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"CONTRIBUTION OF HVSR MEASURES FOR SEISMIC MICROZONATION STUDIES"

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ABSTRACT

The HVSR method applied to seismic noise can be a very useful technique to map the site effects of the territory, to identify the thickness of the soft covering and so the depth of the seismic bedrock. The case of the urban area of Oliveri is presented. Because of its high seismic hazard this area has been subject of first level seismic microzonation. The town lies on a large coastal plain made of mixed fluvial/marine sediments, overlapping a deformed substrate. In order to identify points on the area probably suffering of relevant site effects and to define a preliminary Vs subsurface model, 23 HVSR measurements were performed. A clustering technique of continuous signals has been used to optimize the calculation of the HVSR curves and 42 reliable peaks, in the frequency range 0.1-20 Hz, have been identified. A second clustering technique has been applied to the set of 42 vectors, containing coordinates, frequency and amplitude of each peak, to identify subsets attributed to the same seismic discontinuities. Three main clusters have been identified. The two characterized by lower frequencies have been considered in the HVSR data inversion, as stratigraphic peaks probably caused by the seismic bedrock. Finally, the morphology of the top of the seismic bedrock has been mapped. The deepening of the seismic bedrock below the mouth of the Elicona Torrent suggests the possible presence of a buried paleo-valley.

1. INTRODUCTION

The seismic microzonation of a territory aims to recognize the small scale geological and geomorphological conditions that may significantly affect the characteristics of the seismic motion, generating high stress on structures and consequently produce permanent and critical effects (site effects) [Ben-Menahem and Singh, 1981; Yuncha and Luzon, 2000].

The dynamic characteristics of a seismic phase of body or surface waves, generated by an earthquake and incident on a portion of the ground surface, often show sharp variations. Such variations are frequency dependent and sometimes have extremely local character. Significant increases of peak amplitude of ground shaking are commonly called site effects [Bonnefoy-Claudet et al., 2006b]. In general, these phenomena are controlled by anomalies in the mechanical properties of the shallowest layers of the subsoil, especially when it consists of soft sediments, or by the shape of the topographic surface.

Knowing a very detailed mechanical model of the soft sediments composing the cover layer, it is possible to predict the site effects or even determine univocally the transfer function of the 1D subsoil model by means of numerical calculation [Bonnefoy-Claudet et al., 2006a]. The difficulty and costliness of the reconstruction of a suitable subsurface model using geophysical techniques and the necessity of taking into account then on linear effects [Dimitriu et al., 2000], have led many researchers to develop and adopt more direct techniques that allow to determine approximated empirical transfer functions.

Nakamura [1989] proposed that in correspondence to the resonance frequencies of a sequence of layers, the Horizontal to Vertical Spectral Ratio (HVSR) of the seismic noise presents peaks well correlated with the amplification factor of S waves, generated by earthquakes, between the bottom and the roof of the stratification.

The HVSR technique provides consistent information related to site effects [Nakamura, 1989; Lachet & Bard, 1994; Kudo, 1995; Bard, 1998; Mucciarelli, 1998; Chávez-García et al., 2014; Castro et al., 2017]. The contribution of the ambient vibration prospecting in seismic microzoning has been demonstrated by many recent studies [Albarello et al., 2011; El-Hady et al., 2012, Kurtulmuş & Akyol, 2015; Pandey at al., 2016; Singh et al., 2017].

In regions with unconsolidated sediments with low impedance respect to the underlying bedrock, the HVSR technique provides a good evaluation of the amplification frequencies [Field & Jacob, 1993; Bard, 1998, Borges et al., 2016]. However the uncertainty of estimating thickness of soft sediments can be high if information about subsoil characteristics, noise composition and distribution of the noise sources are not sufficient [Bignardi, 2017].

Furthermore, not necessarily an HVSR peak must be attributed to resonance frequencies of a buried structure. It might also depend on the sources of noise and in such case it will be not correlated with amplification effects on incident waves [Bonnefoy-Claudet et al., 2006b; Kurtulmuş & Akyol, 2015]. Topography can be also an important source of site effects [Chávez-García et al., 1997]. In fact, one of the most controversial aspects in the application of the HVSR technique concerns the criteria for the selection, in the microtremor signals, of appropriate time windows for the calculation of the HVSR curves. However, appropriate techniques based on a cluster analysis algorithm may help to discriminate, between peaks caused by source effects and peaks due to site effects [Rodriguez and Midorikawa, 2002; Capizzi et al., 2014; Martorana et al.; 2014; Capizzi et al., 2015; D'Alessandro et al., 2016; Martorana et al., 2017; Martorana et al., 2018]. The separation of the two effects can allow to determine for each cluster an average HVSR curve better related to the local site effects and to identify all the significant peaks of the H/V spectra.

The cluster analysis can be used also to group HVSR peaks probably due to the same site effect to delimit areas with the same answer to a seismic input [D'Alessandro et al., 2016]. In each point of an area identified by each cluster, it will be reasonable to assume the same site effect. The latter will be characterized in frequency and amplitude with a technique of 2D interpolation of the parameters determined at the measurement points. Although it is not possible to exclude that the frequencies belonging to the same cluster are due to different structures or vice versa, the depth values obtained by inverting the average HVSR curves, if related to peaks of the same cluster, can be interpolated to reconstruct the same seismic reflector.

HVSR inversion produce 1D S-wave velocity models that are used to estimate the depth of the seismic bedrock and thickness and seismic velocity of the overburden deposits [Fäh et al., 2003; Grippa et al., 2011; Bignardi et al., 2016; Borges et al., 2016; Martorana et al., 2017; Picotti et al., 2017]. The wide uncertainty margins of the HVSR inverse models can be reduced using data from other geophysical methods as a priori constraints [Scherbaumet al., 2003; Arai & Tokimatsu 2004; Parolai et al., 2005; Picozzi et al., 2005; Imposa et al., 2016; Pappalardo et al., 2016; Imposa et al., 2017; Picotti et al., 2017].

The Multichannel Analysis of Surface Waves (MASW) revealed a good approach to constrain the near surface portion of the HVSR model [Zor et al., 2010; Capizzi & Martorana, 2014; Castellaro, 2016; Panzera et al., 2016; Martorana et al., 2017].

In zones where stratigraphic drillings are available, a good practice is to constrain HVSR inversion by fixing thickness of near surface layers detected by drilling [Amorosi, 2008; Grippa et al., 2011; Tropeano et al., 2013] and by adding deeper seismic layers to interpret peaks of lower frequencies [Castellaro & Mulargia, 2009, Martorana et al., 2018].

2. GEOLOGICAL SETTING AND REGIONAL SEISMICITY

The studied area is part of the Peloritani Mountains, a segment of the Siculo-Maghrebian chain that is mainly constituted by a pile of tectonic units consisting of Hercynian metamorphic rocks and their Meso-Cenozoic sedimentary covers [Giunta et al., 1998, cum biblio].

In the Peloritani Mountains different deformation steps are related to the Alpine orogeny, superimposed to Hercynian ductile deformations. The Oligo-Miocene contraction has been characterized by several phases in which there has been the formation of folds associated with thrust systems that fragmented and stacked the

