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III. Seismic site response in Siracusa

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

1. Introduction

In the frame of the Italo–Maltese research project (Costituzione di un Sistema Integrato di Protezione Civile Transfrontaliero Italo–Maltese, SIMIT), researches financially supported by the European Community were performed in the area between the south–eastern Sicilian coast and the islands of Lampedusa and Malta. Aim of these studies is to mitigate natural hazards and to develop the geological and geophysical information in the investigated region.

The damage to buildings further to a seismic input is tightly linked, besides their vulnerability, to both the characteristics of the maximum acceleration and frequency of the ground motion, as well as to the features of surface geology. From this point of view, the geophysical and geotechnical characterization of the soil conditions, down to the bedrock, is very important in order to identify the site effects, in terms of fundamental frequencies, for a correct planning of earthquake resistant structures.

The present study aims to investigate on the dynamic properties of main lithotypes outcropping in the Siracusa area and to evaluate the features of the local seismic response. The town of Siracusa is located in the south–eastern coast of Sicily and its downtown, called Ortigia, forms a low hill, shaped as a peninsula surrounded by the sea. The seismological studies were carried out in order to improve the knowledge of problems linked to natural hazards, with the aim of moderate them. The historic part of Siracusa (Ortigia peninsula) was in particular selected as a test site in order to try–out and calibrate the methodologies that were further applied to Lampedusa island. A multidisciplinary approach concerning tectonic, structural, morphologic and lithologic analyses was performed, trying to use the results of the geological–structural surveys to standardize the evaluation of the seismic hazard and to estimate the seismic ground motion expected in the area.

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

The town of Siracusa is located in a wide inlet engraved into a limestone formation. Its downtown, called Ortigia, forms a low hill shaped as a peninsula surrounded by the sea. The area belongs to the Hyblean plateau, which represents the outcropping foreland forming the south eastern portion of Sicily. It is a thick crustal plateau belonging to the Africa foreland domain that flexures northward to the overthrusting Apenninic–Maghrebian orogenic sectors and eastward is separated from the oceanic-type domain of the Ionian Basin by the Malta–Hyblean fault system. Such tectonic structure, trending NW–SE, together with the Scicli normal fault system, located inland and striking in NE–SW direction, characterize at regional scale the tectonics of south eastern Sicily. Seismotectonic information and interpretations available suggest that both fault systems can be identified as possible sources for the seismic activity that affected in historical time the town of Siracusa.

The area is affected by a moderate seismicity, nevertheless, the potentially most hazardous event, witnessed by the seismic history of the area, is represented by the 1693 earthquake that reached a M_W of 7.4 (Rovida *et al.*, 2011). The seismic source for this event is particularly doubtful and debated in literature due to the lack of both a clear evidence of surface faulting and of large magnitude earthquake instrumental records. However, relations between the main offshore fault segments and the high intensity historical earthquakes coupled with tsunamis occurred in this region, suggests that the Malta–Hyblean system represents one of the major seismogenic sources of the whole southern Italy (Bianca *et al.*, 1999; Catalano *et al.*, 2010). The last twenty years of recoded seismic activity show epicenters sparsely located in all the area and the most important moderate size instrumental seismic event occurred on December 13th 1990 which was felt throughout Sicily with a maximum seismic intensity of VII-VIII (Locati *et al.*, 2011).

This earthquake and its aftershocks were located along a 5 km long transverse segment striking EW separating two sub–parallel segments of the Ibleo–Maltese fault scarp (Laurenzano and Priolo, 2005). Although its moderate magnitude (M_W=5.7; Rovida *et al.*, 2011), it caused the collapse of a few buildings, it was felt throughout Sicily with a maximum seismic intensity of VII–VIII (Locati *et al.* 2011). In the Siracusa area the substratum outlines a horst structure formed by a Meso-Cenozoic carbonate sequence with interbedded volcanics (Grasso and Lentini 1982) cropping out in the northern part of the town

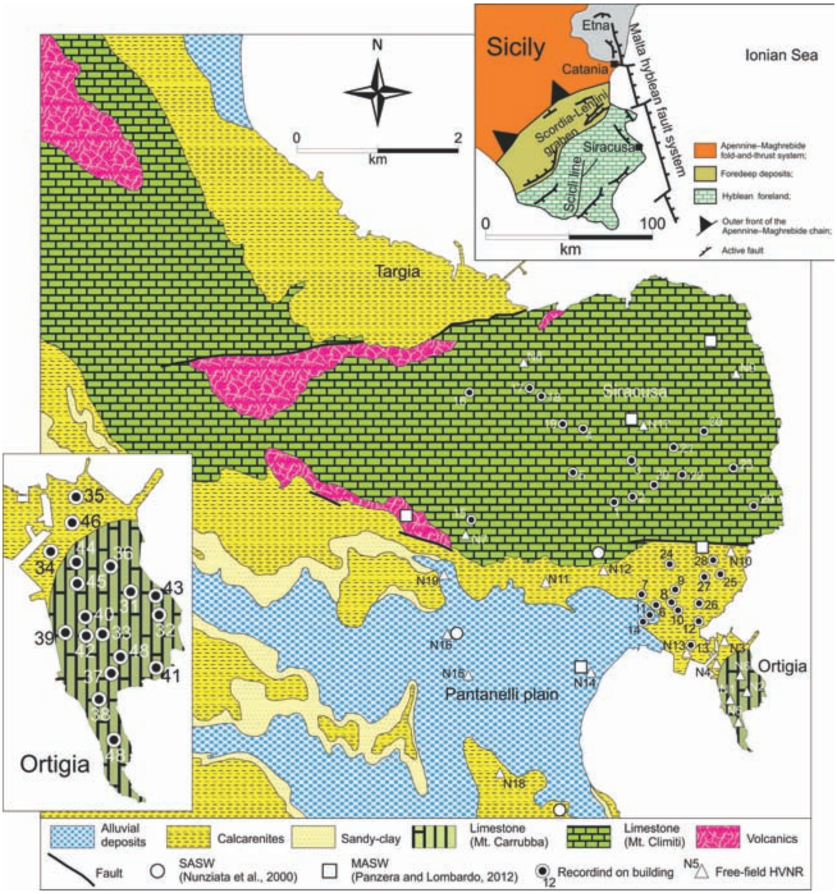

Figure 1. Geo-lithologic map of the Siracusa area (modified from Lentini *et al.*, 1986). The inset map in the upper right portion of the figure shows the tectonic framework of the study area (modified from Lavecchia *et al.*, 2007; Galadini *et al.*, 2001).

