DETAILED GEOPHYSICAL AND GEOLOGIC STUDY IN THE LAMPEDUSA ISLAND: SIMIT PROJECT

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Introduction. Recently, a joint Italo-Maltese research project (Costituzione di un Sistema Integrato di Protezione Civile Transfrontaliero Italo-Maltese, SIMIT) was financially supported by the European community with the aim to improve the geological and geophysical information in the area between the south-eastern Sicilian coast and the islands of Lampedusa and Malta with a final purpose to mitigate natural hazards.

Although this region lies on a seismically active domain of central Mediterranean, the Sicily Channel Rift Zone, knowledge about seismotectonic and local seismic response are at present poorly studied.

In order to improve these, we investigated the island of Lampedusa (Pelagian archipelago) by means a multidisciplinary approach concerning structural, morphologic and lithologic analyses. Results of geological-structural surveys were used to understand local seismic response of the distinct outcropping rocks and its influence on the existing buildings.

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. Current findings contribute to fill up the information gap on the seismic features of this territory.

Geology and tectonics of the study area. 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. 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 placed 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 available seismic database (INGV 1981-2013), the rift zone is characterized by a moderate seismicity, mostly located in the Linosa graben, with shallow events ($h < 25$ km) and magnitude usually from 2 to 4 (Civile *et al*., 2008).

In this scenario, Lampedusa represents a small horst structures formed by Neogene –Quaternary carbonate sequences (Grasso and Pedley, 1985) characterized by the following lithologic unit: 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 (see Fig. 1a). Following Grasso and Pedley (1985), major tectonic lineaments of were found in the eastern part of the island.

Structural measurements performed along the cliff revealed that the area is deformed by a NW-SE oriented wrench zone [Cala Creta fault, see Grasso and Pedley (1985)] 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 slickensides on planes indicating a left-lateral component of motion.

Another tectonic lineaments (Aria Rossa fault), occur 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 irregularity with a quite sharp change in the outcropping lithology.

