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IV. Seismic site response in Lampedusa

Panzera F., Sicali S., Lombardo G., D'Amico S., Galea P.

1. Introduction

In the frame of a joint Italo–Maltese research project (Costituzione di un Sistema Integrato di Protezione Civile Transfrontaliero Italo–Maltese, SIMIT), financially supported by the European Community, a research plan was developed. Its final purpose is to mitigate natural hazards and to improve the geological and geophysical information in the area between the south–eastern Sicilian coast and the islands of Lampedusa and Malta. Although this region lies on the Sicily channel rift zone, a seismically active domain of the Central Mediterranean, knowledge about seismotectonic, seismic hazard and local seismic response is at present quite poor.

In order to improve the awareness of problems linked to natural hazards and with the aim of toning down them, we investigated the island of Lampedusa (Pelagian archipelago). A multidisciplinary approach concerning tectonic, structural, morphologic and lithologic analyses was performed trying to contribute to fill up the information gap on the seismic features of this territory. The results of the geological–structural surveys were used to standardize the evaluation of the seismic hazard and, in particular, to understand the local seismic response of the distinct outcropping terrains and its influence on the dynamic behavior of existing buildings.

In present study, ambient noise recordings were used as seismic input, processing the data collected through spectral ratio techniques. Polarization of the horizontal component of motion was also investigated in order to set into evidence possible directional effects.

2. Geologic, tectonic and seismic features of the study area

The study area is located in the Sicily Channel. Lampedusa is an E–W elongated island located in the central Mediterranean sea, about 200 km south of the Sicilian coastline and 150 km East of Tunisia. The island consists of a 11 km long carbonate shelf that reaches the maximum topographic elevation of 133 m a.s.l.. It represents the main island of the Pelagian archipelago with an area of about 20 km^2 and a coastal length of 40 Km. The morphology of the island and the land features, characterized by a lack of plant covering, as well as a strong wind erosion and placer mining, make the landscape quite similar to North African areas.

From the structural point of view, Lampedusa belongs to the Pelagian block, a foreland domain at the northern edge of the African plate, formed by a 6–7 km thick Meso-Cenozoic shallow to deep-water carbonate successions (Civile *et al.*, 2008; 2013). The island is positioned inside the Sicily Channel, at the southern shoulder of a Plio–Quaternary foreland rift zone that exhibits deep, NW–SE trending, fault-controlled structural depressions (e.g. the grabens of Pantelleria, Linosa and Malta). As revealed by the available seismic database (INGV 1981–2013), the area is interested by the natural seismic activity of the Sicily channel (Civile *et al.*, 2008). The rift zone is in particular characterized by a moderate seismicity, mostly located in the Linosa graben, with shallow events ($h < 25$ km) having magnitude ranging from 2 to 4 (Civile *et al.*, 2008). The Linosa graben seismicity mostly develops along a broad N–S oriented belt starting from Lampedusa Island as proposed by Argnani (1990) on the basis of bathymetric, volcanic and seismic considerations.

Lampedusa represents a small horst structure formed by a Neogene–Quaternary carbonate sequence (Grasso and Pedley, 1985) that, as shown in Figure 1a, is characterized by the following lithologic units: Carbonate lithoclast breccias of late Pleistocene–Holocene age; Aeolian dunes formed of bioclastic grainstones of late Pleistocene; Wave–cut platform and sand raised beaches (late Pleistocene, Tyrrhenian); Bioclastic grainstones (early Pleistocene); Limestones of the Lampedusa Formation that is constituted by the Vallone della Forbice, Capo Grecale and Cala Pisana members of Tortonian–Early Messinian age. Following Grasso and Pedley (1985), major tectonic lineaments of Lampedusa are found in the eastern part of the island (Cala Creta and Cala Pisana). Structural measurements performed along the cliff revealed that the area is deformed by a NW–SE oriented wrench zone (Cala Creta fault) composed of sub–vertical fault segments accompanied by damaged zone consisting of fractures with pervasive pattern. Faults consist mostly of NW–SE oriented and SW dipping reverse structures with slicken sides on planes indicating a left-lateral component of motion (Lombardo *et al.*, 2014). Another tectonic lineament (Aria Rossa fault), is located in the central part of the island. It consist of a NW–SE oriented fault with no evident fault plane but a series of second order fractures and a topographic

