13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 915

MICROTREMOR MEASUREMENTS IN PALERMO, ITALY: A COMPARISON WITH MACROSEISMIC INTENSITY AND EARTHQUAKE GROUND MOTION

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SUMMARY

The city of Palermo is an appropriate test site where the efficiency of microtremors in predicting ground motion properties during earthquakes can be checked. Palermo is a densely populated city with important historical heritage and was object of previous studies. Areas of local amplification of damage were identified in downtown Palermo using historical macroseismic data. Moreover, aftershocks of the September 6, 2002, earthquake (Mw 5.9, 40 km offshore) provided a dataset of seismograms that quantify spatial variations of ground motion. The availability of more than 2000 boreholes in the city allowed a reconstruction of the 3D structure of surface geology, indicating that all the higher damage zones correspond to sediment-filled valleys. The high variability of the surface geology is mostly due to the presence of two filled river-beds of about 150 m width. In the framework of the SESAME project (Seismic EffectS assessment using Ambient Exctations, funded by the European Union), 90 microtremor measurements were performed across several profiles crossing the soft sediment bodies. The measurement points were intensified close to the valley edges (every 20 m), according to our geological reconstruction. H/V spectral ratio on ambient noise (HVSR) show significant variations along each profile: as soon as the transition stiff to soft is crossed, a typical spectral peak exceeding a factor of 3 in amplitude appears in the HVSR. The peak falls between 1 and 2 Hz and, along each profile, the peak disappears as soon as the other edge of the valley is crossed. These results indicate that microtremors are sensitive to the presence of large impedance contrasts of deep soft soil, at least in the Palermo area, with an important implication: the HVSR method seems to be able to recognize conditions potentially favourable to the occurrence of higher damage even when local geological characters are masked by the urban growth. However, we were not able to establish a quantitative correlation between microtremor properties and ground motion (or damage) amplification.

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INTRODUCTION

Palermo is the largest city in Sicily, southern Italy, and is characterized by important historical buildings. In the past centuries several earthquakes produced large damage in this area (Guidoboni [1]) and recently a Mw 5.9 earthquake (September 6th, 2002, 40 km offshore) caused damage of MCS Intensity V-VI in downtown Palermo and in its southern sector (Figure 1). Several churches and historical buildings were seriously damaged but the very high vulnerability of the buildings makes the macroseismic survey results of difficult interpretation (Figure 2).

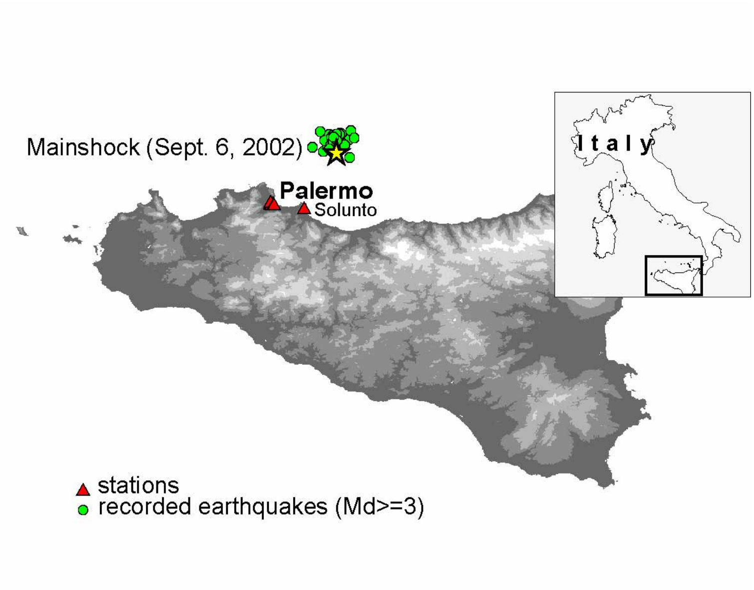

Figure 1. Map of Sicily (Italy) with the location of September 6, 2002, mainshock (star) and its aftershocks (circles) recorded from 7th to 25th of September, 2002. The triangles show the position of Palermo and Solunto (Solu) stations that recorded the seismic sequence.