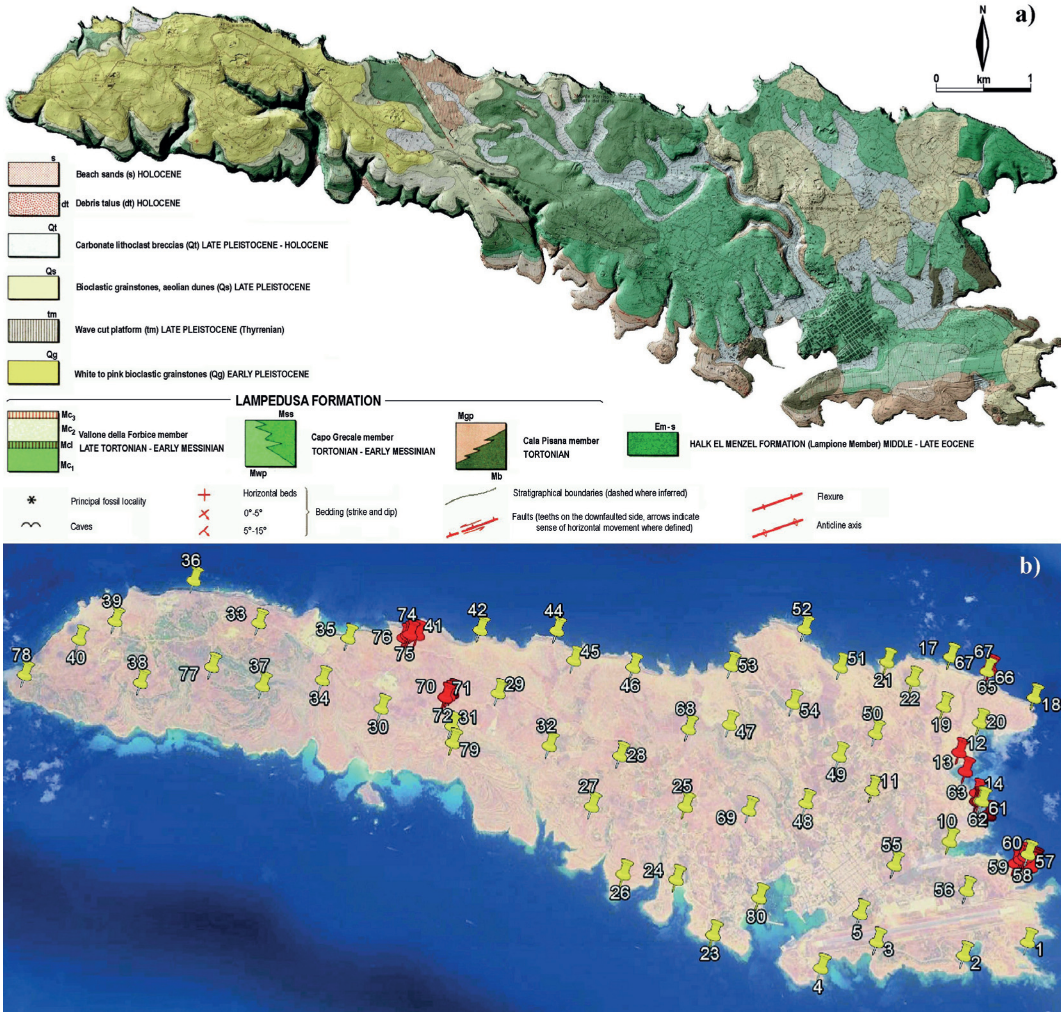

Fig. 1 – a) geologic map of the Lampedusa island (modified from Grasso and Pedley 1985); b) location of ambient noise recording sites.

Methodology. Founded on the outcomes of the geologic survey, eighty measurement sites (yellow pins in Fig. 1b) were almost homogeneously spaced along a grid having size of about 600 m, taking into account the outcropping lithology. Moreover, six transects with four measurement sites each (red pins in Fig. 1b), where achieved along the fault lines and morphologic scarp, mostly located in the eastern part of the island. Ambient noise was also recorded in five buildings, selected as a sample survey of both reinforced concrete and masonry edifices, in order to evaluate their fundamental period. Data recording was carried out using Tromino, a 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 0.5-15 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). 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, 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: 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 that is defined, according to Vidale (1986), as the ratio between the length of the minor and major axes: this parameter approaches 0 when ground motion is linearly polarized. As stressed by Burjánek *et al.* (2010, 2012), the chosen wavelet in the CWT analysis affects all the polarization parameters as well as the analysis resolution. 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. A direct estimate of the polarization angle was therefore obtained through the time-frequency polarization (TFP) analysis (Burjánek *et al.*, 2012).

The dynamic properties of a building are usually described through its natural frequency and the damping ratio. The seismic performance of a building obviously depends on the progression of the frequencies along the input time-history, nevertheless the knowledge of its fundamental frequency at low amplitude values is of primary importance to characterize the initial seismic behaviour of a structure (Mucciarelli and Gallipoli, 2007).

The engineering practice usually derives the dynamic behaviour of buildings through numerical or experimental methods (Gallipoli *et al.*, 2009a, 2009b; Oliveira and Navarro, 2009). The results obtained for different typologies of buildings are often processed, through statistical regression analysis, to achieve empirical relationships that let the estimate of building resonant period (T) as a function of the buildings geometry, usually either the height (H) or the number of floors (N) (Goel and Chopra, 1997; Hong and Hwang, 2000; Messele and Tadese, 2002; Crowley and Pinho, 2006; Panzera *et al*., 2013).

In the present study the dynamic response of buildings is estimated through experimental measurements based on microtremor recordings. The horizontal to vertical noise ratio (HVNR) and the standard noise spectral ratio (SSNR) techniques were used to identify the building's frequencies. Measurements were performed in 5 buildings distinguished according to their construction typology 2 masonry (MA) and 3 reinforced concrete (RC) buildings. As fundamental period for each building we considered the peak with the higher amplitude in both HVNR and SSNR. In each building, 10 minutes length of ambient noise were recorded both at the top and at the ground floor. According to the guidelines suggested by the SESAME (2004), time windows of 10 s were considered, selecting the most stationary part and not including transients associated to very close sources. Fourier spectra were calculated in the frequency band 0.5–15 Hz and smoothed using a triangular average on frequency intervals of ± 5% of the central frequency.

