6) Yerasa fault, 7) Odhou Fault and 8) Larnaca fault zone; in the yellow frame the Strovolos Municipality

In order to obtain synthetic accelerograms with PGA values corresponding to those calculated through a probabilistic approach, we simulated several different scenarios for each fault, with varying magnitudes up to the maximum magnitude for each fault case (Wells & Coppersmith, 1994). Due to the fact that the tested faults were located at different distances from Strovolos and had various geometrical characteristics, the resulting accelerograms showed significant differences in duration and spectral characteristics, despite having the same PGA values (examples for return period of 475 years is shown in Fig. 3). Therefore, the resulting waveforms incorporate the effect of the local seismotectonic regime and are used as a basis for further response analysis for the Strovolos area.

ENGINEERING GEOLOGICAL MODELLING

The engineering geological model for the subsoil of the Strovolos area was defined by analysing and interpreting already available geological surveys data, borehole logs and geotechnical test results, mainly performed within the “Seismic hazard and risk assessment of the greater Nicosia area” project (Panayides *et*

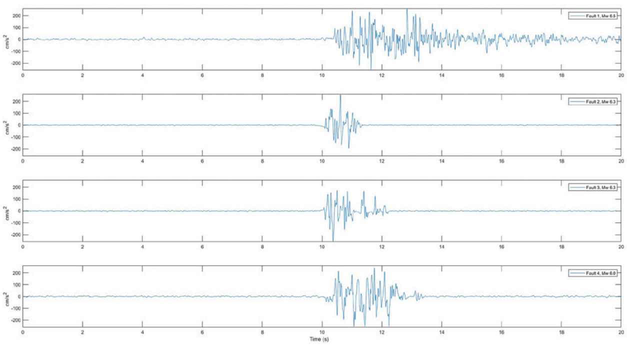

Fig. 3 - Synthetic time series obtained by the DSHA for PGA=0.259 g, corresponding to a return period of 475 years, as calculated by the PSHA

Fig. 4 - View of the recent fluvial deposits (Qal) of the Pedieos River

alii, 2004; Petrides *et alii*, 2004), and specific geomorphological and engineering geological surveys carried out on the site. This model evidenced that the Strovolos urban settlement is built on alluvial deposits of different ages that lie on the Nicosia Formation (Fig. 5 and 6).

In proximity of the Pedieos River recent fluvial deposits (Qal), commonly with 1-2 m of thickness, composed of gravel, sand, silt and clay and some organic material, deposited by modern ephemeral streams in channels eroded into older alluvial deposits, are present (Fig. 4).

Under and laterally to the recent Pedieos River alluvia, two sub-horizontal Quaternary alluvial deposits, from top to bottom, are present: i) Qf2, composed of silt, fine sand and clay, pebbles and cobbles, sparse amounts of organic and archaeological materials, with thickness between 1 and 4 m, and ii) Qf1, composed mainly of sand and gravels, locally characterised by carbonate cementations, whose thickness does not exceed 5 m.

In the study area, as well as in the rest of the Mesaoria plain, below the alluvial deposits the Nicosia Formation is present. In particular, the Nicosia Marl Member (Tnm), composed of marl, silty marl, and small amounts of sand marl, fossiliferous, massive to planar bedded, locally extensively burrowed, with a thickness of about 250 m was identified.

Based on site investigations already performed in the study area, the Nicosia Marl Member can be divided into two parts (Petrides *et alii*, 2004). The upper part consists of stiff yellowish