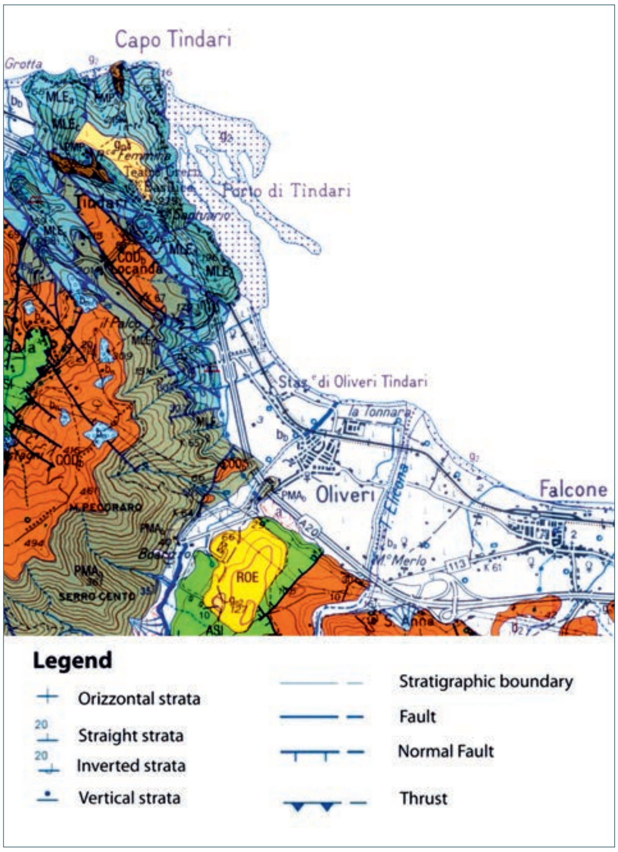

FIGURE 1. Geological map of Oliveri town (from SERVIZIO GEOLOGICO D'ITALIA (2011) - "Foglio Geologico 600 Barcellona Pozzo di Gotto" 1:50.000 CARG-ISPRA): **a)** slope debris; **b_a)** active alluvial deposits; **b_b)** alluvial and litoral deposits; **b_2)** eluvium and colluvium; **b_n)** inactive alluvial terraced deposits; **g_2)** active strandlines (beaches); **g_{n1-5})** terraced marine deposits; **ROE)** Biodetrital calcarenites, clays and sandy clays (Rometta Fm., Upper Pliocene - Middle Pleistocene); **ASI)** Argille Scagliose (Upper Cretaceous); **COD_{b-c})** Capo d'Orlando Flysch: areanaceous facies (arkose) with alternation of clay-marly levels (Upper Oligocene – lower Burdigalian); **PMA_{a-b})** paragneiss and gneissic micaschists, silicate marbles, quartzites and aplo-pegmatitic dykes (**PMP_a**) (Apromonte unit – Paleo-Proterozoic – Permian); **MLE_{a-b-c})** Paragneiss, micaschists, marbles, eclogites, quartzites (Mela unit – Paleozoic).

crystalline basement and their sedimentary covers in different tectonic units. Reverse fault systems (breaching) affected the area since the Upper Miocene, resulting in moderate shortening [Giunta & Nigro, 1998]. At the end of the Miocene the Tyrrhenian rifting produced a series of extensional low angle faults that resulted in a thinning of the chain. During Plio-Pleistocene times the area occupied by the Peloritani Mountains was affected by a strike-slip tectonic phase that generated two different systems: the first one synthetic with right cinematic and oriented NW-SE and E-W; the second one antithetical, mainly left-lateral and oriented N-S and NE-SW [Ghisetti & Vezzani, 1977; Nigro & Renda, 2002].

Around the Oliveri plain there is evidence of active tectonics characterizing a right-lateral shear zone named Aeolian-Tindari-Letojanni fault [Ghisetti, 1979]. This fault zone separates two different geodynamic domains: compressive to west, related to a roughly N-S trusting produced by continental collision, and extensional to east, controlled by NW-SE expansion of the Calabro-Peloritan Arc [De Guidi et al., 2013]. The analysis of seismic and geodetic data, acquired in the last 15 years, and structural and morphological surveys show evidence of tectonic activity in this area to as recent as the middle-upper Pleistocene [Catalano & Di Stefano, 1997; Ghisetti, 1979; De Guidi et al., 2013]. Recent studies, not far from the Oliveri plain, have characterized some geothermal springs and gas vents and discussed on their possible role in the seismic activity of the area [Giammanco et al., 2008]. Based on paleontological data a relevant uplift rate up to 5.5 mm/year has been estimated [Di Stefano et al., 2012].

The lithostratigraphic framework of the substrate of the urban area of Oliveri (Figure 1) is made up by the metamorphic basement of the Aspromonte Unit that is covered uncomfortably by the arenaceous member of the Capo D'Orlando Flysch. Upwards the flyschoid sediments are tectonically overlaid by the Argille Scagliose Antisicilide. The previous deposits are capped by sands and calcarenites of Plio-Pleistocene age. The most recent sediments consist of alluvial and beach deposits.

The Oliveri territory is located in the area 932 of the ZS9 seismogenic zonation of Italy [Meletti and Valensise, 2004]. It includes seismogenic structures largely known through geophysical exploration. The faults in this area partly allow the retreat of the Calabrian Arc and some are synthetic faults that segment the Gulf of Patti. The area 932 is one of the areas with the highest seismic potential of the whole Sicily; in fact. the 1908 Messina earthquake occurred in this area, for which different source mechanisms have been proposed, some of which are, probably, associated with the activation of complex fault systems or blind faults [Ghisetti, 1992; Valensise and Pantosti, 1992; Monaco and Tortorici, 1995].

The high rate of seismicity in the Gulf of Patti and in the area between Alicudi and Vulcano is associated to the two right-slip fault systems, Patti-Vulcano-Salina and Sisyphus, respectively oriented NW-SE and WNW-ESE (Palano et al., 2015 and references therein).

The seismic activity recorded since 1981 in the area surrounding the urban center of Oliveri, represented in Figure 2, is characterized by about 3500 events with local magnitude (ML) greater than 2. Of these about 89% have hypocenters tightly concentrated around an aver-

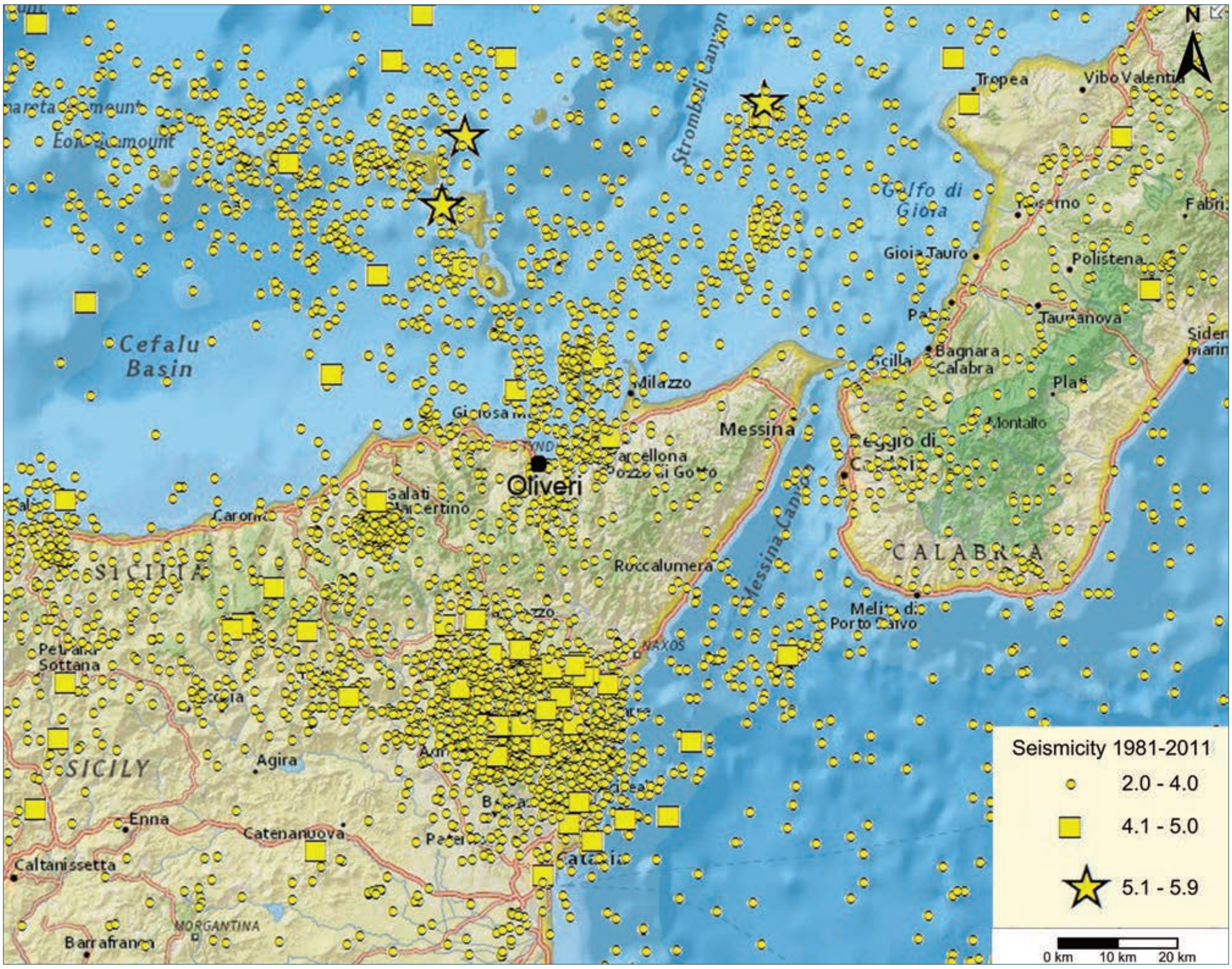

FIGURE 2. Distribution of epicenters of instrumental earthquakes located by the INGV between 1981 and 2011 in North-Eastern Sicily. The town of Oliveri is indicated by a black circle.