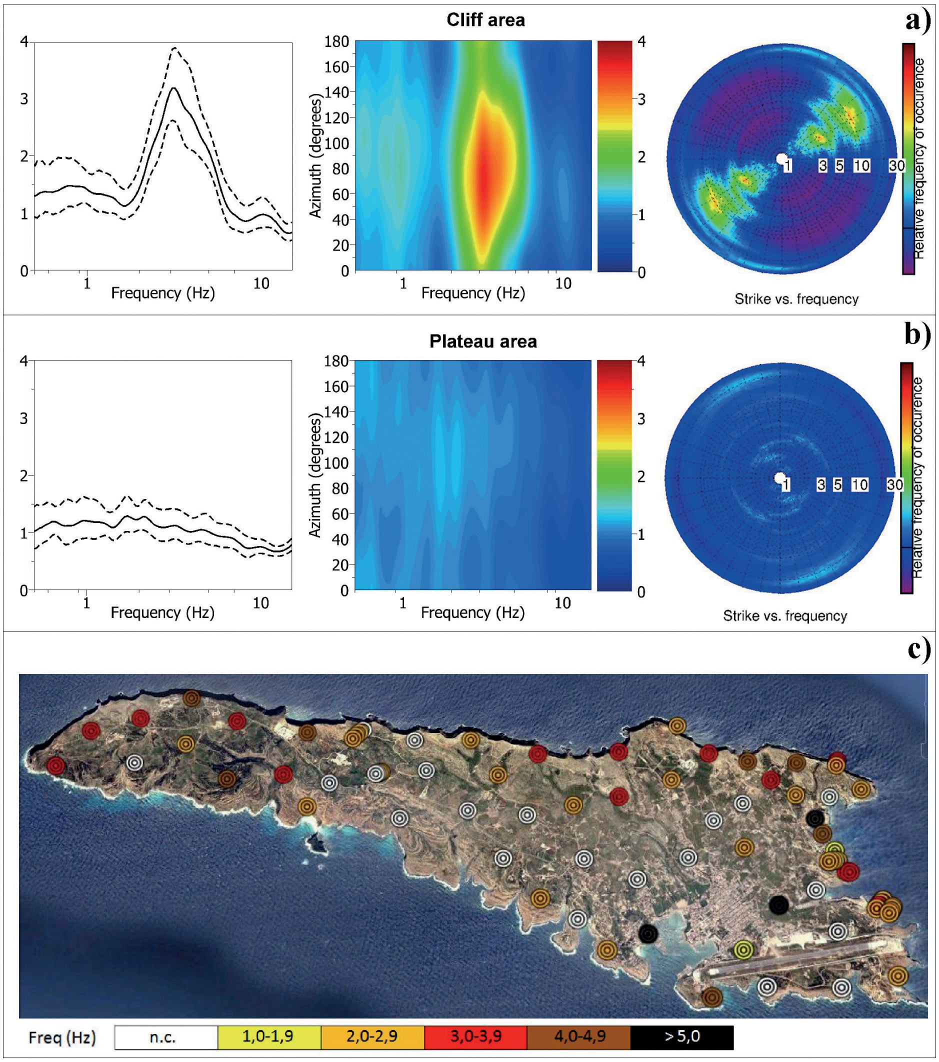

Fig. 2 – a-b) examples of HVNR, directional resonance diagrams and polarization plots observed in the plateau (a) and cliff (b) areas of Lampedusa; c) map of the fundamental frequencies experimentally detected at Lampedusa.

Description of results and concluding remarks. Site effects at a specific location are very important and can be used for engineering purposes to define the regional predictive law and the seismic hazard. A generalized site response concept is indeed useful to create a detailed shaking map for a region where the different outcropping lithologies are known.

The results obtained set into evidence that major 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. 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 point out that in these areas the most ancient and rigid terrains outcrop. This is in good agreement with the stiffness of the limestone formations extensively outcropping in the plateau located in the central part of the island. More pronounced spectral ratio peaks are detected in the measurement sites located close to the outcrops of more recent and soft deposits (eg. #55,#68 in Fig. 1b) and along the transects crossing the Cala Creta fault which marks out the eastern boundary of the island (e.g. #61, #64, #58, #59 in Fig. 1b). Similar well defined spectral ratio peaks 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 Fig. 1b). We can therefore affirm that since Lampedusa is almost entirely formed by calcareous deposits, as a consequence the amplification effects are mostly caused by either morphological or tectonic structures. In Fig. 2 examples of different site response features observed in either the plateau area or nearby the cliffs and the fault lines, are shown.