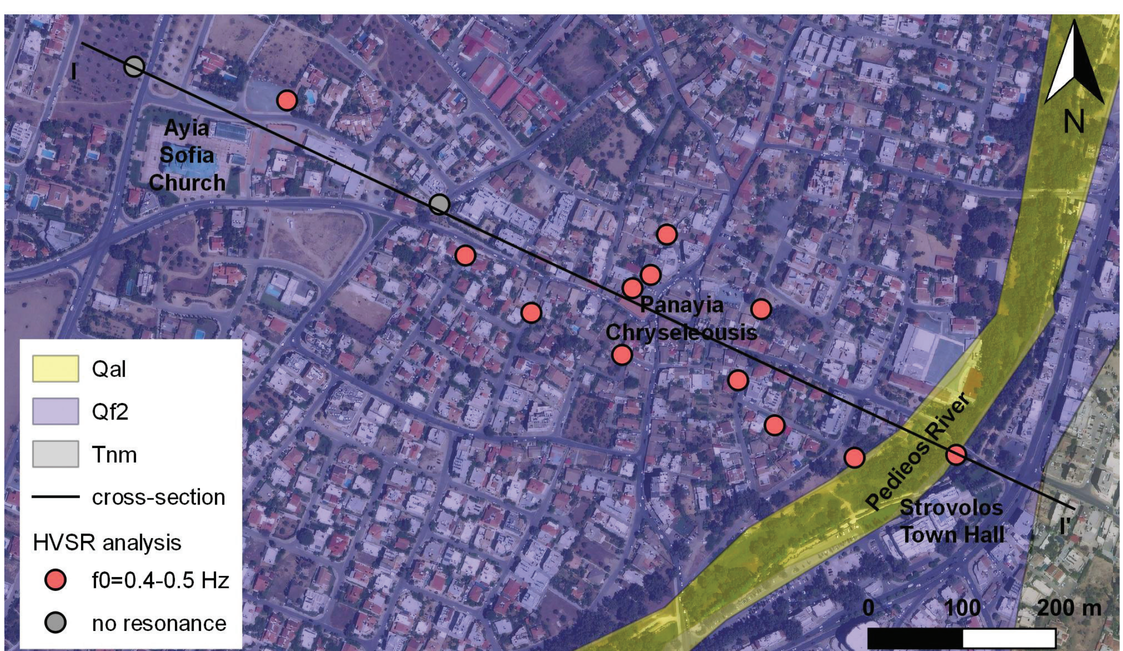

Fig. 5 - Engineering geological map of Strovolos with the site resonance frequency by the HVSR analysis. Legend: Qal - Pedieos River alluvial deposits; Qf2 - Quaternary alluvial deposits mainly composed of silt, fine sand and clay; Tnm - Nicosia Marl Member

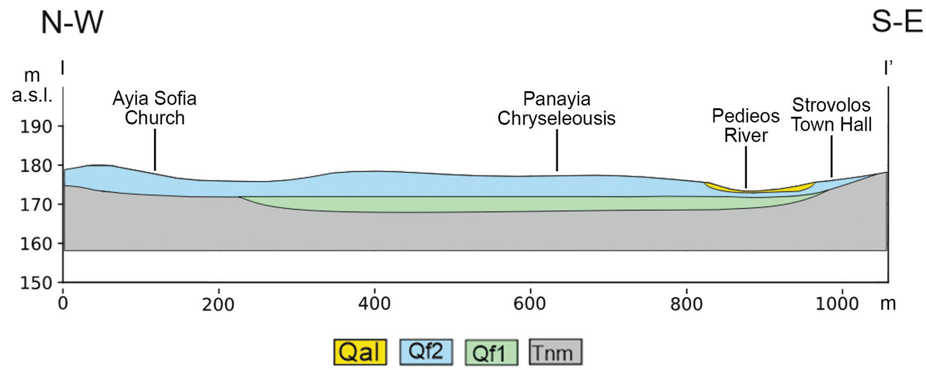

Fig. 6 - Engineering geological cross-section of Strovolos (see Fig. 4 for location). Legend: Qal - Pedieos River alluvial deposits; Qf2 - Quaternary alluvial deposits mainly composed of silt, fine sand and clay; Qf1 - Quaternary alluvial deposits mainly composed of sand and gravels; Tnm - Nicosia Marl Member

marls having a thickness of about 10 m. These yellowish marls are the result of weathering that changed the characteristics and properties of the early levels of the Nicosia Formation. Their lower part is composed of overconsolidated grey marls.

At the bottom of the Nicosia Formation, the Miocene deposits of carbonate platform and calcareous marl deposits of the Lefkara Formation can be identified even if they do not crop out in the study area.

SEISMIC AMBIENT NOISE MEASUREMENTS

Based on the reconstructed engineering geological model, 14 single-station seismic ambient noise measurements were carried out in the Strovolos Municipality area (Fig. 5). The measurements were distributed along the engineering geological cross-section (Fig. 6) covering the zones in which the two different alluvial deposits outcrop, i.e., STR-Z1 with the recent Pedieos river alluvial deposits (Qal) and STR-Z2 with the Quaternary alluvial deposits (Qf2).

The single-station seismic ambient noise measurements were performed using SL06 24-bit digitizers with built-in SS20 three-component velocimeter (2.0 Hz eigenfrequency) by SARA Electronic Instruments, set to a sampling frequency of 200 Hz. Seismic ambient noise was recorded for 1 hour in each measurement point.

The single-station seismic ambient noise measurements were analysed according to the Horizontal-to-Vertical Spectral Ratio (HVSR) technique, proposed by Nogoshi & Igarashi (1970, 1971) and analytically implemented by Nakamura (1989) to evaluate the fundamental resonance frequency of a site (f_0). The HVSR technique can be easily applied to evaluate the 1D stratigraphic resonance in a low S-wave velocity layer lying on a seismic bedrock (Bour *et alii*, 1998; Haghshenas *et alii*, 2008). This is shown by a clear peak in HVSR function (SESAME, 2004) characterised by the "eye-shape" feature in the Fourier amplitude spectra (Castellaro & Mulargia, 2009), i.e., an increase of the horizontal Fourier spectra and a decrease of the vertical Fourier spectrum, and with no marked evidence of polarization.