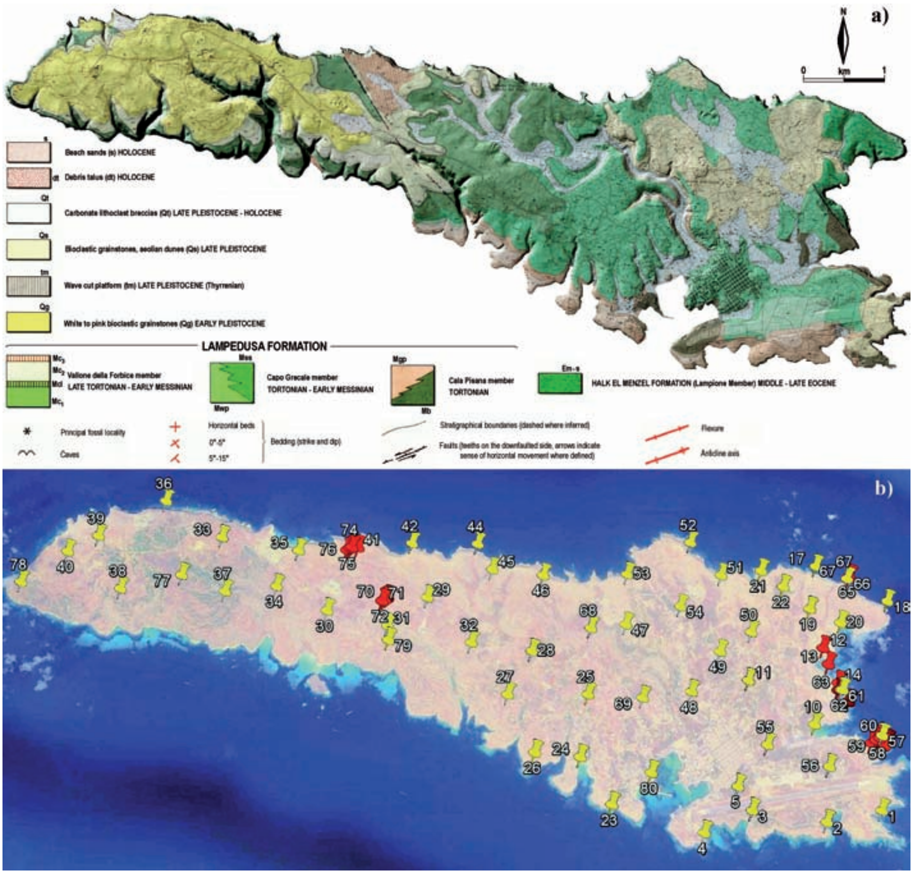

Figure 1. a) Geologic map of the Lampedusa island (modified from Grasso and Pedley 1985); b) Location of ambient noise recording sites.

irregularity with a quite sharp change in the outcropping lithology.

The lithologic homogeneity of the island and the sub–horizontal setting of the outcropping rocks gave rise to the development of a typical Plateau landscape with almost flat morphology carved by deep valleys (Fig. 4 2a). The island is indeed ploughed up by no more active streams that lead to the sea shaping sandy inlets. The different response to the rocks erosion, gave rise also to the development of different coastal landforms. The coastal morphology is therefore characterized by alternating cliffs and bays and in general, high coasts prevail in the north and north–west part of the island whereas low