(Fig. 1). The Cretaceous volcanics, having thickness up to 500 m, locally represent the deepest term (Tortorici, 2000) which is unconformably covered by a sub–horizontal carbonate sequence that stands for the lithotype more frequently cropping out in the Siracusa town (see Fig. 1). The above mentioned sediments are distinguished in two main units, having similar geotechnical features, known in the literature as Mt. Climiti and Mt. Carruba formations. The former, having thickness ranging between 20 and 80 m, lies on the Cretaceous volcanics and consists of compact and well cemented calcarenites, the latter, with an average thickness of about 20 m, is characterized by alternating calcarenites and marlstones. In some sites the carbonate sequence is directly overlaid by sub–horizontal poorly consolidated calcarenites up to 20 m thick (Tortorici 2000) whereas, in the southern part of the study area, sands and sandy clays, up to 20 m thick, overlie the carbonate bedrock. Finally, alluvial deposits fill out the graben of the "Pantanelli" plain (see 1) whilst detritus, having thickness of about 6-8 m, due to anthropic activity and historical ruins, is mainly outcropping in the Ortigia peninsula, the Siracusa downtown.

3. Methodology

It is well known that the damage level and its distribution during an earthquake is strongly affected at local scale by the features of the site response, based on the near–surface and subsurface ground conditions. Moreover, an important role is played by the physical and mechanical features of outcropping lithotypes. The geophysical and geotechnical characterization of the lithothypes laying on the bedrock is indeed very important in order to identify the site effects, in terms of fundamental frequencies, for a correct planning of earthquake resistant structures. The problem of mitigating, at local scale, the risk connected to the occurrence of earthquakes was therefore tackled performing studies on the evaluation of the characteristics of the outcropping lithology as well as on the frequency distribution of the ground motion.

In the present study, the dynamic properties of main lithotypes outcropping in the Siracusa area were evaluated through the non–invasive techniques MASW (Multichannel Analysis of Surface Waves) and ReMi (Refraction Microtremor). Figure 1 shows the location of the measurement sites. The combined use of both methods allowed us to go through the limitations of each approach and, according to suggestions of Park *et al.* (2005), to compare and check the obtained results. MASW tests were performed using a 12-channel seismograph equipped with 4.5 Hz geophones. A linear array having a length of 36–48 m, depending on the available free space at each site, was deployed using a 2–4 m interval pitch between the sensors. An 8 kg hammer source, with a fixed 8 m offset distance was used, recording five shots, 3 s length, with a sample rate of 512 Hz. The same kind of linear array was used for the ReMi measurements, recording 10 min of ambient noise. The passive techniques based on ambient noise recordings, such as the ReMi, provide reliable dispersion curves in the low frequency range as well, taking advantage from the use of natural sources and cultural noise having wavelengths ranging from a few kilometres to a few tens or hundreds of meters, respectively (Okada, 2003). The refraction microtremor technique possesses the advantage that it requires no triggered source of wave energy and it will work best in a seismically noisy urban setting, analyzing the surface waves produced by traffic vehicles, wind responses of trees and buildings (Louie, 2001). MASW and ReMi experimental dispersion curves were carried out using the Grilla 6.1 software (www.tromino.it). The software calculate the f–k spectrum of a seismic section, having the travel time (t) and the distance (x) as the vertical and the horizontal coordinates, respectively. The transform of t gives the frequency spectrum and the transform of the x coordinate gives the wavenumber k spectrum (Lacoss *et al.*, 1969; Kvaerna and Ringdahl, 1986). From the f–k spectrum the phase velocity vs. frequency contour plot, was obtained. This analysis was carried out to calculate dispersion curves of the fundamental mode on the recorded seismograms for MASW (Fig. 2a,b,c,d). In the ReMi technique, the f–k spectra were obtained by subdividing the recorded signal into time windows having length of 5, 10, 15 and 20 s respectively in order to test the effect of increasing subwindows' length. The dispersion curves (Fig. 2a',b',c',d') were computed performing a simply averaging of all the curves showing clear dispersion. The obtained dispersion curves were automatically picked from the displayed trends, sampling a large number of apparent phase velocities. In particular, MASW dispersion curves were picked on spectral maxima whereas, following Louie (2001) suggestions, the ReMi dispersion curves picking was performed at low phase velocity where the spectral ratios just begin to depart from the low ratio of the incoherent noise.

Eventually, following a method similar to the one proposed by Coccia *et al.* (2010), the automatic picking of the dispersion curves was approximated through a regression to a polynomial curve of fifth/sixth degree according to the observed trend (Fig. 3). In present study, the Rayleigh wave dispersion curves, obtained from the (www.geopsy.org) which provides a set of dispersion curve models compatible with the observed dispersion curve.

The surface–wave inversion procedure was performed trying to use not only the fundamental mode but the higher modes as well.