age depth of about 10 km. The remaining 11% consists of events whose hypocenters are aligned on a plane that dips northwestward with an angle of about 60° and are distributed rather uniformly with respect to depths up to 400 km. The sources of these events are located within the Ionian lithospheric slab that dips under the Calabrian Arc [Giunta et al., 2004]. An analysis of completeness of these data sets has indicated a local magnitude threshold equal to about 2.6 [Schorlemmer et al., 2010; D'Alessandro et al., 2011].

The shallow seismic activity has a marked tendency to occur through sequences of aftershocks sometimes preceded by foreshocks. This tendency was assessed in a quantitative way by comparing the estimates of the correlation dimension in the domains of the epicenter coordinates and time, both for the component of the seismicity constituted by events not followed by aftershocks and the main shock of the sequences that for the total set of events [Adelfio et al., 2006]. The estimates of the space and time correlation dimension relating to independent events are close to those expected for uniform distributions, as opposed to those for the total set that are much smaller. The geometric characteristics of the clusters related to the shallower seismicity identify orientations that are consistent with those of the main tectonic structures of the area.

3. HVSR MEASUREMENTS

In the urban area of Oliveri, 23 HVSR measurements have been performed, quite uniformly distributed with a mean spacing of about 250 m. For the measurements the 3 components seismic digital station TROMINO® (Micromed) has been employed.

For each measurement point the recording duration was 46 minutes and the sampling frequency 256 Hz. Each recording was subdivided in temporal windows of 50s. This choice allowed us to have the minimum number of windows selected for the analysis accord-

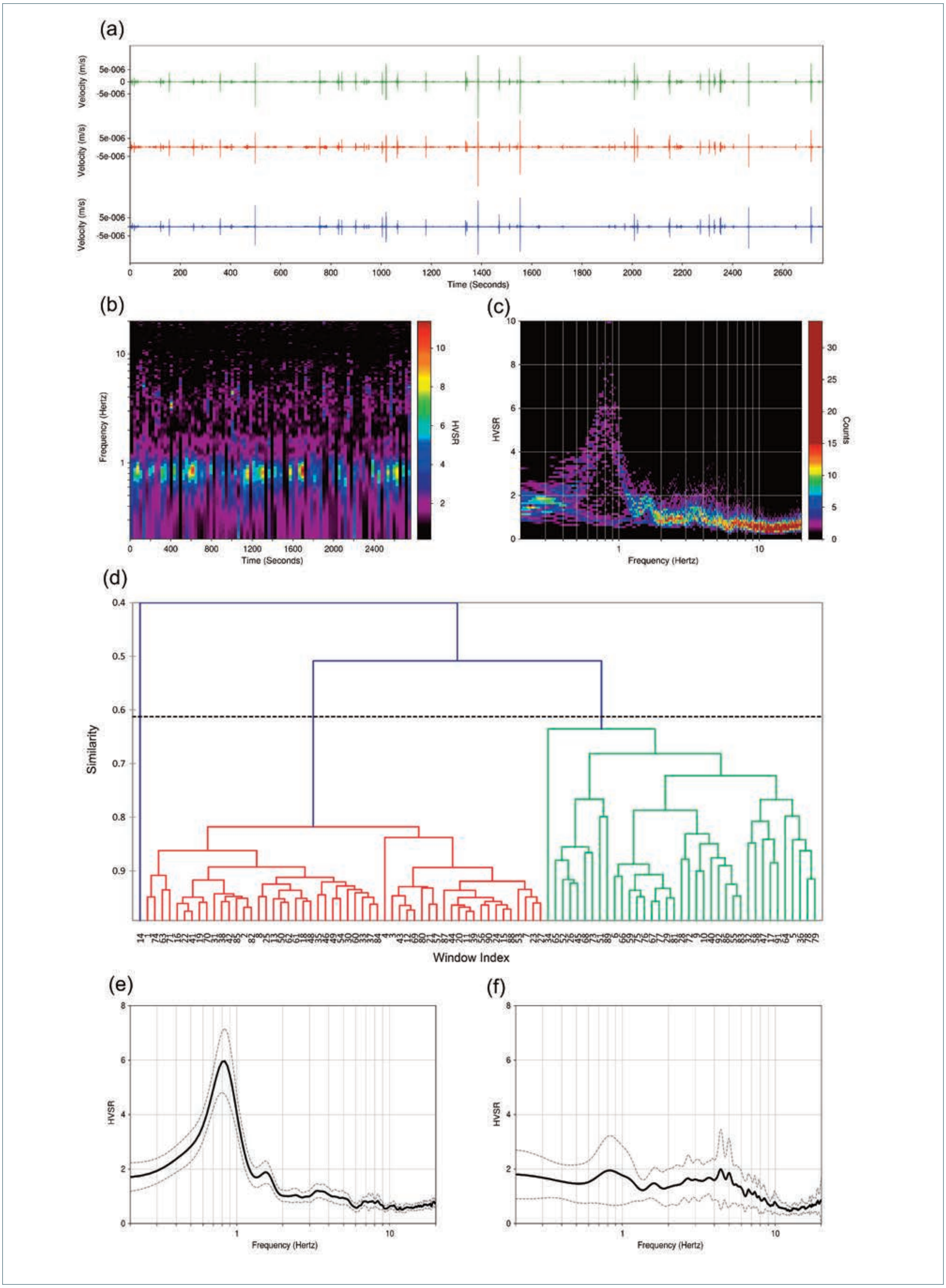

FIGURE 3. HVSR analysis of the microtremor record nr. 7: three components (a); Frequency vs Time and HVSR vs Frequency of the acquired signal (b and c, respectively); dendrogram of cluster analysis (d); HVSR vs Frequency of Cluster red (e); HVSR vs Frequency of Cluster green (f).

ing to SESAME criteria [2004]. Following these criteria, the signal relative to each time window was de-trended and baseline corrected. The analysis was limited to the range 0.1-20 Hz, which is the frequency range of interest for seismic microzonation and earthquake engineering. The data in the frequency domain have been filtered with a triangular window to obtain a smoothing of 10%. The attribution of peaks to resonance phenomena of buried structures has been validated, in agreement with SESAME criteria, by analyzing the standard deviation of the spectral amplitudes and the independence from the azimuth of the mean spectral ratio (Figure 3).

In order to obtain reliable HVSR curves, several acquisition and processing criteria must be adopted. The most important criteria concern the acquisition and extraction modes from a continuous record, of an optimal set of analysis time windows, for the evaluation of a HVSR function, dominated by the effects of buried geological structures [SESAME Project, 2004]. This last is probably the most controversial aspect in the HVSR technique implementation. Several authors believe that spikes and transients in microtremors bring information highly dependent from the sources and therefore cannot be used to estimate resonance frequencies of sites [Horike et al., 2001; SESAME Project, 2004]. Therefore, they exclude the non-stationary portion of the recorded noise, thus considering only the low-amplitude part of signal, for the computation of the average HVSR function. Other authors [Mucciarelli and Gallipoli, 2004], instead, suggest that the non-stationary large-amplitude noise windows should not be removed, because these, generally, carry subsoil information that improves the correlation between the noise and earthquakes HVSR curves.