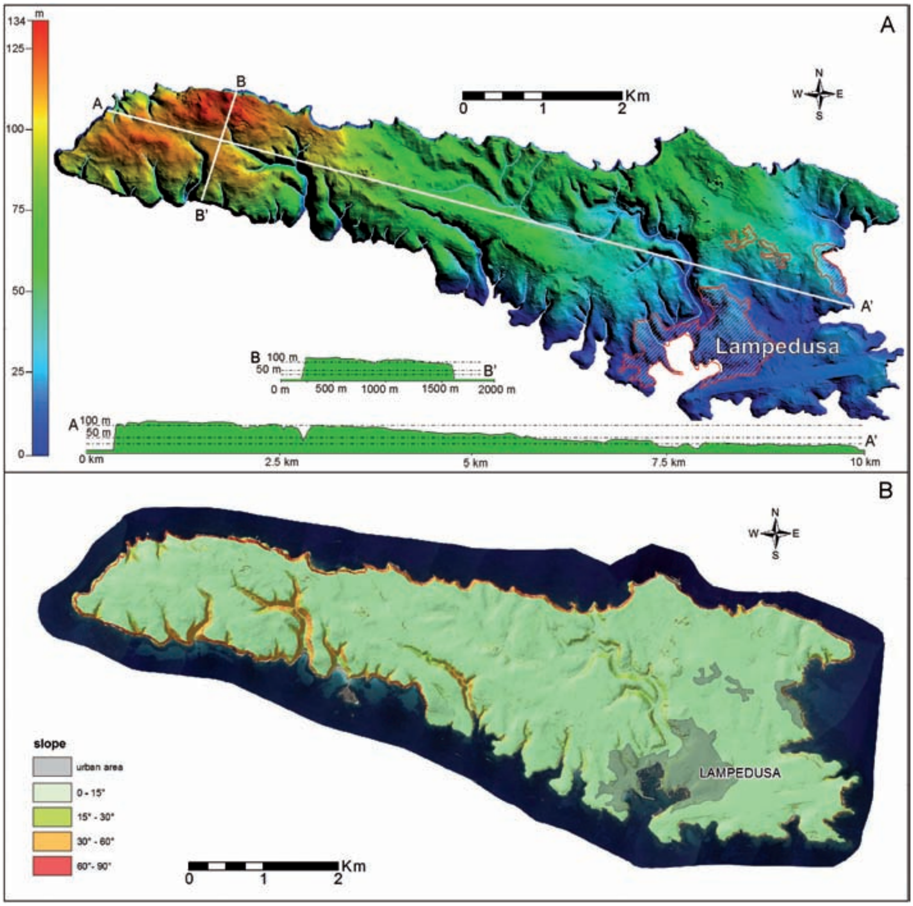

Figure 2. a) Sketch of the morphologic features A) and slope classes B) at Lampedusa island.

coasts are more common in its southern portion (Fig. 2b) where fair slopes prevail.

3. Methodology

The damage distribution during an earthquake is due to the combined effects of seismic hazard in the investigated area, the features of the local site response, based on the near–surface and subsurface ground conditions, as well as on the dynamic features of the erected buildings. As a consequence of this, the problem of mitigating the risk connected to the occurrence of earthquakes was tackled performing studies both on the seismic hazard estimate, as well as on the evaluation of the site response. In the present study the features of the local seismic response will be described paying particular attention to the modifications, in terms of frequency distribution and amplitude, to which a seismic input undergo as a consequence of the characteristics of the outcropping lithology and geologic structures.

A quick estimate of the surface geology effects on seismic motion is provided by the horizontal to vertical noise spectral ratio technique (HVNR). This technique firstly introduced by Nogoshi and Igarashi (1971), was put into practice by Nakamura (1989) and became in recent years widely used since it provides a reliable estimate of the fundamental frequency of soft soil deposits (see Lermo and Chavez–Garcia, 1993). Although the scientific community has questioned the existence of simple direct correlation between HVNR amplitude values and the actual site amplification (see Mucciarelli, 1998; Rodriguez and Midorikawa, 2002), such method is widely used since it significantly reduces field data acquisition time and costs. The basic hypothesis for using ambient noise is that the resonance of a soft layer corresponds to the fundamental mode of Rayleigh waves, which is associated with an inversion of the direction of Rayleigh wave rotation (Nogoshi and Igarashi, 1971; Lachet and Bard, 1994). The reliability of such an approach has been asserted by many authors (e.g., Lermo and Chavez–Garcia, 1993), who have stressed its significant stability in local seismic response estimates. It is commonly accepted that, although the single components of ambient noise can show large spectral variations as a function of natural and cultural disturbances, the HVNR spectral ratio tends to remain invariant, therefore preserving the fundamental frequency peak (Cara *et al.*, 2003).

Ambient noise recordings were performed in eighty measurement sites (yellow pins in Figure 1b) spacing them almost homogeneously along a grid having size of about 600 m and taking into account the outcropping lithology. Moreover, six transects with four measurement sites each (red pins in Figure 1b), where achieved across the fault lines and morphologic scarps, mostly located in the eastern part of the island. The ambient noise was recorded using Tromino, a compact 3–component velocimeter particularly suitable for field measurements. Time series of 20 minutes length were recorded using a sampling rate of 128 Hz and processed through the Horizontal to Vertical Noise spectral Ratio technique (HVNR). Time windows of 20 s were considered and the most stationary part of the signal was selected excluding transients associated to very close sources. In this way the Fourier spectra were calculated in the frequency range 0.1-30.0 Hz and smoothed using a proportional 20% triangular window. Following the criteria suggested by the European project Site EffectS assessment using AMbient Excitations (SESAME 2004), only the spectral ratio peaks having amplitude greater than two units, in the frequency range 0.5–30 Hz, were considered significant.