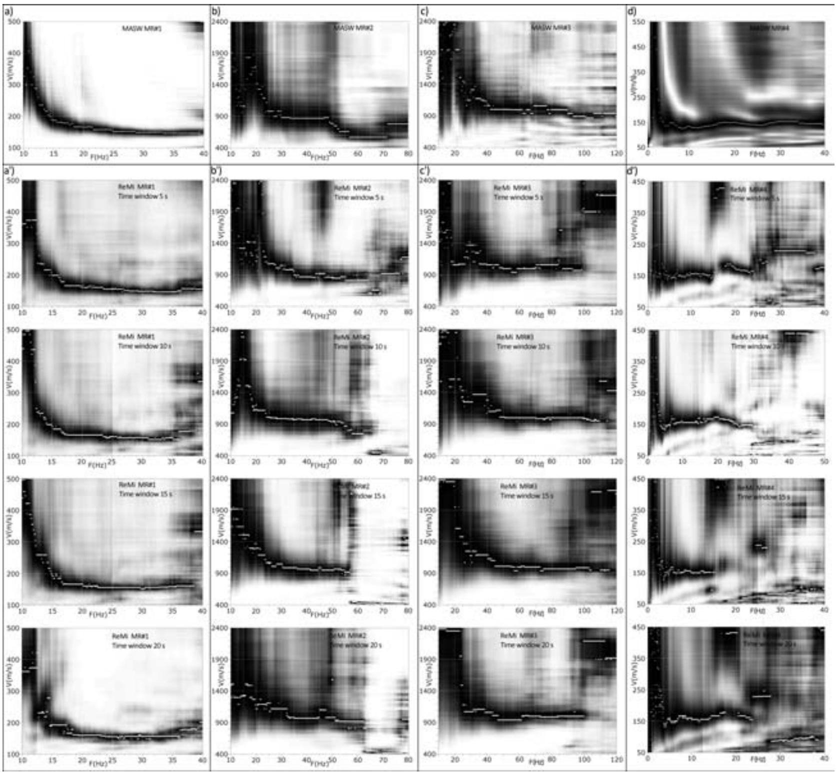

Figure 2. Phase velocity vs. frequency contour plot spectra for MASW (a, b, c, d) and ReMi (a', b', c', d') tests.

To identify each mode in the velocity–frequency spectrum we performed a visual check in order to find out the zone characterized by low amplitude values, where the apparent dispersion curve could pass from one mode to another, as suggested by Maraschini *et al.* (2010). Inversion of the experimental dispersion curve was obtained after a rough definition of the parameters: shear wave velocity (VS), thickness, compressional wave velocity (VP), Poisson's ratio and density.

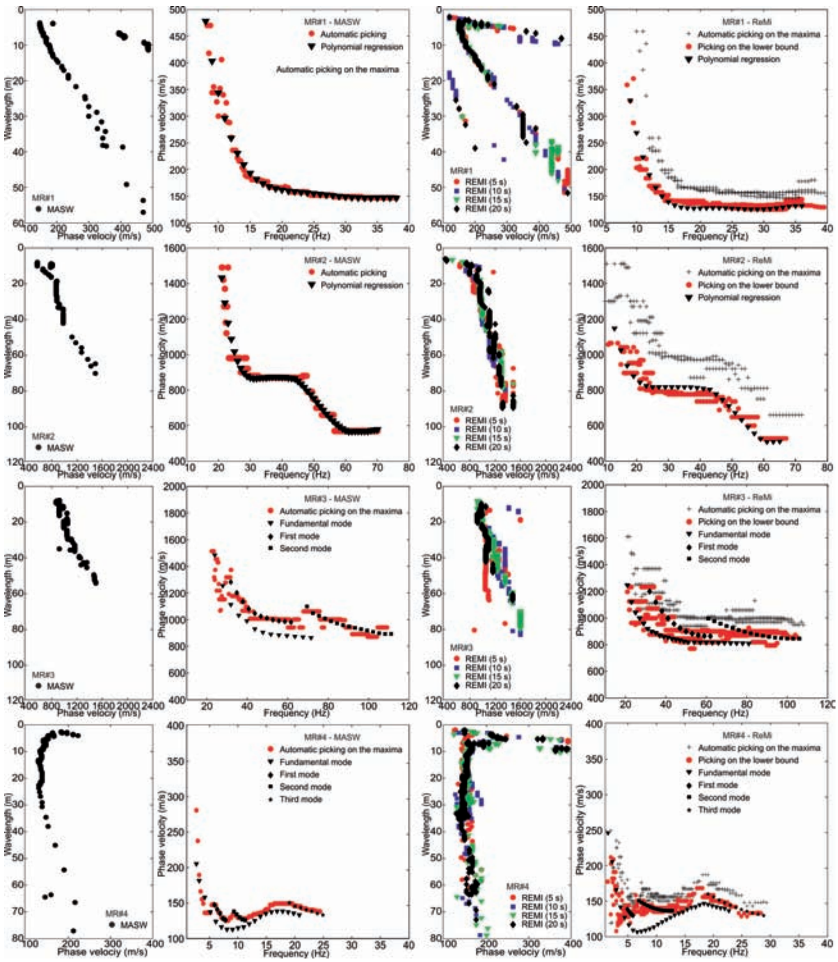

Figure 3. Rayleigh waves phase velocities as a function of wavelength and corresponding polynomial regression curves obtained from the automatic picking of Fig. 2 spectra plots at each site.

As regards the site response evaluation, 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 (Lermo and Chavez–Garcia, 1993; Gitterman *et al.*, 1996; Seekins *et al.*, 1996). 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; Maresca *et al.*, 2003; Al Yuncha *et al.*, 2004), 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 about sixty sites in the Siracusa–Ortigia area (Fig.1) selected by taking into account the space distribution of the main outcropping lithotypes. 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 HVNR technique. 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 0.5–30.0 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.