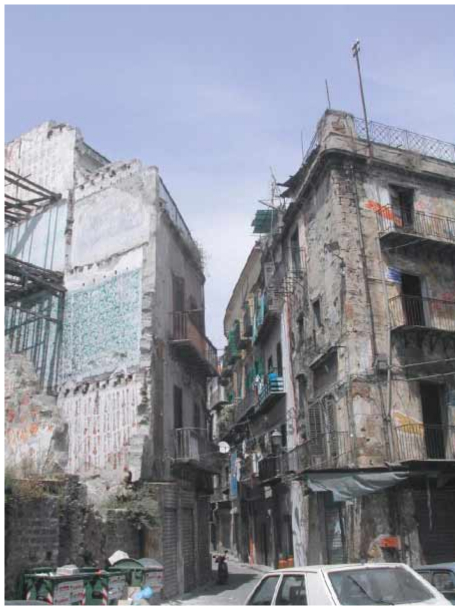

Figure 2. Buildings in downtown Palermo.

The seismic sequence of the September 6, 2002 earthquake was recorded by eight temporary stations installed in the urban area to study the seismic response in downtown Palermo using aftershock recordings (Azzara [2]; Figure 1). The location of these stations sampled different geological formations, identified in previous studies as responsible of the damage distribution of three past earthquakes (Figure 3).

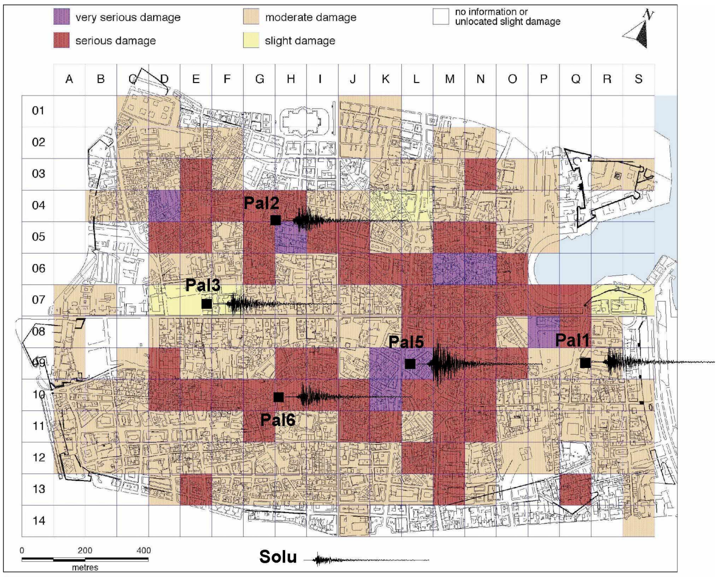

Figure 3. Map of downtown Palermo with the cumulative damage of three past earthquakes. The color scale indicates the prevalent maximum level of damage (above 50%) of the three earthquakes, occurred within the existent buildings in a 100x100 m cell (from Guidoboni [1]). The squares are the seismic stations of Azzara [2] with a recorded aftershock (Sept. 20, 2002, 23:05 GMT; Ml 4.4).

Guidoboni [1] showed that the damage distribution of these past earthquakes (September 1, 1726, Me 5.7, Is VIII-IX; March 5, 1823, Me 6.0, Is VIII; January 15, 1940, Me 5.3, Is VII) was related to the presence of two ancient rivers, Papireto and Kemonia, which were buried and filled during the 17th century (Figure 4a). The geometry of those two river-beds and the structure of the surface geology (Figure 4b) are very well constrained by a detailed stratigraphic and geotechnical dataset deriving from 2500 geo-referenced boreholes ubicated in the city area, 600 of them within 2.5 Km^2 historic centre. This dataset is organized in a Geographic Information System (GIS) designed to assess natural hazards in the urban area (CITY-GIS, see Giammarinaro [3]). The two river beds are about 150 m wide and 10-30 m deep, and they met in downtown Palermo reaching the sea at the old harbor.