Experimental spectral ratios obtained in the measurement sites located along the transects, were also calculated after rotating the horizontal components of motion (Spudich *et al.*, 1996) by steps of 10 degrees starting from 0° (north) to 180° (south) in order to investigate about the possible presence of directional effects. However, in presence of lateral and vertical heterogeneities or velocity inversion, the HVNR can be "non–informative" due to the occurrence of amplification on the vertical component of motion (Di Giacomo *et al.*, 2005). Thus in this study we also applied the time–frequency (TF) polarization analysis proposed by Vidale (1986) and exploited by Burjánek *et al.* (2012) in order to provide a direct estimate of the polarization angle. This technique can provide quite robust results, overcoming the bias that could be introduced by the denominator spectrum in the HVNR calculation. Following Burjánek *et al.* (2010 and 2012), the continuous wavelet transform (CWT, see Kulesh *et al.*, 2007) is applied to signals in order to select time windows whose length matches the dominant period. The signals are thus decomposed in the time–frequency domain and the polarization analysis is applied. For each time–frequency pair, polarization is characterized by an ellipsoid and is defined by two angles: the strike (azimuth of the major axis projected to the horizontal plane from North) and the dip (angle of the major axis from the vertical axis). Another important parameter is the ellipticity of the particle motion that, according to Vidale (1986), is defined as the ratio between the length of the minor and major axes. This parameter approaches 0 when ground motion is linearly polarized as typically observed for body waves. Polarization strike and dip obtained all over the time series analyzed are cumulated and represented using polar plots where the contour scale represents the relative frequency of occurrence of each value, and the distance to the center represents the signal frequency in Hz. In order to assess whether ground motion is linearly polarized, the ellipticity is also plotted versus frequency.

3.1. *Description of results and concluding remarks*

A detailed investigation about the features of the local seismic response in Lampedusa was undertaken among the goals set by the SIMIT project. Site effects at a specific location are indeed very important and can be used for engineering purposes and to define shaking maps and the seismic hazard. The evaluation of the site response is therefore useful to create a detailed shaking map for a region where the different outcropping lithologies are known.

Figure 3, shows a map of the surface distribution of the fundamental frequencies experimentally observed in the different recording sites. The results obtained by processing the ambient noise measurements set into evidence that most of the spectral ratio peaks are detected in the frequency range 2.0–4.5 Hz. Going into more details, we observe that these peaks often do not reach two amplitude units (left panel in Figure 4a). Such behavior is more evident both in the south–eastern part of the island, as well as in its central and western portion.

Comparison with the Lampedusa lithology points out that in these areas the most ancient and rigid terrains of the Lampedusa formation outcrop. These findings are in good agreement with the stiff ness of the limestone formations extensively outcropping in the plateau shaping the central part of the island. More pronounced spectral ratio peaks (right panel in Figure 4a) are detected in the measurement sites located close to the outcrops of more recent and soft deposits (eg. #55, #68 in Figure 1b) as well as along the transects crossing the Cala Creta and Cala Pisana faults which mark out the eastern boundary of the island (e.g. #61, #64, #58, #59 in Figure 1b). The example displayed in Figure 4b shows, besides the HVNR spectral peak, the directional resonance and the polarization plot obtained in a recording site located nearby the fault. The polarization of the horizontal components of motion, evaluated in the measurement sites located nearby the fault lines, show that the largest amplifications occur at high angle from the fault strike (Lombardo and Rigano, 2006; Panzera *et al.*, 2014; Panzera *et al.*, 2015) as can be observed in Figure 5 where the azimuths of the fractures and those of the polarization of the horizontal component of motion are compared. On the other hand, measurements performed at increasing distance from the fault zone do not show a similar behavior. This suggests that the observed directional effects can be ascribed to the fault fabric (Panzera *et al.*, 2014; Panzera *et al.*, 2015). Similar well defined and pronounced spectral ratio peaks (central panel in Figure 4a) are detected in the transects performed perpendicularly to the strike of the morphologic escarpments existing in the north eastern side of the island (e.g. #65, #66 in Figure 1b). Figure 6 shows some examples of HVNRs and directional resonance diagrams that were obtained from ambient noise recordings performed in proximity of such escarpments.