Ambient noise spectral ratios were also calculated after rotating the horizontal components of motion by steps of 10 degrees starting from 0° (north) to 180° (south) in order to investigate about the possible presence of directional effects (Spudich *et al.*, 1996). However, in presence of lateral and vertical heterogeneities or velocity inversion, amplification on the vertical component of motion can take place (Di Giacomo *et al.*, 2005). In such instances, the HVNR can be "non–informative" so that, 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; 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. 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.

4. Description of results and concluding remarks

The evaluation of the local seismic response in the Siracusa area was undertaken using a twofold approach based on the interpretation of the Rayleigh waves dispersion curves, obtained from MASW and ReMi prospections, and on the HVNR obtained through the Nakamura's technique.

The use of techniques based on the propagation of surface waves made possible the detection of the $V_{S,30}$ features for the main outcropping lithotypes and consequently the classification, according to the Eurocode8 (2003), of the investigated sites. A fitting between the HVNR frequency peaks and the theoretical ellipticity was also performed in order to get information about the deeper part of the estimated Vs profiles, testing at the same time if the depth reached through the investigations was adequate to characterize the considered lithotypes. The obtained results pointed out that sometimes, as for instance in the Pantanelli plain (MR#4 in Figure 1), the linear array length was not adequate. Figure 4 shows the results of the dispersion curve inversion, performed with the "neighborhood algorithm". In MR#1,

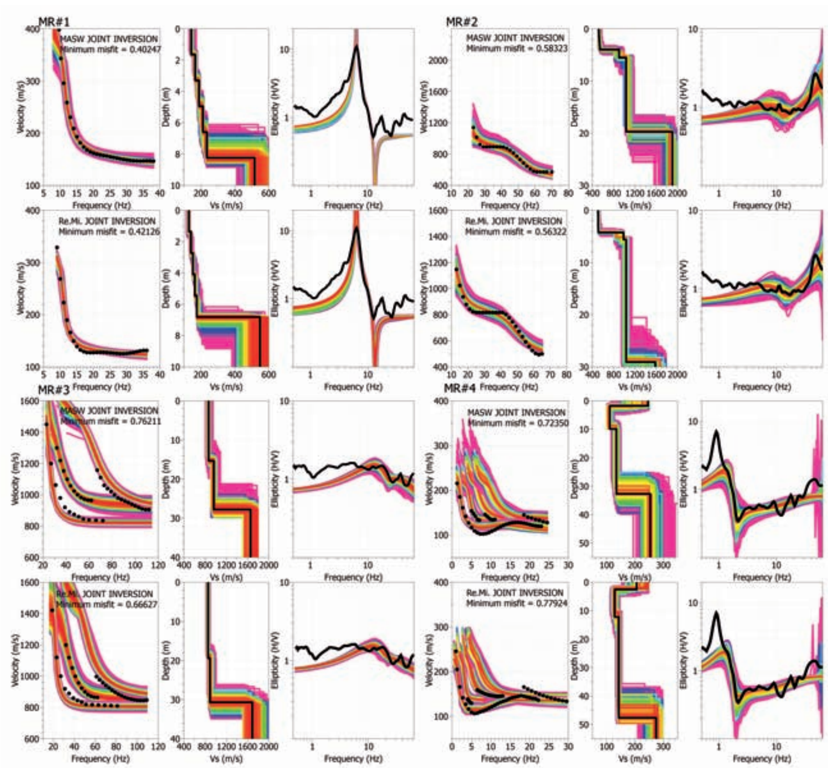

Figure 4. Dispersion curves, shear wave velocity profiles and ellipticity curves obtained from the joint inversion of the experimental phase velocities (black dots) and the HVNR curves (gray lines); black line in the Vs profiles indicates the best estimated model.

located on the detritic-clay and Mt. Climiti limestone, values of $V_{S,30}$ 340 m/s; 500 m/s were obtained and, it is possible, according to the Eurocode8 (2003), to classify such site in a C soil category. MR#2, Mt. Climiti limestone, with $V_{S,30}$ 1000 m/s, is Class A (Eurocode8), MR#3, Mt. Carrubba limestone, shows $V_{S,30}$ 900m/s (Class A Eurocode8) and MR#4, located on the alluvial deposits ($V_{S,30}$ 900m/s), being an inversely dispersive profile, do not allow assigning a soil category.

It has to be remembered that the physical and mechanical features of outcropping lithotypes are very important to characterize the maximum acceleration and frequency of the ground motion which, ultimately, is tightly linked to damage of buildings. The geophysical and geotechnical characterization of the lithotypes laying on the bedrock is indeed very important in order to identify the site effects, in terms of fundamental frequencies, for a correct planning of earthquake resistant structures. As a result of the above mentioned classification of the main outcropping lithotypes, a wide scale $V_{S,30}$ grid map (see Fig. 5) was inferred by combining present experimental data and literature ones (Nunziata *et al.*, 2000; Panzera & Lombardo, 2013). Such output would be particularly useful to work out shaking maps for the Siracusa–Ortigia area that will take into account the potential seismic effect due to the local geology.

The HVNR technique allowed us to identify the fundamental frequency of the main lithotypes characterizing the study area. In order to better describe and interpret the HVNR features in term of site response and local geology, they were subdivided into different groups through a cluster analysis (see Fig. 6), detecting the optimal number of clusters by the Akaike Information Criterion (AIC, Akaike, 1974). Cluster (a) consists of six measurement points (#1, #2, #3, #4, #12 and #13), performed in the Ortigia area on outcropping limestone, characterized by peaks in the frequency range 1.0–3.0 Hz. These spectral ratio peaks can be explained in terms of a topographic effect. As a matter of fact, such HVNR peaks cannot be justified as linked to the lithologic features since the physical properties, obtained from both the MASW and ReMi experiments (MR#2 and MR#3) are typical of a stiff rock (Vs>900 m/s). The clusters (b) and (e) include HVNRs obtained for the sites #5, #9, #14 and #15. They show two dominant peaks in the frequency ranges 1.0–3.0 and 4.0–10.0 Hz. The first frequency range, similarly to cluster (a), can be ascribed to the particular seismic site response observed in the Ortigia peninsula whereas, the spectral ratio peaks in the frequency range 4.0–10.0 Hz could be related to some local shallow lithologic features such as ground motion linked to the vibration of small blocks at high frequency values (Burjànek *et al.*, 2010).