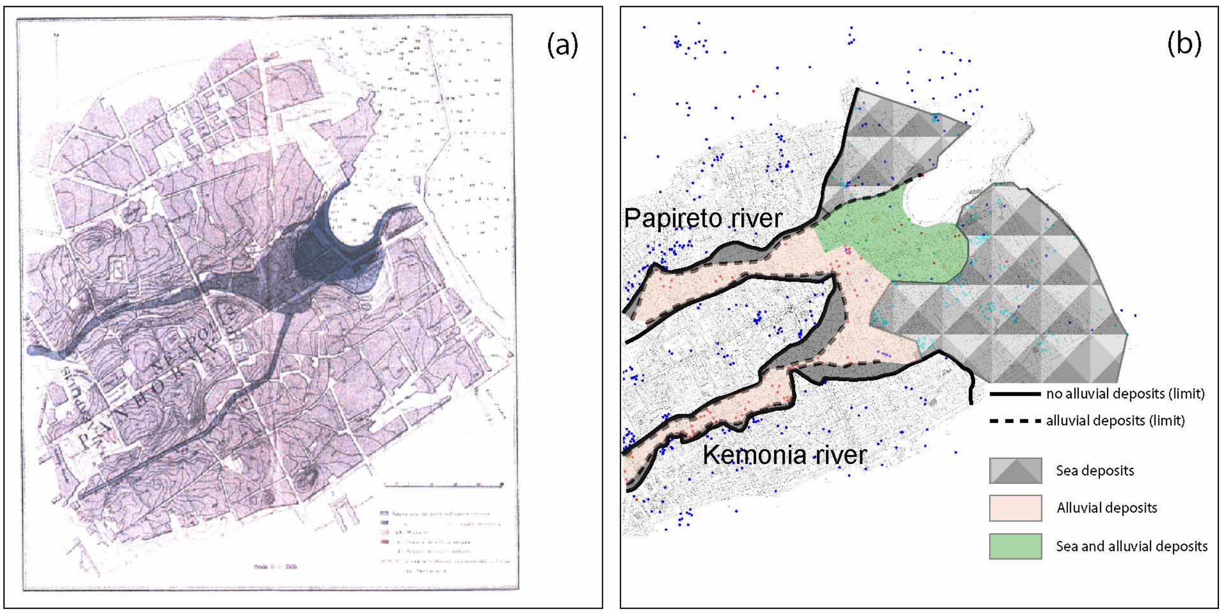

Figure 4. (a) Historical map of downtown Palermo showing the two rivers Papireto and Kemonia before the 17th century; (b) simplified geological map based on the presence or absence of soft deposits, both sea and alluvial, from borehole information.

For all these reasons, Palermo was selected as test-site of the SESAME project (Seismic EffectS assessment using Ambient Exctations), a project funded by the European Union to evaluate the reliability of the ambient noise measurements in predicting properties of ground motion during earthquakes (Bard [4]). In particular, this experiment concerns with the empirical evaluation of the horizontal-to-vertical spectral ratio technique (HVRS) within urban environment of cities affected by strong earthquakes (Theodulidis [5]).

AMBIENT NOISE EXPERIMENT

Setup of the experiment

The goal of the experiment was to perform a dense grid of noise measurements within urban environment, sampling the different geological formations and damage distribution. We planned several profiles of measures with a spatial sampling between measurement points from 50 to 25 meters. The smaller distance was chosen when the profiles crossed the sharp geological transitions in proximity of the two old river-beds. The GIS developed by the University of Palermo (CITY-GIS; Giammarinaro [3]) allowed us to easily locate the measurement points taking into account buildings, streets and borehole information.

Figure 5 shows the position of 90 measurement points:
profile A-A’: crossing the two old river-beds;
profile B-B’: at the confluence of the two old rivers;
profile C-C’: crossing the Oreto river valley;
profile D-D’: east of A-A' but crossing the two river-beds where minor thickness of alluvial sediments was found;
profile E-E’: where sea sediments covered the alluvial ones;
grid: between the profiles A-A' and B-B', to improve the resolution in the confluence area of the two rivers, the most complex part because the variation of sea level throughout the centuries changed several times their original flow.

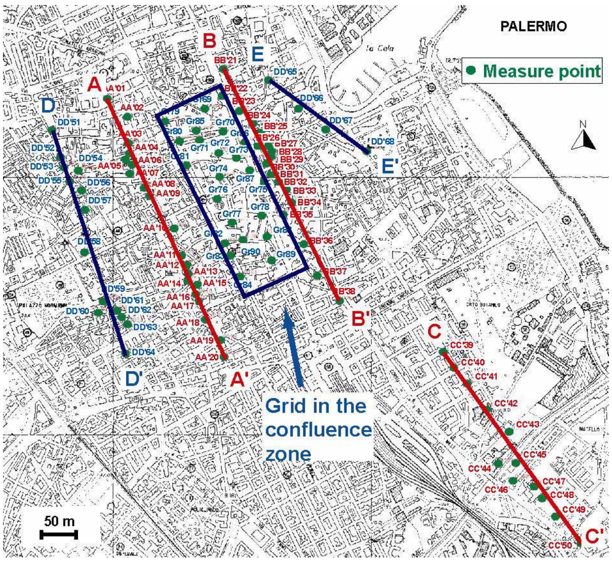

Figure 5. Location of the measurement points.

The experiment lasted 5 days (May 2003) and the measurements were performed by six teams with assistance of many students of the Geology department of the University of Palermo.