The windows selection can be made in time and frequency domain. In both cases, the selection of the windows is arbitrary. Practically the visual inspection of the windows makes the processing long and farraginous and the result is strongly dependent by the skill of the operator, while its reliability is difficult to assess quantitatively.

In a first level seismic microzonation, after the identification of the peaks of the HVSR curves attributable to resonance effects, it is necessary to delineate areas of similar behaviour in seismic perspective. The identification of these areas involves the simultaneous assessment of several parameters such as the frequency and amplitude of the resonance frequencies, and the positions and the mutual distances between the measuring points [Bragato et al., 2007]. The task becomes particularly difficult when it is possible to identify on the HVSR curves different peaks associable with different resonance frequencies of the investigated site.

To overcome the aforementioned problems, we have implemented two automatic procedures based on cluster analysis.

4. CLUSTER ANALYSIS OF HVSR DATA

Cluster analysis is the task of grouping a set of objects in such a way that objects in the same group (called cluster) are, in some sense, more similar to each other (internal cohesion), than to those in other groups (external isolation). It is a main task of exploratory and a common technique for statistical data analysis. Clustering is, typically, an unsupervised process and the results of the application of different algorithms to the same data set may be very different from each other. For this reason, the assessment of the clustering algorithms is fundamental. Several clustering validation approaches have been developed [Gan et al., 2007; Everitt, et al., 2011], mainly based on the concepts of homogeneity and separation. We used the variance decomposition method as measure of cluster quality, using the within-class and the between-classes variances as measure of homogeneity and separation, respectively [Gan et al., 2007; Everitt et al., 2011]. A good clustering should identify a small number of clusters characterized by a within-class variance lower than the between-classes one. Both the procedure proposed are based on the Hierarchical Clustering (HC) Algorithms [Gan et al., 2007; Everitt et al., 2011]. The HC algorithms are explorative methods for which it is not necessary to fix a priori the number of clusters. HC methods work with a measure of proximity between objects to be clustered. The proximity measure is selected to be suitable to the nature of the data.

Hierarchical clustering algorithms can be agglomerative or divisive. In the Agglomerative Hierarchical Clustering (AHC), or bottom-up approach, each object begins the process as the only member of its own cluster and the process is concluded with the inclusion of all the objects in a single cluster. In the Divisive Hierarchical Clustering (DHC), or top-down approach, instead, all observations are initially placed in a single cluster, which is subdivided iteratively until to obtain N clusters. Application of both AHC and DHC verifies that the two algorithms lead to very similar solutions, but the first kind of processing is less time-consuming.

After many tests [D'Alessandro et al., 2016] providing a fair representation of the data space properties, the implemented procedures are based on the AHC algorithm and used the Average Linkage (AL) criterion, in which the dissimilarity between the objects A and B is the average of the dissimilarities between the objects of A and the objects of B [Gan et al., 2007; Everitt et al., 2011].

For the identification of the optimal set of analysis windows to estimate the average HVSR curve, we adopted the Standard Correlation defined according to D'Alessandro et al. [2016] as a measure of proximity, taking into account both the position and amplitude of the peaks present on the HVSR curves.

To define representative clusters of HVSR peaks, aiming at defining homogeneous areas in seismic perspective, it is important that the process of clustering takes into account all the parameters involved; these are obviously the period and the amplitude of each peak. In addition to these parameters, we could consider also the values of the same parameters in the neighbouring points. For this reasons, in the implemented clustering procedure, we have defined the following proximity measure:

$$S_{ij}=1-(\alpha T_{ij} + \beta A_{ij} + \gamma D_{ij});\ \text{with}\ \alpha+\beta+\gamma = 1 \qquad (1)$$

where T_{ij}, A_{ij} and D_{ij} are normalized Euclidean distance in the parameters space (period, amplitude and measurement position, respectively) and α, β and γ are weights to be assigned to the respective distances. These parameters are reported in Table 1. The results of the analysis carried out are summarized in dendrograms and generally the variance decomposition are adopted as optimal criterion for the choice of the proximity cut levels.

5. FREQUENCY MAPS

The HVSR data have revealed the likely presence of amplification of ground motion in the frequency range 0.7-2.2 Hz, over a large part of the urban area. The thickness of the soft coverage in few places where it is known and its lithological composition suggest that the cause of amplification is the resonance of coverage itself.

The clustering procedure, used to group peaks of HVSR average curves related to different sites, has allowed to identify areas characterized by site effects probably caused by the same buried structure. Considering the parameters of such peaks as sampling of spatial trends that are continuous on the area containing the measuring points, it is possible to estimate the expected peak amplitude and frequency at each point of the area by two-dimensional interpolation techniques.

In the cluster algorithm the elements of the similarity matrix are the weighted averages of Euclidean relative distances between the quantitative parameters of a pair of peaks. Each difference between pairs of parameters is normalized by the maximum difference in the sample [Capizzi et al., 2014; Martorana et al., 2014; Capizzi et al., 2015; Martorana et al., 2017].

To avoid the inclusion in the same cluster of more peaks relative to the same measurement point, the normalized relative distance of coincident points was placed equal to 1. The choice of the weights to be assigned to the Equation (1) should be made on the basis of proper statistical parameters, considering importance and reliability of each parameter. These parameters must allow to quantify the goodness of the clustering procedure, such as homogeneity and separation of the clusters.

The resonance period of a site is a very important parameter and surely the most robust one that can be estimated from the HVSR curve. The resonance period is linked to the local geology in term of S-wave velocity and thickness of the resonant layer. On the other hand, the associated amplitude value is not a robust parameter. In fact, only if the microtremors wave-field consist of body waves, the shape of the HVSR curves is mainly controlled by the S-wave transfer of the shallowest sedimentary layers and therefore the peaks amplitude may be straightforward related to subsoil amplification factors. The topographical distance is instead a parameter of high importance, both for the identification of homogeneous areas in seismic perspective, and also as an indirect measure of the reliability of peaks of the HVSR curves associated to resonance effects.

In order to identify the optimal weights values for the clustering procedure we have tried to cluster our data using all the possible combinations of weights ranging between 0.1 and 0.8, with step of 0.1. The values of weights able to provide the best result in term of variance decomposition (minimum within-class and maximum between-classes variance) were the following: α=0.7, β=0.1 and γ=0.2.

The clustering highlighted three clusters: B (Blue), R (Red), G (Green), respectively, consisting of 8, 3 and 18, peaks. Figure 4 shows the dendrogram of the clustering process. Different criteria can be used to find the optimal threshold. Following Celeux and Soromenho (1996), the cut level was determined using internal entropy level criterion to maximize the homogeneity within classes.

Figure 5 shows the characteristics of the clusters in

Meas. Point	Peak ID	Longitude	Latitude	Frequ. (Hz)	Ampl.	Cluster	Bedrock depth (m)
1	1	15.06687	38.12591	0.73	4.49	R	73
2	2	15.06341	38.12689	1.23	5.58	G	39
3	3	15.05991	38.1279	0.95	4.23	G	42
4	4	15.05707	38.12983	0.77	8.12	R	60
5	5	15.05526	38.13224	0.82	5.96	R	61
6	6	15.05507	38.12756	1.03	6.17	G	60
7	7	15.0568	38.12629	1.00	5.35	G	48
8	8	15.05957	38.12424	1.35	5.10	G	48
9	9	15.06272	38.12502	1.00	7.09	G	45
10	10	15.06512	38.12472	0.92	6.48	G	50
11	11	15.06541	38.12177	1.23	4.51	G	33
12	12	15.06266	38.12299	0.93	4.68	G	45
13	13	15.06425	38.11965	1.53	6.00	B	
14	14	15.06093	38.12103	1.10	3.56	G	29
14	15	15.06093	38.12103	1.73	2.71	B	
15	16	15.05718	38.12165	1.83	3.22	B	
16	17	15.05475	38.11899	0.90	4.28	G	33
16	18	15.05475	38.11899	1.63	4.35	B	
17	19	15.05174	38.12241	0.90	2.57	G	32
17	20	15.05174	38.12241	2.00	4.94	B	
18	21	15.04939	38.11947	0.87	2.60	G	31
18	22	15.04939	38.11947	1.60	2.67	B	
19	23	15.04696	38.11441	0.87	3.12	G	30
19	24	15.04696	38.11441	2.20	4.23	B	
20	25	15.0517	38.11631	1.20	4.54	G	31
21	26	15.0547	38.11428	0.95	4.41	G	39
21	27	15.0547	38.11428	1.73	4.31	B	
22	28	15.05022	38.11198	1.10	5.39	G	25
23	29	15.05851	38.11805	1.00	3.83	G	58

TABLE 1. Measurement point, Peak ID, UTM coordinates, frequencies of the significant peaks, H/V ratios, cluster identification and bedrock depth. All reported peaks respect standard deviation criteria for a reliable H/V peak [SESAME, 2004].