In cluster (c) the spectral ratio curves show a tendency towards a slight and constant increase in amplitude that reach a value of 2–3 units at frequencies greater than 7.0 Hz. This moderate amplitude increase appear related to the modest velocity contrast existing between the calcarenites (#18 and #19) or the slightly fractured limestone with respect to the massive Mt. Carrubba limestone forming the underlying bedrock (#6, #7, #10, #23, #24).

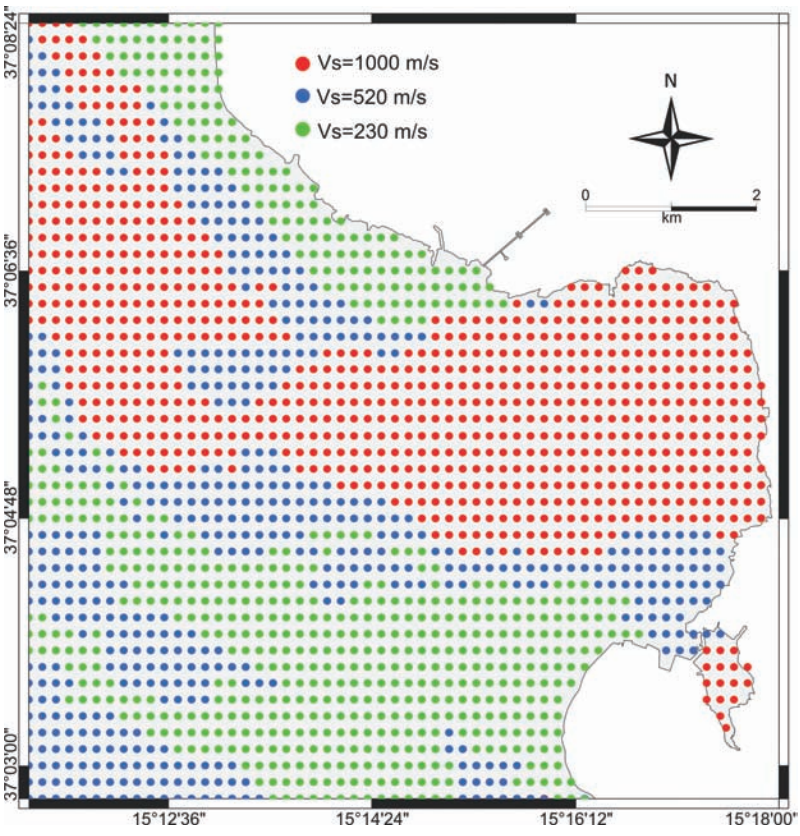

Figure 5. $V_{S,30}$ grid map of the Siracusa–Ortigia area.