The HVSR analysis was carried out using the Geopsy software (Wathelet *et alii*, 2020) for each single-station seismic ambient noise measurement as follows: i) computation of the Fast Fourier Transform (FFT) for the three motion components on non-overlapping time windows of 40 s with 5% cosine taper; ii) application of the smoothing function by Konno & Ohmachi (1998) on the single-window FFT spectra; iii) computation of the single-window HVSR as FFT spectra ratio between the quadratic mean of the two horizontal components (H) and the vertical component (V); iv) computation of the mean HVSR function by averaging the single-window HVSR. In addition, the Geopsy software was used also to analyse the possible polarization of the HVSR peaks. Using this specific tool, the average HVSR was computed from 0° to 180° every 10° and the HVSR curve was reconstructed in the horizontal plane as a function of the azimuth.

The results of the analysis carried out on all the measurements on both the recent Pedieos River alluvial deposits (Qal) and the Quaternary alluvial deposits (Qf2) presented a main HVSR peak at about 0.4-0.5 Hz, anticipated by a secondary weaker HVSR peak at about 0.3 Hz (Fig. 5 and 7). No other HVSR peaks were observed at higher frequencies. In a few cases, the HVSR curve does not reach an amplitude value equal to 2 (i.e., the threshold value to consider significant a HVSR peak) and the measurement was classified with no resonance (Fig. 5).

Considering the low frequency value, the HVSR peak at about 0.4-0.5 Hz could represent a deep seismic impedance contrast, probably related to the contact between the Nicosia Formation and the Miocene deposits of carbonate platform and calcareous marl deposits of the Lefkara Formation. This result evidences that no significant seismic impedance contrast exists between the alluvial deposits (i.e., Qal, Qf2, Qf1) and the Nicosia Marl Member (i.e., Tnm), but the whole multi-layered stratigraphic sequence seems to act as a resonant body on the deep contact with the Lefkara Formation. The presence of the "eye-shape" feature in the Fourier amplitude spectra at the same frequencies confirms that the main