Instrumentation

The six seismological stations were composed by a triaxial Lennartz Le3D-5sec sensor with a Lennartz MarsLite digitizer. In order to ensure a uniform recording functionality, we tested simultaneously the six stations together with an additional station equipped with Kinematics K2 digitizer and Episensor (clipping level set to 0.5g). Figure 6 shows the seven average HVSR computed over the same time intervals: the six Marslite-Le3D-5sec are in very good agreement, whereas the K2-Episensor is quite different below 2.5 Hz. This behavior confirms the general results of Task A - WP02 deliverable of the SESAME project regarding the low level of confidence using accelerometers for noise survey (WP02 Deliverable D01.02 [6]).

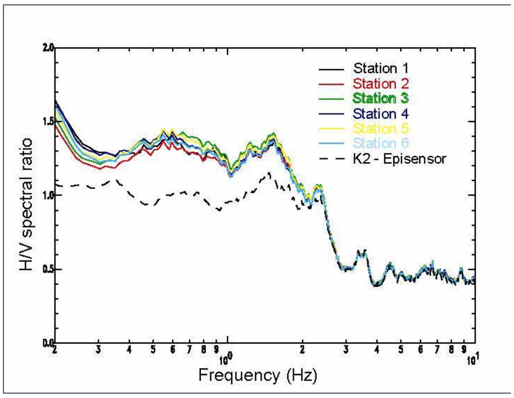

Figure 6. Test on seismic stations functionality.

Experimental conditions

We followed the guidelines of the SESAME project on technical requirements for the measurements (WP02 Deliverable WP02-D08.02 [7]), avoiding as much as possible roads with heavy traffic and underground structures. We set a sample rate of 125 sps and the default gain to 32. The minimum recording time was 30 minutes, but a longer record was required in critical situations. The local meteorological conditions were stable: constant temperature during the day (around 25 °C), no wind or rain.

However, measurement conditions in urban areas are very difficult: almost all the measures were performed coupling the sensor with the asphalt or pavement; rarely we found an open area with natural soil (Figure 7), and we had no information about the location of underground structures; we often increased the recording time because of nonstationarity in ambient noise (cars, pedestrians, markets; Figure 8). Because of all these uncertainties, the location of measurements was carefully checked by the teams, a lot of sites were repositioned during the field operations and it was required to intensify the measurement sites to have a better confidence in the results.

Figure 7. Examples of sensor-ground coupling.

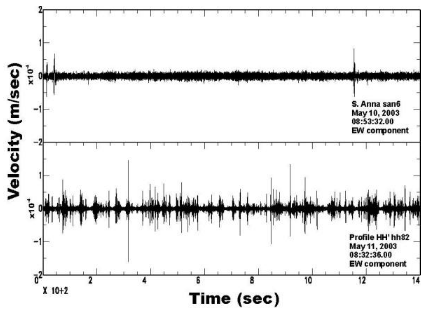

Figure 8. Noise records at an undisturbed (top) and disturbed (bottom) site.

DATA ANALYSIS

J-Sesame software

The recorded data were processed with the software realized within the SESAME project (J-SESAME software, V1.05; WP03 Deliverable D09.03 [8]). Table 1 lists the default parameters used for the window-processing module and for the HVSR computation. We used the automatic window-selection algorithm and we required at least 10 windows of 25÷60 seconds length to compute the average HVSR. The windowed signal was corrected for the offset, cosine tapered and a FFT routine was applied; the spectra were then smoothed using the Konno-Omachi algorithm and the two horizontal components spectra were merged with a quadratic mean before the division by the vertical component spectra. Finally the geometric mean of HVSR was calculated.

Table 1
Default parameters used for the analysis

WINDOW-PROCESSING Module	**HVSR PROCESSING Module**
# *Stla* = 1.0 sec	# *freq_spacing:* fft
# *Tlta* = 25 sec	# *offset_rem:* r_mean
# *Minimum threshold* = 0.5	# *taper:cos:* 5
# *Maximum threshold* = 2.0	# *instrument_resp:* no
# *Window length* = 60 sec	# *smooth:konno-ohmachi:* 40
# *Overlapping* = 0.0	# *merge_type*: quadratic
	# *single_component:* no
	# *average_type:* log
	# *single_win_out:* no

Resonance frequency and its amplitude
The main purpose of this study was to check whether the frequency and amplitude of peaks in the HVSR of seismic noise recordings can be related to the geological condition and/or the damage occurred during past earthquakes. The last version of the J-SESAME software allowed us to automatically calculate the resonance frequency and its standard deviation. However, the analysis required also a visual inspection of the HVSR often characterized by a broad peak or even several narrow peaks with comparable amplitude (Figure 9). This effect is probably due to the complexity of the geological structure of Palermo that contributes to a strong variability of the peaks shape.