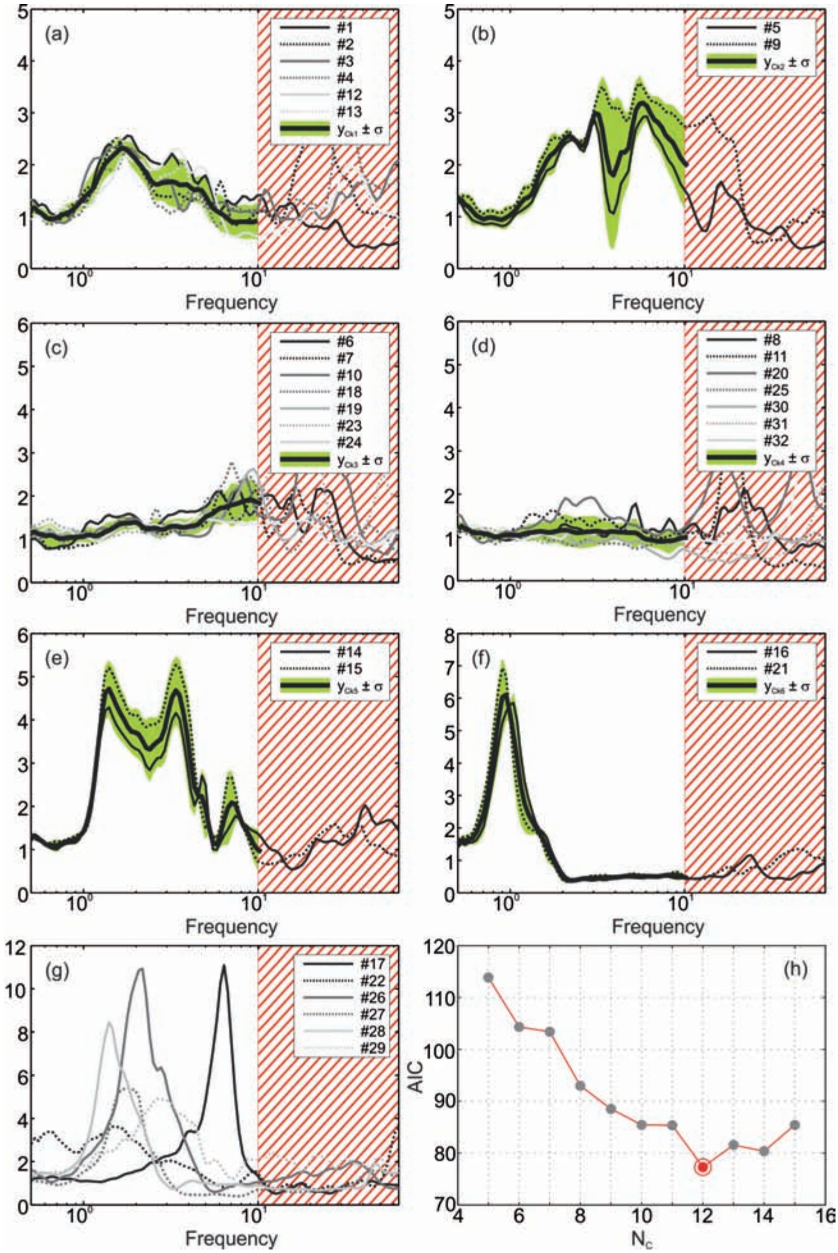

Figure 6. HVNRs groups, obtained through cluster analysis (a, b, c, d, e, f, g) and Akaike Information Criterion parameter vs. the number of clusters (h) from measurements performed in the Siracusa area. Continuous and dotted thin lines show each HVNR; thick black lines and gray areas point out the average HVNR for each cluster and the corresponding ±ς; gray patterned area delimitates the frequency range not considered in the cluster analysis.

Slightly fractured limestone is indeed characterized by V_S ≈500 m/s (see site MR#2) whereas, a V_S value of about 350 m/s is available from literature (Tortorici, 2000) as regards the calcarenites. The HVNRs obtained for the carbonate sequence (#8, #11, #20, #30, #31 and #32) and the volcanics (#25), constitute cluster (d) which shows a flat spectral ratio plot. This result is in good agreement with the experimental shear wave velocities, obtained through the MASW and ReMi experiments (seeMR#2 and MR#3) pointing out that these formations represent the local bedrock. Cluster (f) is formed by the HVNRs obtained from measurements points #16 and #21. They show pronounced spectral ratio peaks at about 1.0 Hz which can be related to the presence of thick (40–50 m) alluvial deposits and soft sandy–clay sediments having a V_S of about 130–140 m/s (see MR#4). The group (g) includes all the measurement points (#17, #22, #26, #27, #28, #29) each outlining a cluster. They represents either anomalous behaviors related to the high velocity contrast existing between the detritus or the sandy clay formation and the limestone (see MR#1), as well as pronounced spectral ratio peaks related to the presence of thick alluvial deposits and soft sandy–clay sediments. Moreover, pronounced spectral ratio peaks at frequencies higher than 10.0 Hz (not considered in the cluster analysis) are sometimes observed in the sites located on limestone and calcarenites. Such feature can be a consequence of the high velocity contrast existing between the limestone and the thin layers of detritus that often overlay such formation. Examples of HVNRs typically observed in the rigid and soft terrains outcropping in the Siracusa–Ortigia area, are shown in Figure 7 together with the diagrams setting into evidence the possible existence of directional effects.

Trying to summarize the results of HVNR performed in the Siracusa–Ortigia area, it can be pointed out that well–defined spectral ratio peaks are mostly observed in the recording sites located on the alluvial deposits, as well as on the coarse detritus and sandy clay. No significant spectral ratio peaks are present both in all sectors where limestone outcrop and in all the sites where calcarenites directly overlay the limestone. It has also to be pointed out that in some portions of the limestone outcrops, either where such lithotype is partially covered by detritus or where a morphologic effect can be recognized, pronounced spectral ratio peaks are identified. The limestone can be considered as the local bedrock, being the lithotype showing the higher shear wave velocities.

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

In addition to the previously described survey, an experiment was performed aiming to estimate the seismic response in the Ortigia peninsula (downtown Siracusa), investigating on the existence of possible topographic effects linked to its particular shape. Amplification of the ground motion in a topographic irregularity is generally linked to the focalization of seismic waves at its topmost part due to the existence of diffraction, reflection and conversion of the incident waves (Bard, 1982). Such amplification effects are frequency–dependent so that resonance phenomena occur when the wavelength of the incident wave is comparable to the horizontal dimension of the hill. Moreover, the influence of the topography on ground motion is linked to the sharpness of the ridge crest (Géli *et al.*, 1988; Bard and Riepl–Tomas, 1999). This ground–motion amplification mechanism at ridge crests is in principle similar to the well–known effects in the seismic design of buildings, which appears to apply at a larger scale to mountains as well (Buech et al, 2010).

The upper part of a hill shows indeed increasing resonant motion with respect to the whole of the structure. Moreover, significant directional effects, transverse to the major axis of the ridge, are often observed (Spudich *et al.*, 1996).

To evaluate such effects, We computed the HVNRs in some selected recording sites located in Ortigia (see Fig. 8 lower right panel), by dividing the N–S and the E–W components of motion by the vertical one (V), separately. It appears evident (Fig. 8) that the E–W/V spectral ratios are more pronounced in amplitude than the N–S/V ones, especially in the range 1.0–3.0 Hz. Figure 9 shows a direct comparison of the rotated HVNRs and the results of noise polarization analysis for all recording sites. Both methodologies agree, indicating, particularly in the frequency range 1.0–3.0 Hz, that maxima of HVNR amplitudes take place at 90–100° and maxima of the horizontal polarization strike in the E–W direction. Spectral ratio peaks observed in the frequency range 3.5–10 Hz (Figs. 8, 9) show a more complex pattern of directional effects. In 3.9, for instance, a strong NW–SE directionality (site 1), as well as a N–S direction (sites 7 and 12) and a N–S direction together with an E–W one (site 8) are evident. Such high–frequency directional variability cannot be easily interpreted. In our