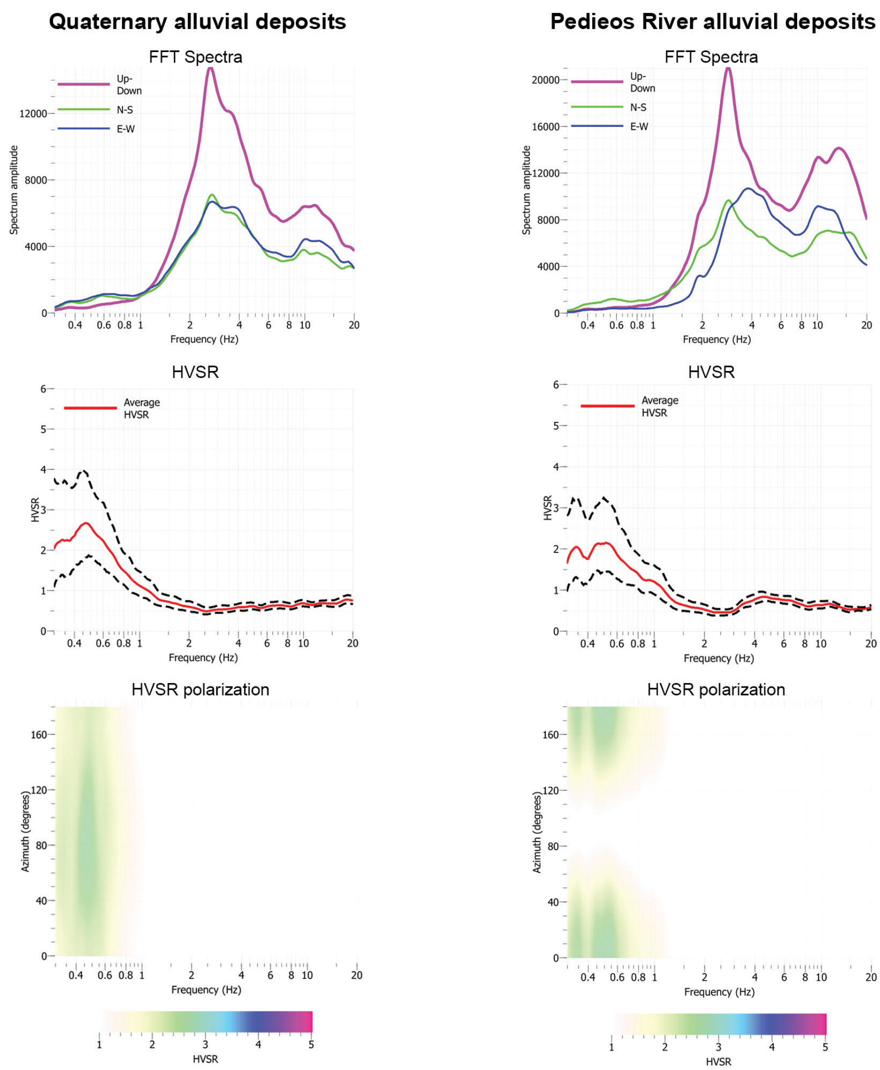

Fig. 7 - Examples of FFT spectra, HVSR function (the dashed black lines show the standard deviation of the curve) and HVSR rotate plot at Strovolos obtained on the Quaternary alluvial deposits (left panel) and Pedieos River alluvial deposits (right panel)

HVSR peak can be associated with a seismic resonance, even if the presence of slight polarization features identifies a not purely 1D seismic resonance.

NUMERICAL MODELLING OF LOCAL SEISMIC RESPONSE

In order to quantify the seismic local response in the Strovolos Municipality area, a 1D numerical modelling of seismic wave propagation was performed using the Strata software (Kottke & Rathje, 2008). This software allows to compute the dynamic site response of a one-dimensional soil column using linear wave propagation with strain-dependent dynamic soil properties and an analysis with an equivalent linear approach in the frequency domain.

The input motions used in the modelling are based on the synthetic accelerograms produced with the basic seismic hazard assessment. A set of 7 recordings of real earthquakes was obtained for each analysed return period (i.e., 50, 475 and 2000 years) by the REXELweb tool (Sgobba *et alii*, 2021). In particular, a mean elastic response spectrum was computed for the synthetic accelerograms obtained for each return period and given to the REXELweb as a spectrum target. In this way, for each return period the tool provided a set of 7 earthquake recordings from the European Strong Motion Database (ESD) and the Italian Accelerometric Archive (ITACA) that ensures the spectrum compatibility between their mean elastic response spectrum and the one computed on the synthetic accelerograms (i.e., target spectrum).

To perform the modelling, 2 seismostratigraphic columns were extracted from the engineering geological cross-section of Strovolos

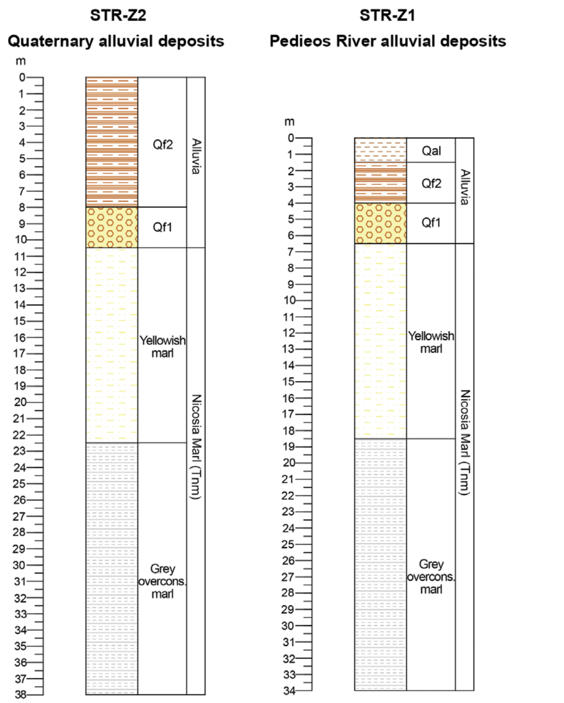

Fig. 8 - Seismostratigraphic columns obtained at Strovolos on the Quaternary alluvial deposits (STR-Z2, left panel) and Pedieos River alluvial deposits (STR-Z1, right panel)

to represent the different subsoil conditions recognised in the site (Fig. 8): i) STR-Z1 with the Pedieos River alluvial deposits at the top and ii) STR-Z2 with the Quaternary alluvial deposits at the top. A value or a range of values of unit weight volume (γ_n) and shear wave velocity (V_s) was associated to each litotechnical unit based on available geotechnical data (Petrides *et alii*, 2004). Dynamic parameters as shear stiffness and damping curves were obtained from already published data on similar soils.

A first linear elastic simulation was initially performed, by the Strata software, to validate the seismostratigraphic columns in terms of thickness of the layers, relative unit weight volume (γ_n) and shear wave velocity (V_s) values. In this regard, the values of these two parameters were varied within the value range shown by the geotechnical data up to a frequency value correspondence between the HVSR peak obtained by the seismic ambient noise measurements and the amplification function obtained by the modelling with Strata. Considering the high variability of the V_s values in the overconsolidated marls of Nicosia Marl Member, varying from 382 to 825 m/s, and the absence of a resonance indicating a superficial seismic impedance contrast, the V_s in the grey overconsolidated marls of this member was progressively increased of 100 m/s every 50 m of thickness, starting from 382 m/s in the upper part up to reach the value of 825 m/s at 250 m depth, where the unit was assumed as the local seismic bedrock. Under this depth the seismic bedrock in the column modelled by Strata was fixed.