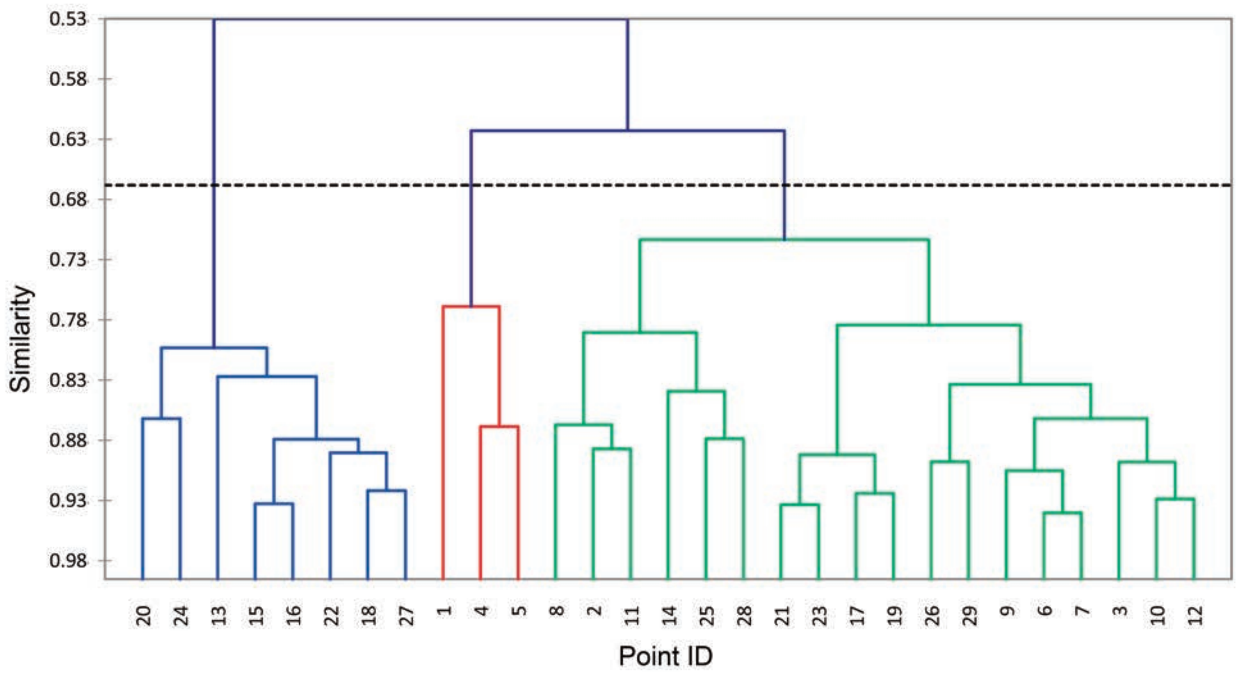

FIGURE 4. Dendrogram of the clustering process of picks detected by the 23 HVSR measurement points, the location of which is showed in fig. 9. The cluster analysis groups three clusters: blue, red and green.

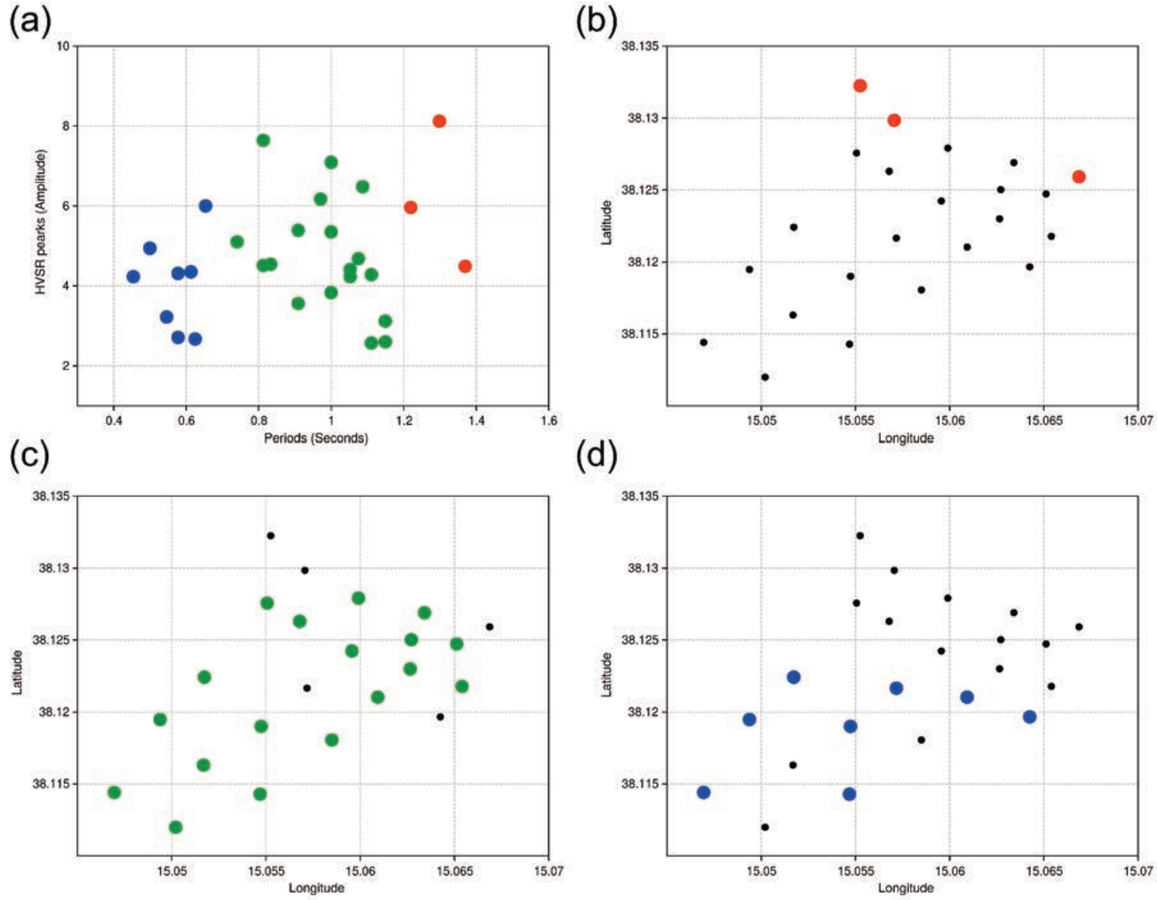

FIGURE 5. (a) Scatter plot of amplitude versus peak period for the four HVSR clusters; (b) spatial distribution of cluster R (red); (c) spatial distribution of cluster G (green); (d) spatial distribution of cluster B (blue).