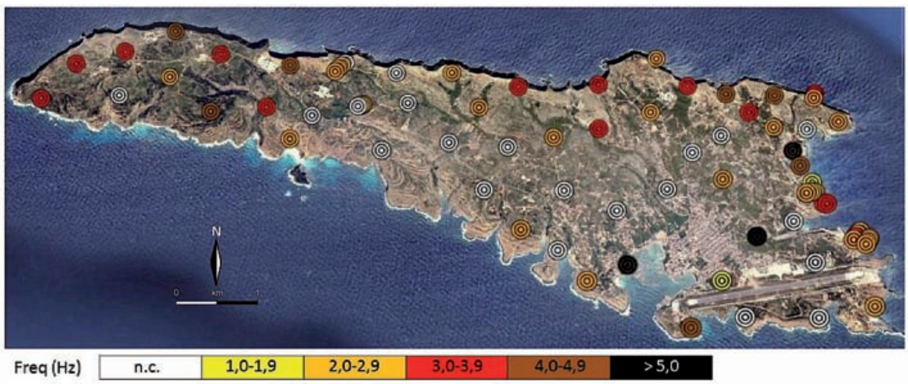

Figure 3. Map of the fundamental frequencies experimentally detected at Lampedusa.

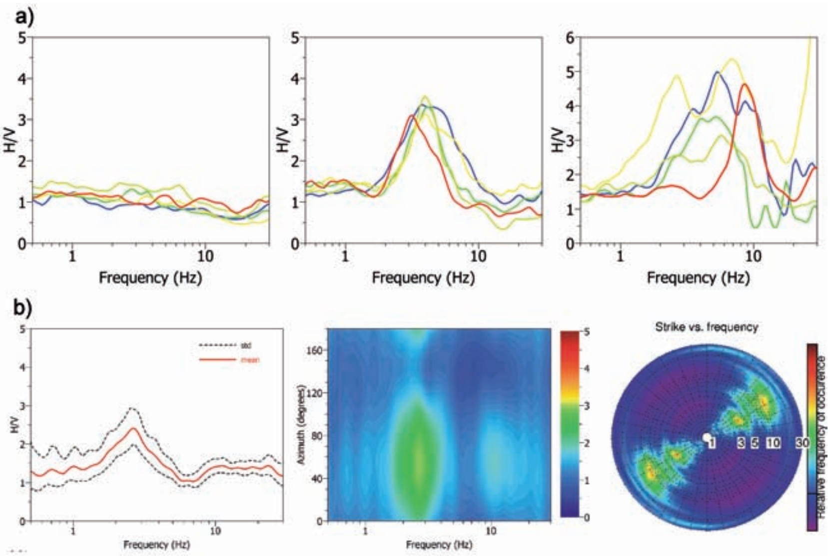

Figure 4. a) Examples of HVNR results subdivided in three groups. left panel flat HVNR; central panel HVNR with a clear peak at about 3.5 Hz, observed in sites located near the cliff areas; right panel HVNR characterized by high frequencies fundamental peak in sites in which outcrops soft deposits. b) Example of HVNR, directional resonance diagrams and polarization azimuth plot obtained in the Cala Creta fault area.

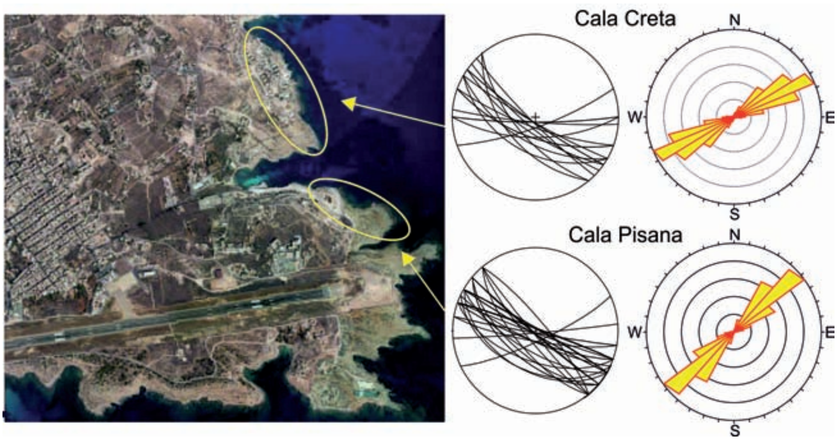

Figure 5. Polarization azimuths of the fractures and the horizontal components of motion in the faults located in the eastern area of Lampedusa.