Table 1 reports the obtained physical and geotechnical parameters associated with each litotechnical unit, that were used in the performed numerical modelling by adopting an equivalent linear solution.

Lithotecnical unit	γ_n (kN/m^3)	Vs (m/s)	Dynamic curves
Qal	18.00	209	Vucetic & Dobry (1991) for PI = 30
Qf2	18.00	173	Vucetic & Dobry (1991) for PI = 30
Qf1	20.00	336	Rollins *et alii* (1998) mean for gravels
Tnm - yellowish marl	19.20	282	Martino *et alii* (2015) for softened UMV
Tnm - grey overconsolidated marl	19.00	382-825	Martino *et alii* (2015) for softened UMV

Tab. 1 - Litotechnical units with the main physical and dynamic parameters identified at the Strovolos site

The numerical models were performed using the Strata software using a linear equivalent analysis for the three sets of earthquake recordings obtained for return periods equal to 50, 475 and 2000 years. This simulation allowed to obtain the acceleration time histories and an elastic response spectrum (5% damping) for each analysed return period (Fig. 9).

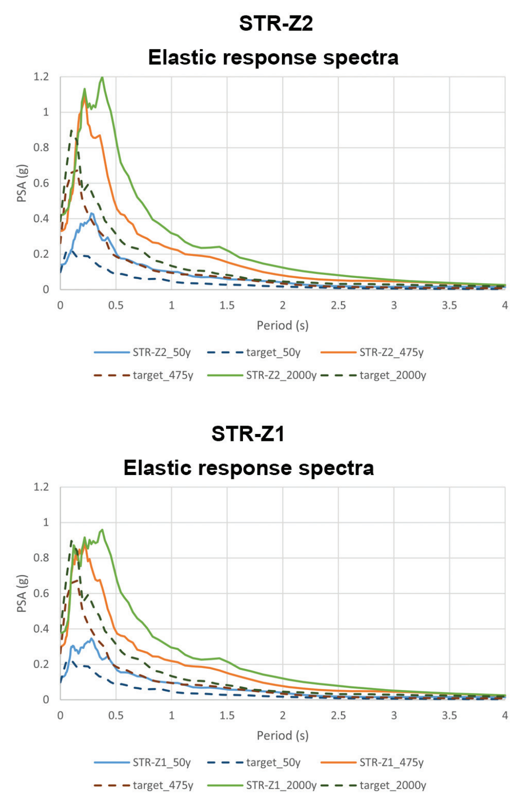

Fig. 9 - Elastic response spectra for return periods of 50, 475 and 2000 years obtained at Strovolos on the Quaternary alluvial deposits (STR-Z2, top panel) and Pedieos River alluvial deposits (STR-Z1, bottom panel); the target elastic response spectra obtained by the base seismic hazard analysis are also shown

The elastic response spectra evidenced an increase of the seismic motion in both the subsoil conditions for all the analysed return periods with respect to the target elastic response spectra computed on the basic seismic hazard analysis. Such modification of the seismic motion can be observed in terms of both increase of PGA values and a general rise of the whole elastic response spectra in all the periods of analysis with respect to the basic seismic hazard. A major increase of the seismic motion can be observed in the case of the Quaternary alluvial deposit outcropping (i.e., STR-Z2) with respect to the case of the Pedieos River alluvial deposit outcropping (i.e., STR-Z1); this is probably due to the presence of a thicker layer of alluvial deposits in the first case (see Fig. 8). The elastic response spectra obtained for each return period can be provided to evaluate the type of interventions suitable to improve the buildings performance in case of seismic shaking.

CONCLUSIONS

An assessment of the basic seismic hazard in the Strovolos municipality area was carried out for three different return periods (i.e., 50, 475 and 2000 years) by joining probabilistic and deterministic approaches to obtain synthetic acceleration time histories for the faults identified in the area and, subsequently, a study of the local seismic response of the area was carried out.

An engineering geological modelling for the subsoil in the investigated area as well as single-station seismic ambient noise measurements were performed; two different seismostratigraphic columns (i.e., STR-Z1 and STR-Z2) varying in terms of alluvial deposit thickness were derived from log-stratigraphy correlations.

The elastic response spectra obtained from 1D numerical simulations, provided, for all the considered return periods, an increase of the seismic motion in terms of both greater PGA values and a general rise of the whole elastic response spectra in all the periods of analysis with respect to the basic seismic hazard. Such an increase is more relevant in the zone where the alluvial deposits are thicker.