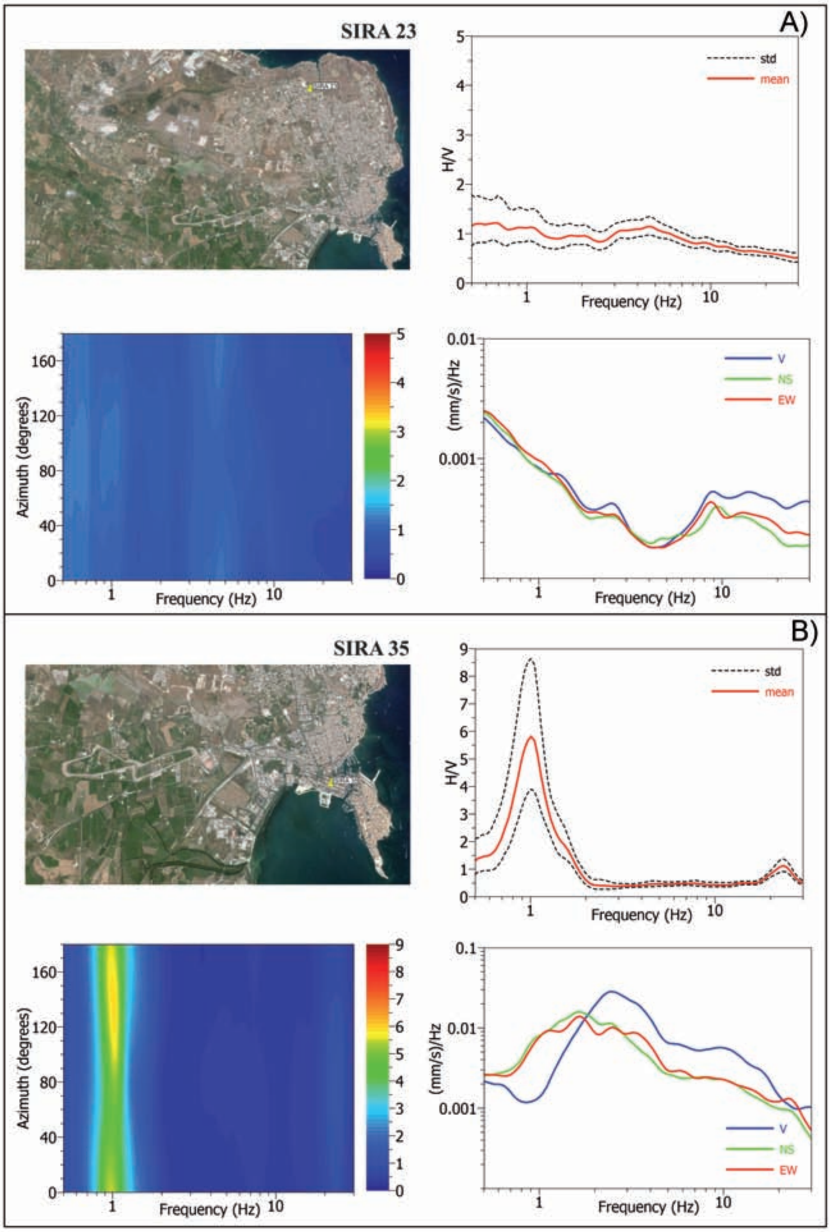

Figure 7. Examples of HVNRs observed in the stiff (A) and soft (B) terrains outcropping in the Siracusa–Ortigia area; the lower panels refers to diagrams setting into evidence the possible existence of directional effects.

opinion a possible explanation could be linked to local shallow lithologic features. As observed by Burjánek *et al.* (2010), high–frequency ground motion can indeed be controlled by the vibration of smaller blocks that imply both different resonant frequencies and directions.

We have also compared field data observations with the theoretical resonance frequency (f_0) expected for the topographic effects in Ortigia hill. We adopted the relationship $f_0 = Vs/L$, where L is the width of the hill (about 700 m; see Fig. 8 lower right panel) and Vs is the shear wave velocity of the limestone outcropping in the peninsula (1,000 m/s) (Bouchon 1973; Géli *et al.*1988). The predicted value, $f_0 =$ 1.4 Hz, is consistent with the observed spectral peaks, in the range of 1.0–3.0 Hz. In general, the amplification of ground motion connected to the surface topography is directly related to the sharpness of the