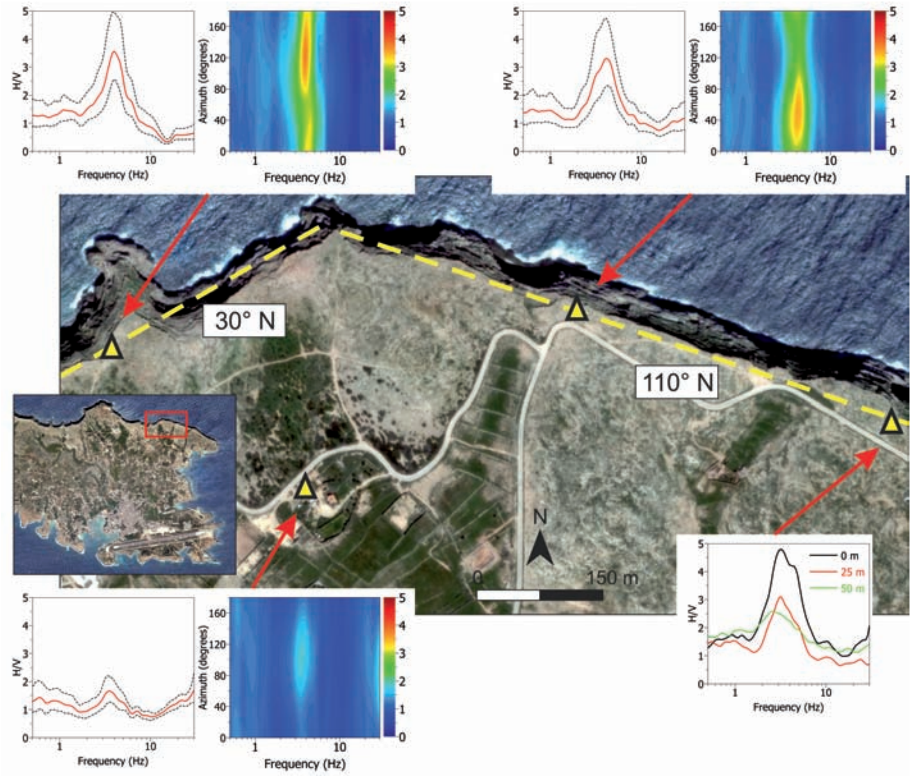

Figure 6. Examples of HVNRs and directional resonance diagrams from ambient noise recording sites located in the north–western cliffs of Lampedusa island.

We can therefore affirm that since Lampedusa is almost entirely formed by calcareous deposits, the amplification effects are mostly caused by either morphologic or tectonic structures.

All the obtained results for the Lampedusa area, are available in the webgis: http://webgis.protezionecivilesicilia.it/simit/.

We can in conclusion affirm that the use of ambient noise records showed to be a reliable and not expensive technique for a quick characterization of the local seismic response in the study area. This kind of studies has given significant suggestions about potential critical conditions linked to local amplification phenomena. The results obtained set into evidence that besides the characteristics of the near–surface geology, the morphology and the presence of fault lines strongly influence the local amplification of the ground motion and the occurrence of directional effects. Major amplification effects take indeed place on the soft deposits that partially fill up the incisions of old pre–existing streams as well as in the neighbouring of both morphologic escarpments and faults. On the contrary, HVNR with not significant spectral ratio peaks are observed on the calcareous plateau. Rotated spectral ratios and polarization analysis highlighted the presence of evident directional effects in proximity of both faults and cliffs. The polarization of the wave–field assumes major values at wide angles (between 60°–90°) with respect to the structures strike.

As a final point, it is worth to remember that this kind of studies appear to be particularly useful to governmental agencies tasked with emergency response and rescue. Besides, the adopted techniques have proved to be a useful tool for a quick characterization of the soil properties, allowing the identification of macro–areas having a similar local seismic response and, at the same time, pointing out the existence of micro–areas where more detailed investigations have to be planned.

Panzera F.[1], Sicali S.[1], Lombardo G.[1], D'Amico S.[2], Galea P.[2]

1. Dipartimento di Scienze Biologiche, Geologiche e Ambientali, Università di Catania, Italy. Corresponding author: Panzera F., fpanzera@unict.it.

2. Department of Geosciences (previously at Physics Department), University of Malta, Msida, Malta.