These results will be useful to evaluate the type of interventions suitable to improve the building performance in the case of future earthquakes in the Strovolos settlement area.

ACKNOWLEDGEMENTS

This research was carried out in the framework of the H2020-MSCA-RISE-2018 project "STructural stABiLity risk assEssment - STABLE" (Grant Agreement number: 823966).

The authors are grateful to P. Christou and P.A. Fokaides (Frederick University) for their support in organising field activities and to G. Grechi (Sapienza Università di Roma) and L. Schilirò (CNR-IGAG) for their useful support during the field activities.

In the present study: L. Messina contributed for engineering geological modelling and seismic ambient noise measurements within the framework of his master's thesis; B. Antonielli, R. Iannucci, A. Paciello and S. Martino performed engineering-geological modelling and carried out and analysed seismic ambient noise measurements; R. Iannucci and S. Rivellino performed numerical modelling of local seismic response; V. Karastathis, A. Mouzakiotis and C. Maniatakis performed basic seismic hazard analysis; F. Bozzano, M. Coradini and C. Saroglou supervised the research; R. Iannucci, L. Messina and A. Mouzakiotis prepared the draft paper; all the authors contributed in discussing the results and writing the final version of the manuscript.

REFERENCES

Algermissen T. & Rogers A. (2004) - *A Cyprus earthquake hazard assessment: Maps of probabilistic peak ground acceleration and uniform-hazard pseudo-absolute acceleration spectral response*. In: De Coster M., Zomeni Z., Panayides I., Petrides G. & Berksoy O. (eds.) - *Seismic hazard and risk assessment of Greater Nicosia area*. UNOPS Report, Nicosia (Cyprus), chapter **5**: 1-72.

Ambraseys N.N. & Adams R.D. (1993) - *Seismicity of the Cyprus region*. Terra Nova, **5**(1): 85-94.

Atkinson G.M. & Boore D.M. (1995) - *Ground-motion relations for eastern North America*. Bulletin of the Seismological Society of America, 85(1);17-30.

Antonielli B., Bozzano F., Fiorucci M., Hailemikael S., Iannucci R., Martino S., et alii (2021) - *Engineering-geological features supporting a seismic-driven multi-hazard scenario in the Lake Campotosto area (L'Aquila, Italy)*. Geosciences, **11**(3): 107.

Badal J., Vázquez-Prada M. & González Á. (2005) - *Preliminary quantitative assessment of earthquake casualties and damages*. Natural Hazards, **34**(3): 353-374.

Baroz F. (1979) - *Étude geologique dans le Pentadactylos et de La Mésaoria (Chypre septrionale)*. Ph.D. thesis, University of Nancy, 365 pp.

Beresnev I. A. & Atkinson G. M. (1997) - *Modeling finite-fault radiation from the ω n spectrum*. Bulletin of the Seismological Society of America, **87**(1): 67-84.

Boore D. M. (1983) - *Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra*. Bulletin of the Seismological Society of America, **73**(6A): 1865-1894.

Bour M., Fouissac D., Dominique P. & Martin C. (1998) - *On the use of microtremor recordings in seismic microzonation*. Soil Dyn. Earthq. Eng., **17**(7-8): 465-474.

Cagnan Z. & Tanircan G. B. (2010) - *Seismic hazard assessment for Cyprus*. Journal of Seismology, **14**(2): 225-246.

Campbell K.W. & Bozorgnia Y. (1994) - *Near-source attenuation of peak horizontal acceleration from worldwide accelerograms recorded from 1957 to 1993*. In: Proceeding of the 5th US National Conference on Earthquake Engineering, Earthquake Engineering Research, 283-292.

Castellaro S. & Mulargia F. (2009) - *The effect of velocity inversions on H/V*. Pure Appl. Geophys., **166**: 567-592.

Gass I.G. & Masson-Smith D. (1963) - *The geology and gravity anomalies of the Troodos Massif, Cyprus*. Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, **255**(1060): 417-467.

Gaudiosi I., Del Monaco F., Milana G. & Tallini M. (2014) - *Site effects in the Aterno River Valley (L'Aquila, Italy): comparison between empirical and 2D numerical modelling starting from April 6th 2009 Mw 6.3 earthquake*. Bulletin of earthquake engineering, **12**(2): 697-716.

GEOTER (2005a) - *Study of active tectonics in Cyprus for seismic risk mitigation*. Final report. Report GTR/CYP/1005-170.

GEOTER (2005b) - *Study of active tectonics in Cyprus for seismic risk mitigation. Map of quaternary faults of Cyprus. 1:250,000 scale map*. Report GTR/CYP/0905-170.

Grünthal G., Wahlström R. & Stromeyer D. (2013) - T*he SHARE European Earthquake Catalogue (SHEEC) for the time period 1900-2006 and its comparison to the European-Mediterranean Earthquake Catalogue (EMEC)*. Journal of Seismology, **17**(4): 1339-1344.