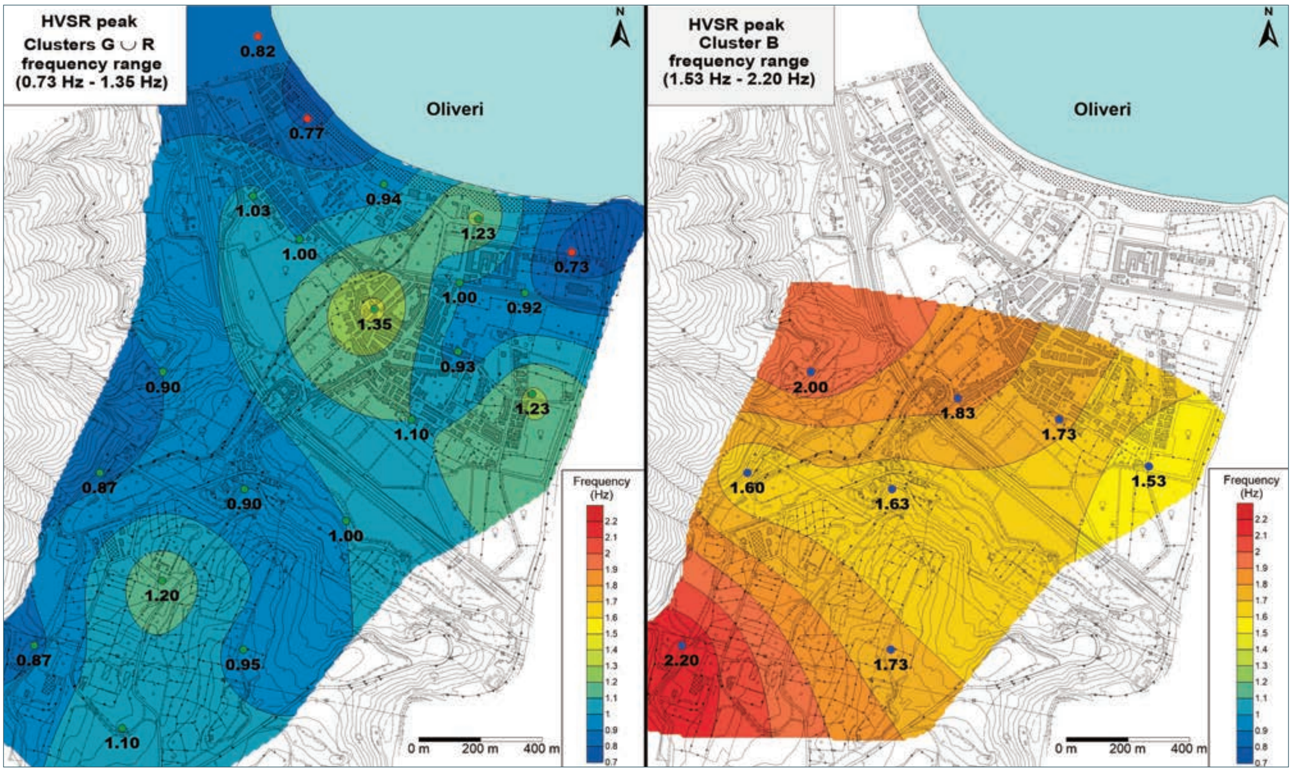

FIGURE 6. HVSR peak frequency maps of cluster G ∪ R (left) and cluster B (right).

the diagram H/V vs. period and their spatial distribution. As the two clusters G and R are very near in the scatter plot and their areas have an empty intersection, it was considered reasonable to assume that they represent the effects of a single source phenomenon. In particular it is assumed that G and R are related to the resonance effect of a covering layer delimited at its base by the same discontinuity surface with variable depth. Conversely the cluster B, characterized by higher frequencies respect to $G \cup R$, shows the resonance effects of the sedimentary cover down to a shallower interface. Therefore, two different maps can be reconstructed, each of them grouping, and separately representing, the continuous trend of the frequency for the clusters $A \equiv G \cup R$ and B. For the processing of the maps, the Kriging algorithm has been applied to interpolate the experimental peak frequencies at the nodes of a regular grid with spacing equal to 10 m. The frequency maps are plotted using a contour equidistance equal to 0.05 (Figure 6). An area south of the town, interesting for the urban planning, seems to be characterized by higher amplification at frequencies greater than 1.5 Hz (Figure 6, right).

6. BEDROCK MAPPING BY INVERSION OF HVSR MEASUREMENTS

The determination of the parameters that characterize the subsoil from the H/V curves provides unreliable results if it does not rely on an initial model already representative of the real geological stratification, well constrained by drilling data, and geological and/or geophysical surveys. It should be also pointed out that, due to lateral variations of geologic parameters (porosity, water content, fracturing degree, etc.), the mechanical properties of each layer will not be uniformly distributed. This can lead to less accuracy on the estimate of the depth of geological interfaces and in particular the top of the seismic bedrock.

Taking into account the available geological information, the H/V curves have been inverted to estimate the depth of the seismic bedrock, also reported in Table 1.

Theoretical HVSR curves were calculated by the code of Lunedei and Albarello [2009] based on the assumption that environmental noise is composed by the superimposition of random multi modal plane waves moving in all the directions at the surface of a flat layered visco-elastic Earth. It is assumed that these waves propagate as Rayleigh and Love waves generated by a uniform distribution of random independent point sources located at the surface of the Earth. Since body waves are not considered, this assumption is realistic only if sources are located far enough from the receiver. This implies that a source-free area exists around the receiver [Lunedei and Albarello, 2009] and, consequently, all the time windows of the signal showing noise suspected to be caused by near sources must be removed.

Unfortunately, it has been possible to constrain the thicknesses of the layers in the inversion of the HVSR curve using only the data of two boreholes. The first is located close to Torrente Elicona (Figure 7), the second is located close to the Castello hill. The analysis of the core of the first one shows the presence of anthropic deposits in the first 1.6 m, followed by 3.4 m of well graded sand with gravel elements of metamorphic origin, 5.5 m of silty sand, with rare rounded gravel elements, and 5.4 m of poorly graded sand. The altered substrate, according to its mechanical characterization by HVSR data, seems to be composed by incoherent sand and grey silt. The analysis of core samples permitted to recognize bivalve fauna. The groundwater level is placed at a depth of 7.5 m. The core relative to the second well shows evidence of a tectonic dislocation that put in contact the “Argille Scagliose” unit with the metamorphic basement. In the northern side of Torrente Castello, the flyschoid cover has a thickness of about 20 m while, in the southern part, the thicknesses of clay and calcarenite covers exceed 45 m (Figure 9). The nature of the covers is related to the sedimentary contribution of the rivers and sea level fluctuations. We considered reliable inverse models with misfits about equal or less than 1. Misfits were calculated as a sum of squared differences between observed data and calculated ones, normalized by the variance.

To define the starting model for the inversion, the values of shear-wave velocity of the cover available for the studied area were used. In particular, we considered about 200 to 250 m/s for alluvium and about 350 to 400 m/s for the silty sands deposits.

The depth of transition of the shear wave velocity from less to greater than 800 m/s is considered the depth of the seismic bedrock. When evaluating the reliability of the estimate of this depth, we must consider that the trends represented are heavily influenced by the interpolation process between the HVSR measuring points. To avoid interpolation between depths of interfaces due to different geological structures, we decided to group and correlate frequencies related to the same cluster. However it is not possible to exclude that frequencies belonging to the same cluster are due to different structures or vice versa.