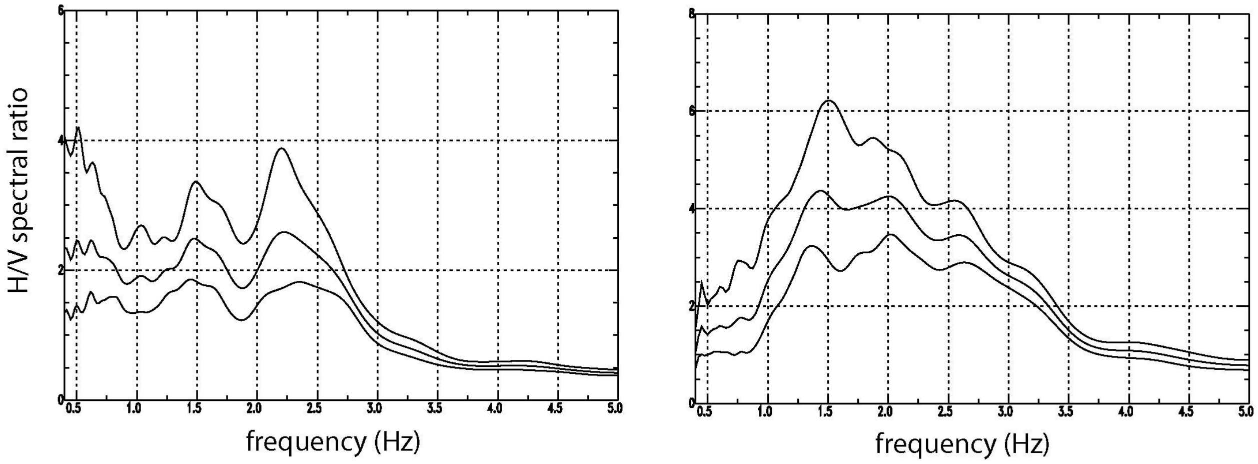

Figure 9. Example of HVSR (average and +- one standard deviation) at two sites.

We selected the resonance frequencies reaching amplitude values larger than 2. We also classified the measured resonance frequencies and their amplitudes in 4 classes, assigning a fictitious frequency value of zero and amplitude value of one for points where the resonance frequency was not peaked or with amplitude < 2.

RESULTS AND DISCUSSION

Comparison with geology

The stratigraphic and geotechnical dataset of the historical centre allowed a detailed reconstruction of the 3D structure of surface geology (within 40 meters depth). The area is characterized by Pleistocenic-Holocenic deposits overlying the Numidian Flysch (Oligo-Miocene ages). The stratigraphy is schematized from bottom to top in: silty clayey sands ("Argille Azzurre", Early Pleistocene), calcarenite deposits (Lower-Middle Pleistocene), sea and alluvial deposits (Holocene), filling material. Downtown Palermo is crossed by two ancient rivers and the thickness of their soft deposits varies towards east (confluence region) from 10 to more than 20 meters for the Papireto river, and from 15 to more than 30 meters for the Kemonia river.

We first compared the results of the HVSR analysis with a simplified geological map where we defined the areas with or without sea or/and alluvial deposits (Figure 10). The sites where we did not recognize a resonance frequency are all outside the identified valleys of the Kemonia and Papireto rivers. Within the river beds the frequency values decrease moving east, where the sediments deepen. The lowest values of frequency are in the zone of confluence of the two rivers where also sea deposits are present (Figure 10a). The amplitude of the resonance frequencies (Figure 10b)is higher in the zone of confluence of the two rivers, wheras the Papireto river-bed has higher amplitudes than the Kemonia ones. However, the HVSR amplitudes inside the river beds can vary from one class to the others at close measurement sites.