Haghshenas E., Bard P.-Y., Theodulidis N. & SESAME WP04 Team (2008) - *Empirical evaluation of microtremor H/V spectral ratio*. Bull. Earthq. Eng., **6**: 75-108.

Harrison R.W., Newell W.L., Batihanli H., Panayides I., McGeehin J.P., Mahan S.A. et alii (2004) - *Tectonic framework and Late Cenozoic tectonic history of the northern part of Cyprus: implications for earthquake hazards and regional tectonics*. Journal of Asian Earth Sciences, **23**(2): 191-210.

ICMS Working Group (2008) - *Indirizzi e criteri per la microzonazione sismica – Guidelines for seismic microzonation*. Conferenza delle Regioni e delle Province autonome. Dipartimento della Protezione Civile. https://www.centromicrozonazionesismica.it/it/download/category/3-linee-guida.

Kalogeras I., Stavrakakis G. & Solomi K. (1999) - *The October 9, 1996 earthquake in Cyprus: seismological, macroseismic and strong motion data*. Annals of Geophysics, **42**(1): 85-97.

Klimis N. S., Margaris B. N. & Koliopoulos P. K. (1999) - *Site dependent amplification functions and response spectra in Greece*. Journal of Earthquake Engineering, **3**(2): 237-247.

Konno K. & Ohmachi T. (1998) - *Ground-motion characteristics estimated from spectral ratio between horizontal and vertical com-ponents of microtremor*. Bull. Seism. Soc. Am., **88**: 228-241.

Kottke A.R. & Rathje E.M. (2008) - *Technical Manual for Strata*. PEER Report 2008/10, Pacific Earthquake Engineering Research Center College of Engineering, University of California, Berkeley (CA).

Lord A.R., Panayides I., Urquhart E., Xenophontos C. & Malpas J. (2000) - *A biochronostratigraphical framework for the Late Cretaceous-Recent circum-Troodos sedimentary sequence, Cyprus*. In: *Proceedings of the Third International Conference on the Geology of the Eastern Mediterranean*. Geological Survey Department, Nicosia, Cyprus, **289**: 289-297.

Macerola L., Tallini M., Di Giulio G., Nocentini M. & Milana G. (2019) - *The 1-D and 2-D Seismic Modeling of Deep Quaternary Basin (Downtown L'Aquila, Central Italy)*. Earthquake Spectra, **35**(4): 1689-1710.

Malpas J. & Xenophontos C. (1999) - *Geological map of the Ayia Varvara-Pentalia Area. 1:25,000 scale map*. Geol. Survey Dep., Cyprus.

Martino S., Lenti L., Gélis C., Giacomi A.C., Santisi d'Avila M.P., Bonilla L.F., et alii (2015) - *Influence of Lateral Heterogeneities on Strong-Motion Shear Strains: Simulations in the Historical Center of Rome (Italy)*. Bulletin of the Seismological Society of America, **105**(5): 2604-2624.

Moscatelli M., Albarello D., Scarascia Mugnozza G. & Dolce M. (2020) - *The Italian approach to seismic microzonation*. Bulletin of Earthquake Engineering, **18**(12): 5425-5440.

Motazedian D. & Atkinson G. M. (2005) - *Stochastic finite-fault modeling based on a dynamic corner frequency*. Bulletin of the Seismological Society of America, **95**(3): 995-1010.

Nakamura Y. (1989) - *A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface*. Quarterly Report of Railway Technical Research Institute (RTRI), **30**(1): 25-33.

Necdet M. & Anil M. (2006) - *The geology and geochemistry of the gypsum deposits in Northern Cyprus*. Geosound, 48-49.

Nogoshi M. & Igarashi T. (1970) - *On the propagation characteristics of microtremors*. J. Seism. Soc. Japan., **23**: 264-280. (in Japanese with English abstract)

Nogoshi M. & Igarashi T. (1971) - *On the amplitude characteristics of microtremors*. J. Seism. Soc. Japan., **24**: 24-40. (in Japanese with English abstract)

Panayides I., Necdet M., Harrison R., Newell W., Batihanli H., Tsiolakis E., Zomeni Z., Berksoy O., Özhűr A., McGeenin J. & Mahan S. (2004) - *Seismic hazard and risk assessment of Greater Nicosia area.* In: De Coster M., Zomeni Z., Panayides I., Petrides G. & Berksoy O. (eds.). UNOPS Report, Nicosia (Cyprus), chapter **2**: 1-68.

Papadimitriou E.E. & Karakostas V.G. (2006) - *Earthquake generation in Cyprus revealed by the evolving stress field*. Tectonophysics, **423**(1-4): 61-72.