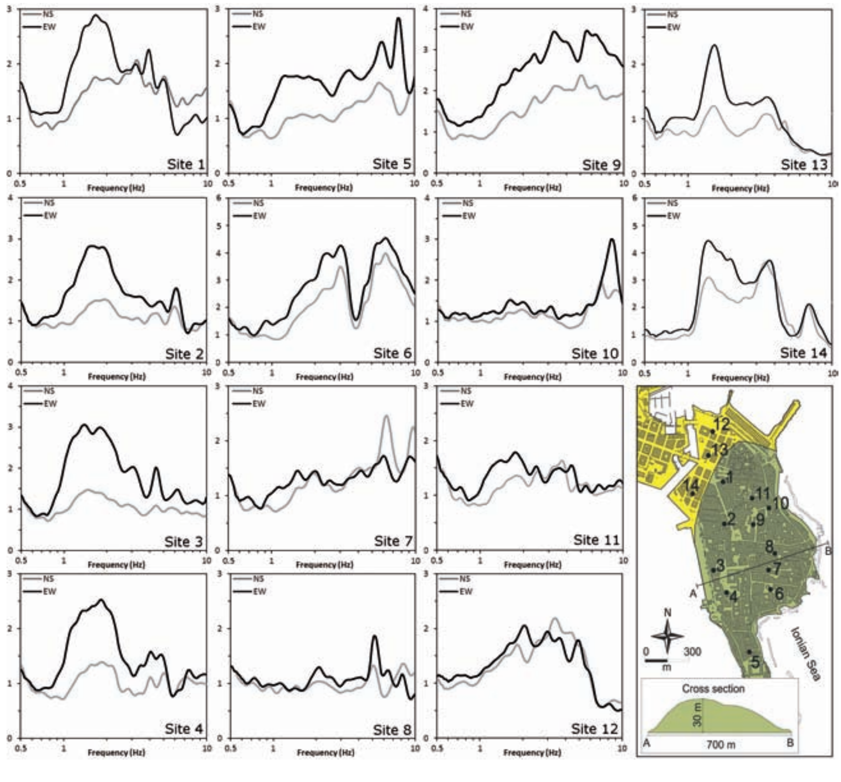

Figure 8. Spectral ratios (HVNR) obtained from ambient noise measurements performed in the Ortigia peninsula.

topography (Bard 1994). In such instances topographic effects become clearly detectable with experimental and numerical approaches. In our study, the gentle topography and the homogeneous lithology of the Ortigia peninsula make it an ideal and simple case study for investigating topographic effects using ambient noise records. The Ortigia hill has a natural frequency of about 1.4 Hz and shows an E–W preferential direction of vibration. The specific directional effects in ambient noise, well defined both in space and in a narrow frequency band (1.0–3.0 Hz), are signs of a normal mode of vibration of the hill (Roten *et al.*2006). It seems important to state that the reliability of ambient noise records for studying topographic effects is supported by the concept that in a natural hill the horizontal component of the ground motion shows an amplitude greater than the vertical one (LeBrun *et al.* 1999).

It can therefore be assumed that, similarly to what is observed in civil structures, especially when a simplified topography and lithology is present, data coming from ambient noise measurements can be used profitably to characterize the topographic effects.

The findings of present study point out a good reliability of the HVNR technique for evaluating the site response linked to shallow lithologic features, as well as the influence of topography on the local seismic response. It is, however, necessary to verify if the observed directional effects are connected to coherent polarized noise sources linked to cultural activity and/or meteorological noise. For this reason, in the present study, the noise measurements were recorded on different days and at different hours. Our results showed a good stability of the site response directionality in the investigated area regardless of date or time of day. Our results support the use of this quick and inexpensive technique and further confirm the importance of estimating the local seismic response to reduce the potential risk of building damage as a result of ground motions.

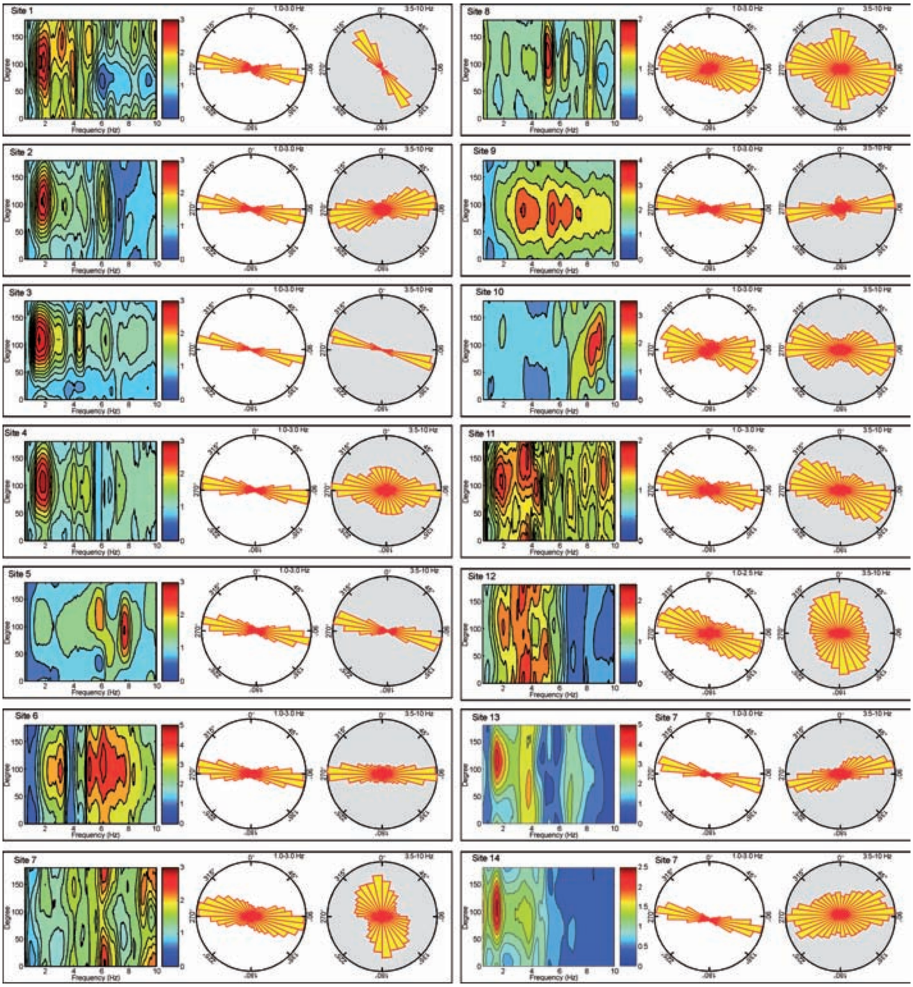

Figure 9. Contours of the geometric mean of the spectral ratios as a function of frequency (*x* axis) and direction of motion (*y* axis) and polarization rose diagrams calculated in the ranges 1–3 Hz and 3.5–10 Hz, respectively.

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

1. Dipartimento di Scienze Biologiche, Geologiche e Ambientali, Università di Catania, Italy. Corresponding author: Lombardo G., lombardo@unict.it.

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