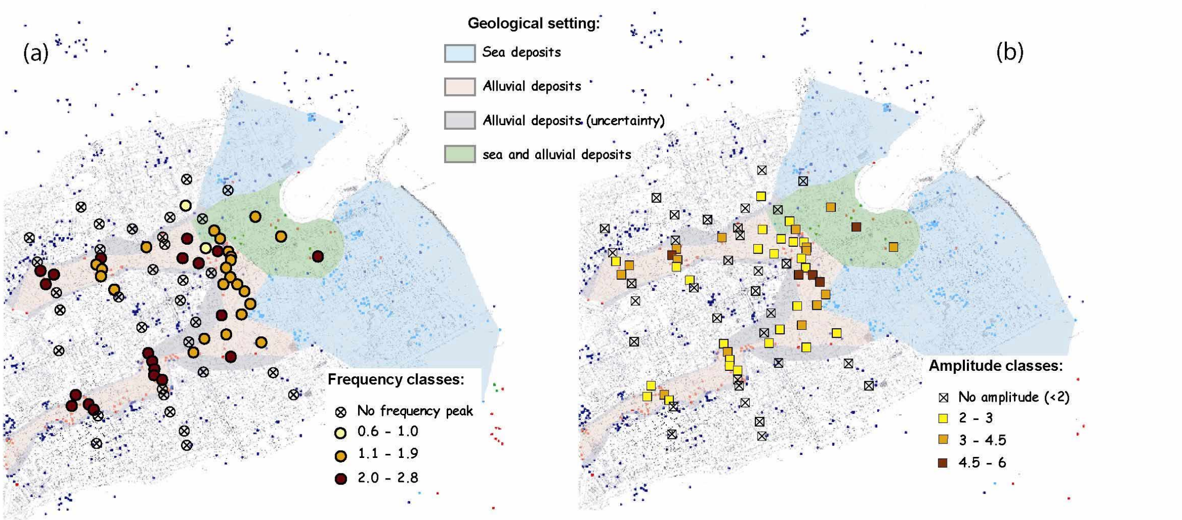

Figure 10. Simplified geological map (see Figure 4) with (a) frequency and (b) amplitude values as obtained from the HVSR.

We then compared the contour plot of HVSR for the AA' profile (Figure 5) as a function of distance and frequency with the corresponding geological section (Figure 11). A resonance frequency around 2 Hz appears where the profile crosses the deepest part of the two filled river-beds. This kind of representation shows that the HVSR is a very good indicator of the presence of soft sediments.

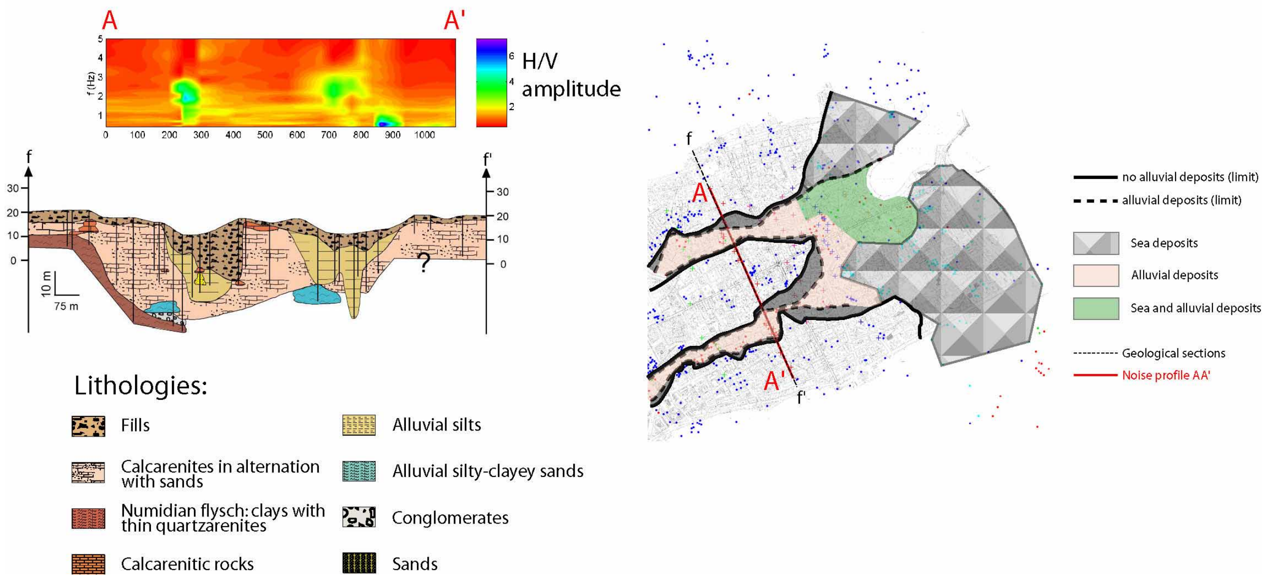

Figure 11. HVSR values for the AA' profile as a function of distance and frequency and the corresponding geological section

Comparison with aftershock spectral ratios

During the seismic sequence following the Mw=5.9 earthquake of Sept. 6, 2002, Azzara [2] installed eight temporary stations in downtown Palermo (Figure 3). They analyzed the recordings of 20 earthquakes of magnitude >2.8 applying different spectral techniques to estimate the empirical site response with both earthquake and ambient noise data.