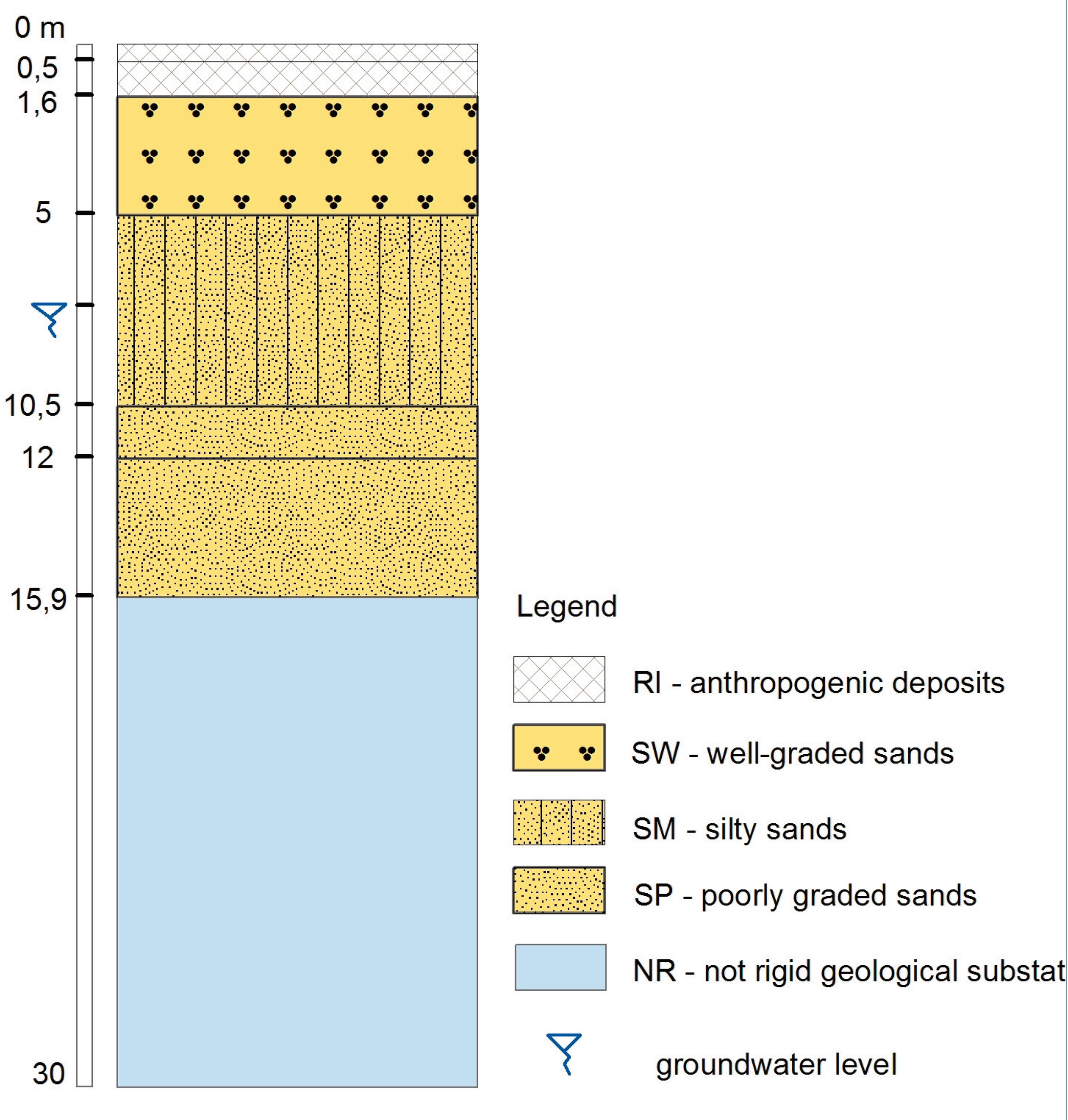

FIGURE 7. Stratigraphic column of the borehole close to Torrente Elicona. Stratigraphy is indicated in legend.

In almost all the HVSR measurements carried out on the alluvial material a maximum peak is mostly evident in the range 0.7 - 1.4 Hz (Figure 6, left). This, by the inversions results, seems to be related to a variation of the shear-wave velocities that, under a depth of 40-60 meters reach values attributable to a seismic bedrock (about 800 m/s).

Analyzing the 1D inverse models (Figure 8) derived by inverting HVSR measurements, estimates of the depth of the seismic bedrock have been obtained. These, together with other reliable data like drilling and other geophysical surveys, were used to construct the map of the thickness of the sedimentary cover (Figure 9, left) and the elevation map of the top of seismic bedrock above sea level (Figure 9, right). The estimates of the depth of the bedrock were interpolated by imposing a constraint of a depth equal to zero in areas where geological strata with elastic characteristics of seismic bedrock outcrop. The Kriging interpolation algorithm was used, obtaining a grid with equidistance between nodes equal to 10 m.

The contour map of the bedrock depth was obtained

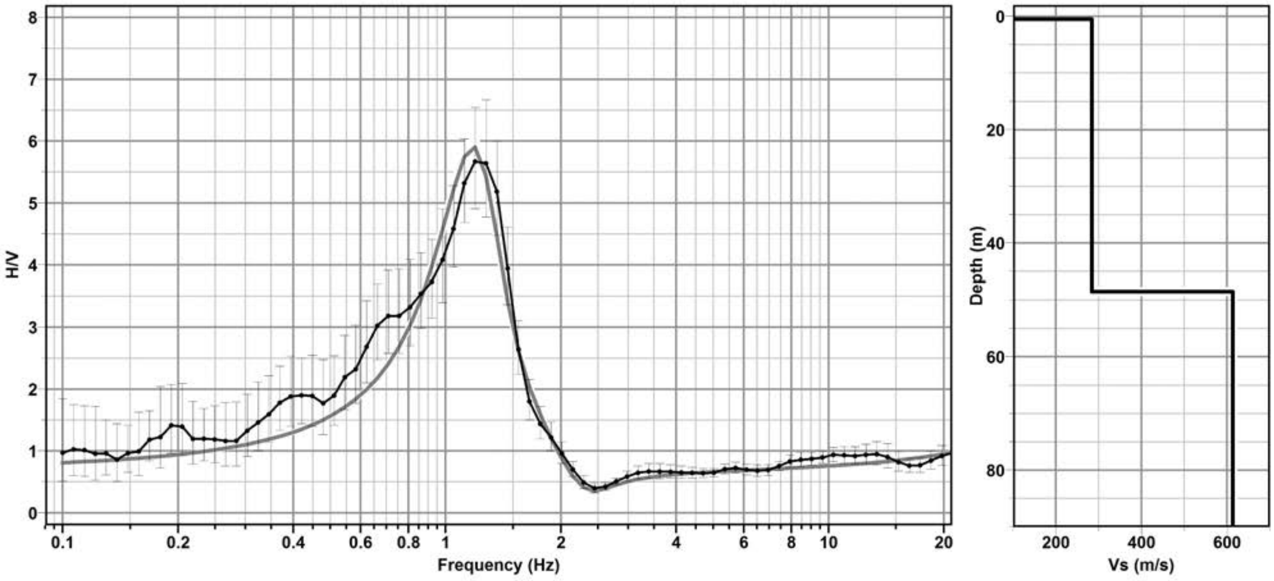

FIGURE 8. Inversion of the HVSR ellipticity curve of the measurement point n.2. (left) Experimental HVSR curve (black line) compared with theoretical (grey line). (right) Inverse model of shear waves velocity.

by extracting from the Digital Elevation Model of the area a grid of points equidistant 50 m. From these points the corresponding grid of the depth of the bedrock was subtracted.

This choice was made in order to obtain a trend of the isobaths that was not excessively tied to topographic detail but which, however, did not present unrealistic areas with higher elevations of the topographic surface. It should however emphasize that the real detail of the maps cannot be higher than the sampling density of the HVSR measurements, which generally is not less than 300 m.