Papaioannou C. (2001) - *A model for the shallow and intermediate depth seismic sources in the eastern Mediterranean region*. Boll. Geofis. Teor. Appl., **42**: 57-74.

Papazachos B.C. & Papaioannou C.A. (1999) - *Lithospheric boundaries and plate motions in the Cyprus area*. Tectonophysics, **308**(1-2): 193-204.

Pergalani F., Pagliaroli A., Bourdeau C., Compagnoni M., Lenti L., Lualdi M., et alii (2020) - *Seismic microzoning map: approaches, results and applications after the 2016–2017 Central Italy seismic sequence*. Bulletin of Earthquake Engineering, **18**(12): 5595-5629.

Petrides G., Efthymiou M., Necdet M., Berksoy O. & Oznesil H. (2004) - *Drilling and Engineering Geology*. In: De Coster M., Zomeni Z., Panayides I., Petrides G. & Berksoy O. (eds.) - *Seismic hazard and risk assessment of Greater Nicosia area*. UNOPS Report, Nicosia (Cyprus), chapter **3**: 1-35.

Robertson A.H.F., Eaton S., Follows E.J. & Payne A.S. (1995) - *Depositional processes and basin analysis of Messinian evaporites in Cyprus*. Terra Nova, **7**(2): 233-253.

Rollins K.M., Evans M., Diehl N. & Daily W. (1998) - *Shear modulus and damping relationships for gravels*. Journal of Geotechnical and Geoenviromental Engineering, **124**(5): 396-405.

Segou M., & Voulgaris N. (2013) - *The use of stochastic optimization in ground motion prediction*. Earthquake spectra, **29**(1): 283-308.

Serpetti M., Carlucci R., Di Iorio A., Bozzano F., Antonielli B., Martino S., et alii (2020) - *Stable: structural stability risk assessment*. In: 8th International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2020), SPIE, **11524**: 120-128.

SESAME (2004) - *Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations: measurements, processing and interpretation*. Deliverable D23.12 European Commission - Research General Directorate Project No. EVG1-CT-2000-00026 SESAME.

Sextos A., De Risi R., Pagliaroli A., Foti S., Passeri F., Ausilio E., et alii (2018) - *Local site effects and incremental damage of buildings during the 2016 Central Italy earthquake sequence*. Earthquake Spectra, **34**(4): 1639-1669.

Sgobba S., Felicetta C., Russo E., D'Amico M., Lanzano G., Pacor F., Luzi L., Baraschino R., Baltzopoulos G. & Iervolino I. (2021) - *The online graphical user interface of REXELweb for the selection of accelerograms from the engineering strong motion database (ESM)*. In: Proceedings of the 39° online GNGTS Conference, 22-24 June 2021.

Sorrentino L, Cattari S, Da Porto F, Magenes G & Penna A (2019) - *Seismic behaviour of ordinary masonry buildings during the 2016 central Italy earthquakes*. Bulletin of Earthquake Engineering, **17**(10): 5583-5607.

Soulas J. P. (2001) - *Active tectonics studies in Cyprus for seismic risk mitigation: the greater Paphos area final report*. Geological Survey Department of Nicosia, Nicosia, Cyprus, 24 pp.

Stewart J.P., Zimmaro P., Lanzo G., Mazzoni S., Ausilio E., Aversa S., et alii (2018) - *Reconnaissance of 2016 Central Italy earthquake sequence*. Earthquake Spectra, **34**(4): 1547-1555.

Stucchi M., Rovida A., Gomez Capera A.A., Alexandre P., Camelbeeck T., Demircioglu M.B., et alii (2013) - *The SHARE European earthquake catalogue (SHEEC) 1000-1899*. Journal of Seismology, **17**(2): 523-544.

Swarbrick R.E. (1993) - *Sinistral strike-slip and transpressional tectonics in an ancient oceanic setting: the Mamonia Complex, southwest Cyprus*. Journal of the Geological Society, **150**(2): 381-392.

Varone C., Lenti L., Martino S. & Semblat J.F. (2021) - *Spatial variability of the urban ground motion in a highly heterogeneous site-city configurations*. Bulletin of Earthquake Engineering, **19**(1): 27-45.

Vucetic M. & Dobry R. (1991) - *Effect of soil plasticity on cyclic response*. Journal of Geotechnical Engineering, **117**(1): 89-117

Wathelet M., Chatelain J.-L., Cornou C., Di Giulio G., Guillier B., Ohrnberger M. & Savvaidis A. (2020) - *Geopsy: A user-friendly open-source tool set for ambient vibration processing*. Seismol. Res. Lett., **91**(3): 1878-1889.

Wells D. L. & Coppersmith K. J. (1994) - *New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement*. Bulletin of the seismological Society of America, **84**(4): 974-1002.

Received June 2022 - Accepted July 2022