Their results show that the amplification level of empirical transfer functions increases from the stiffest formations present in city (Numidian Flysh) to the areas characterized by thick alluvial or sea deposits, where the greatest amplification can be as large as 10 in the frequency range 1-3.5 Hz. The horizontal spectral ratio to a reference site (H/H) gives the greatest values of spectral amplification (Figure 12). The other two methods (H/V on earthquakes and ambient noise) are able to point out the first resonance mode. However, they underestimate the amplification level and only in presence of thick soft soils the results are consistent.

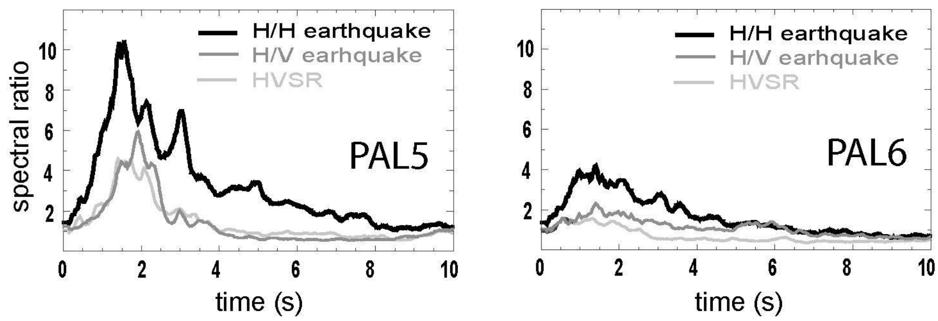

Figure 12. Average of horizontal spectral ratios, referred to Solunto site, and H/V on earthquakes compared with the H/V on ambient noise. The signals were recorded at PAL5, which suffered the greatest level of damage during the Sept. 6, 2002, earthquake, and at PAL6 (see Figure 3).

Comparison with damage

We investigated a possible correlation between the HVSR results and the level of damage in Palermo for past earthquakes. The damage description of Guidoboni [1] is very similar to that adopted for the European Macroseismic Scale 1998 (EMS-98), allowing us to immediately translate it to EMS-98 damage grades (table 2).

Table 2
Translation of the damage colour scale of Guidoboni [1] in EMS 1998 scale

Damage from Guidoboni [1]	EMS98: description of damage to masonry buildings	Colour scale	EMS98 classification
No damage	**-**	White	
Slight damage cracks to the plastering, collapse of ornamental or protruding elements	**Negligible to slight damage (no structural damage, slight non-structural damage)** Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.	Yellow	**Grade 1**
Moderate damage fissures to inside walls, collapse of vaults or ceilings	**Moderate damage (slight structural damage, moderate non-structural damage)** Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.	Orange	**Grade 2**
Serious damage total collapses, deep fissures, disconnections, leaning walls	**Substantial to heavy damage (moderate structural damage, heavy non-structural damage)** Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls)	Red	**Grade 3**
Very serious damage total collapse of the buildings or most of it	**Very heavy damage (heavy structural damage, very heavy non-structural damage)** Serious failure of walls; partial structural failure of roofs and floors	Purple	**Grade 4**
-	**Destruction (very heavy structural damage)** Total or near total collapse	-	**Grade 5**

In Figure 13 the cumulative damage map of Figure 3 is superimposed to the HVSR frequency and amplitude classification of measurement points. The damage distribution is well correlated with the presence of peaked frequencies (Figure 13a). However, it is difficult to associate a clear correspondence between different classes of frequency and damage grade. The comprehensive variation of resonance frequency is within 0.9 and 2.8 Hz, a range potentially dangerous for the buildings in downtown (3 to 5 storeys), whose age and type of construction is quite uniform (the building vulnerability is expected to be high but without strong spatial variations). The correlation between damage and HVSR amplitudes (Figure 13b) is difficult to quantify. However, the largest HVSR amplitudes are recorded close to the zones where the highest grade of damage has been observed.