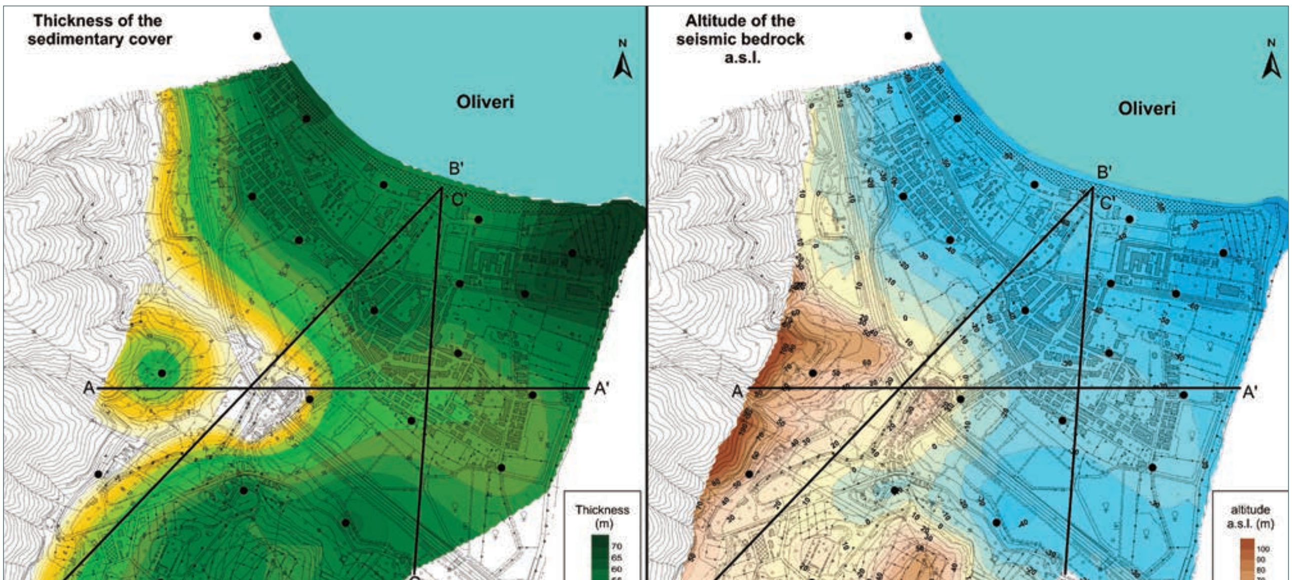

FIGURE 9. Oliveri. Left) Map of the thickness of the sedimentary cover. Right) Map of the altitude of the seismic bedrock above sea level.

7. DISCUSSION OF RESULTS

The reliability of the resulting 3D model is limited by the lack of geophysical and borehole data, which would have allowed to better constrain the values of the unknown parameters of the model.

Based on the 3D trend of seismic bedrock, of geological information from field surveys, and from published geological maps, three geological sections were drawn (Figure10). In the section A, oriented from west to east, it is possible to observe, in the westernmost part, the stratigraphic overlay of the Flysch of Capo D'Orlando on the metamorphic substrate, which is dislocated by normal faults. The alluvial deposits of coastal plain are onlapping on the substrate whose lithology is not known in most of the area (sections B and C in Figure 10) due to the lack of information deriving from deep boreholes. Therefore, the only information is related to geophysical analysis. Finally, along the Oliveri plain some catalogues (e.g. ITHACA) and structural studies [Ghisetti & Vezzani, 1977] testify the occurrence of an active fault that in geological sections is approximately shown.

The reconstructed model suggests the presence of two buried riverbeds separated by heights. The sediment thickness in these two areas is about 45 m. In the seismic bedrock map (Figure 9, right) it is possible to observe as the rivers bed suffer a migration toward the present day position. According to the bedrock map the high ground that separates the two depressions has a depth of 40 m while the floor of basins shows a depth of 60-70 m. In the southern part of the town there is another basin in which the bedrock has a depth of 40 m. This could be related to another minor river joined with the main Torrente Elicona. Based on hydrogeological information the presence of groundwater level in the floodplain is attested at a depth shallower than 15 m. This condition makes the floodplain exposed to liquefaction risk.

8. CONCLUSIONS

The technique of the inversion of the HVSR curves has been applied on passive seismic data coming from microtremor measurements to study the site effects of amplification of seismic motion and to define the geological setting of the urban area of Oliveri, in the northern coast of Sicily (Italy), for purposes of seismic microzonation.

The use of techniques of cluster analysis in the seismic noise processing, based on an Agglomerative Hierarchical Clustering (AHC) algorithm, allowed to sep-

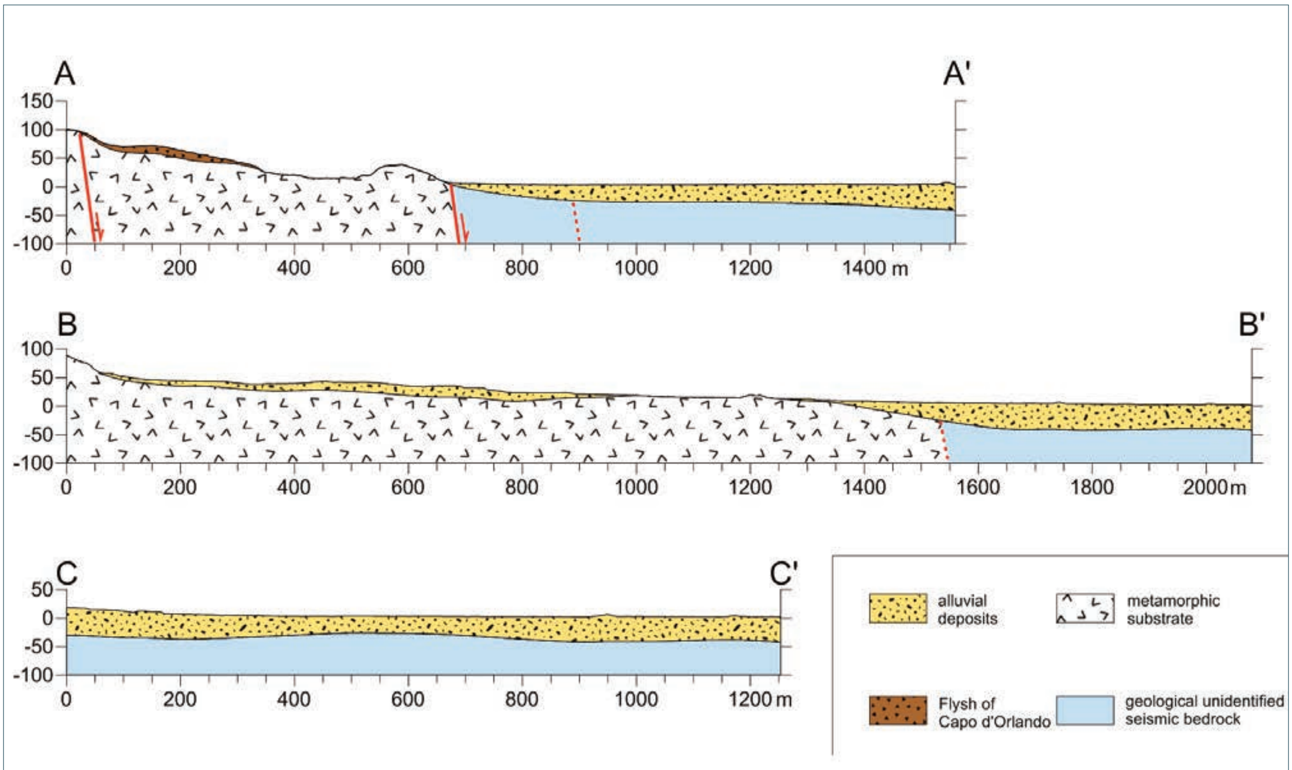

FIGURE 10. Oliveri. Sections representing the seismic bedrock and the soft cover. The tracks of the sections are plotted in Figure 9.

arate the noise windows in clusters with spectral effects due to subsurface structures and clusters dominated by accidental interference effects between wave trains of a different nature. The average spectral ratio of the cluster dominated by structural effects is generally characterized by smaller variance of the frequencies and amplitudes of the significant peaks, compared to those of the peaks determined with standard methods.

A successive clustering procedure has been used to group the main HVSR clusters of peaks and to associate them with areas characterized by site effects reasonably caused by the same buried structure. Assuming that the three main identified clusters contain peaks produced by resonance effects of layers with varying thickness, the possible trend of the top of the seismic bedrock was reconstructed by inversion of the HVSR curves constrained with geological and lithological information and considering a minimum lateral variability of the physical and geometrical parameters.

The interpretation of the HVSR peaks pertaining to the same cluster was supported by a detailed study of the outcropping geology and of the tectonic history. This allowed to build a detailed map of the seismic bedrock and to assess the geological and tectonic hypotheses on the urbanized investigated area. The lack of drilling data did not resolve all the uncertainty about the geological hypotheses.

The study highlighted that HVSR technique, accompanied by proper statistical techniques aimed at recognizing and discriminating peaks of the same stratigraphic origin, can be a valuable method not only for the estimate of the site amplification effects, but also for the assessment of the main geological and tectonic structures that define the seismic bedrock and the coverage deposits.

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