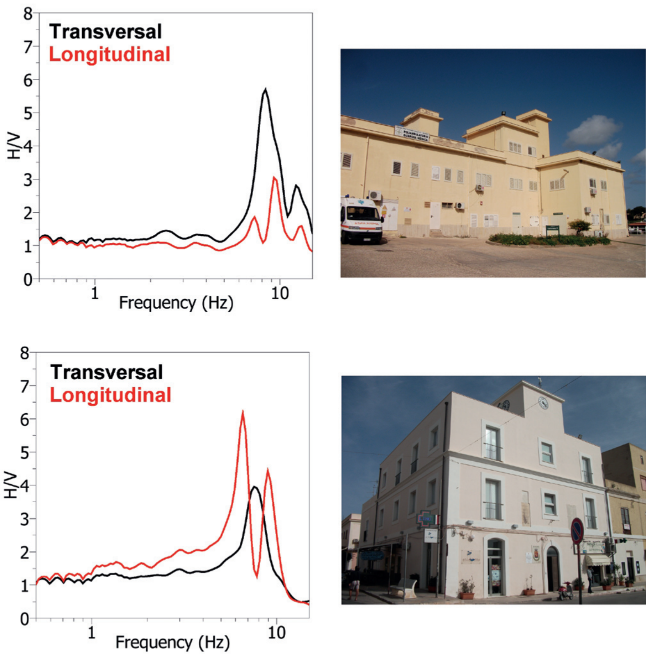

Fig. 3 – Examples of fundamental frequencies as observed from SSNRs obtained through ambient noise recorded in two different buildings in Lampedusa.

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.*, 2012). On the other hand, measurements performed at increasing distance from the fault zone do not show a similar behavior and this suggests that the observed directional effects can be ascribed to the fault fabric (Panzera *et al.*, 2014).

The measurement performed on buildings allowed us to infer the fundamental period of the investigated buildings, showing that there was no particular soil-to-structure effects.

More pronounced and dominant spectral ratio peaks were observed in tall and isolated buildings whereas, secondary spectral ratio peaks were observed in case of adjacent buildings, independently from their typology of construction (see examples in Fig. 3). It is interesting to mention that the fundamental periods experimentally evaluated appear smaller than those obtained through the use of the relationships proposed by the official norms (OPCM, 2005; Eurocode8, 2003).

We can finally 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 and the experimental evaluation of building fundamental periods, as well as investigations about possible soil-to-structure interactions. This kind of studies appear to be particularly useful to governmental agencies tasked with emergency response and rescue. Indeed, performing a detailed geologic study, together with the evaluation of the local seismic response and the dynamical properties of buildings in the island of Lampedusa has given significant suggestions about potential critical conditions due to soil-structure interaction and local amplification phenomena. The results obtained can be summarized as follow:

- A detailed survey, especially performed in the areas of major interest from the geological point of view, such as landslide prone areas was carried out;
- In the Cala Creta Fault area a careful geological descriptions and stratigraphic logs were provided;
- The integration of Grasso and Pedley (1985) findings with new stratigraphic and structural analyses, allowed obtaining a more precise attribution of the different litho-stratigraphic units.
- The complexity of the near-surface geology, as well as the morphology strongly influence the local amplification of the ground motion and the occurrence of directional effects.
- Major amplification effects take place on the soft deposits that partially fill up the incisions of old pre-existing streams and mostly 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 highlight 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.
- Spectral ratios of the ambient noise measurements provided reliable estimates of the fundamental period of analyzed buildings. The measured periods were used to obtain period-height relationships which set into evidence that the experimental values are lower than those postulated by Eurocode8 (2003). Such finding could be explained by considering the contribution of the infill walls that modern codes do not consider adequately.
- Significant differences were observed between the fundamental periods obtained for reinforced concrete and masonry buildings, the former being usually higher than the latter. This behaviour appear related to the different stiffness of the structures and to the presence of connected adjacent buildings.

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