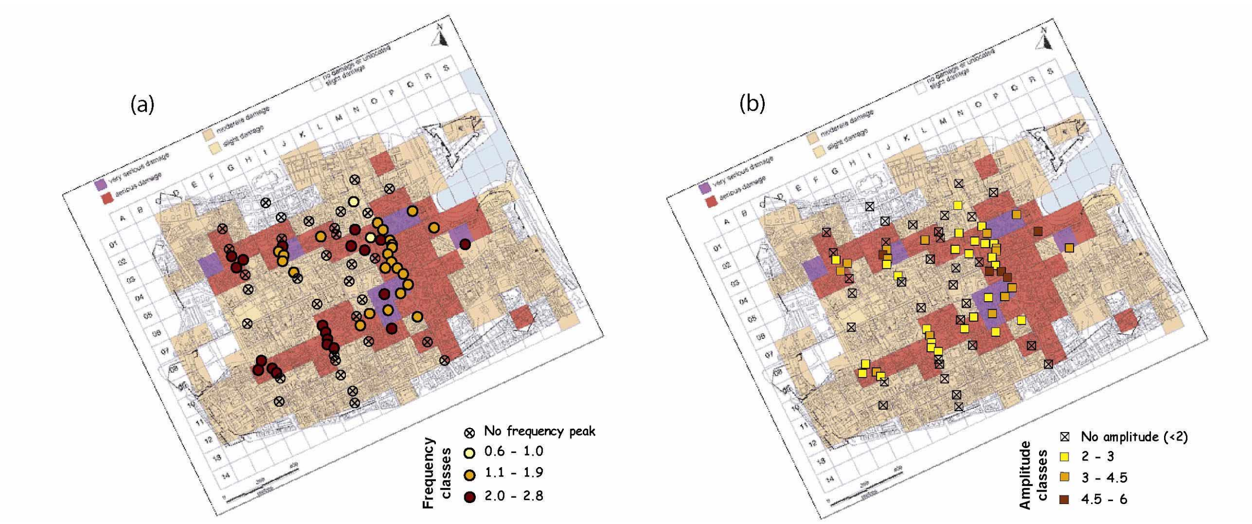

Figure 13. Cumulative damage map (see Figure 3) with (a) frequency and (b) amplitude values as obtained from the HVSR.

In order to better understand the real extent of this correlation, we plot the EMS 98 damage grade found for each cell as a function of the HVSR frequency and amplitude of points falling on the corresponding cell (Figure 14). As we already observed for Figure 13, the correlation between frequencies and different damage grade is only qualitative. The lowest frequencies (f<1Hz) and the lowest amplitudes (amplitude<2.8) correspond to lowest damage grades, whereas the largest amplitudes are well correlated with the highest grades. However, the resonance frequencies above 1 Hz could be responsible for each of the 3 different damage grades, and a wide range of amplitudes corresponds to damage grade 3.

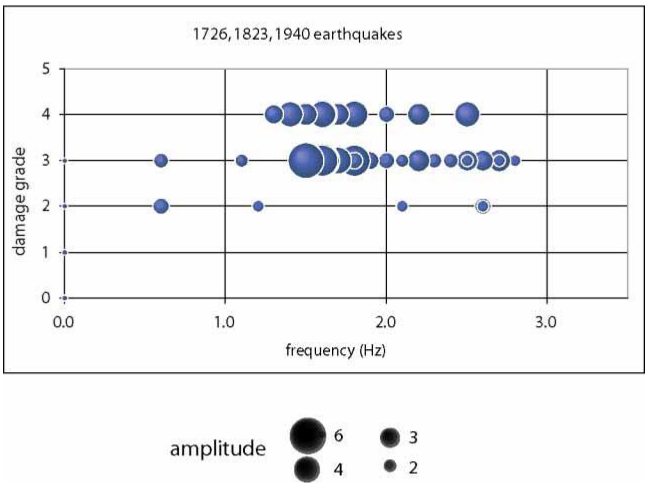

Figure 14. EMS 98 damage grade as a function of the HVSR frequency. The circle size is proportional to its amplitude.

Conclusions

Palermo is a very important historical city damaged by several earthquakes. A detailed map of damage distribution is available, derived from a very dense set of macroseismic data, and the 3D structure of the surface geology has been reconstructed through a GIS designed to assess natural hazards in the urban area. We performed ambient noise measurements at a large number of sites within the historical centre. The comparison of the HVSR analysis with the empirical transfer function on earthquakes and with the geology and damage distribution highlighted that:

1) The HVSR method is generally able to point out the fundamental frequency when is applied to sedimentary sites with a relevant impedance contrast respect to the underlying bedrock.

2) The amplitude of this peak seems not well correlated with the S-wave amplification, and the method fails in finding the higher resonance frequencies.
3) HVSR is a very good indicator of the presence of soft sediments. A resonance frequency appears inside the identified valleys of the Kemonia and Papireto rivers and its value decreases where the sediments deepen. The amplitude distribution of the resonance frequencies can vary within close measurement sites.
4) The damage distribution is well correlated with the presence of peaked frequencies but the correspondence between different classes of frequency and damage grade is only qualitative.

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