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SITE AMPLIFICATION IN THE EPICENTRAL AREA OF THE 31/10/2002 EARTHQUAKE (MOLISE, ITALY): COMPARISON BETWEEN DAMAGE DATA, MICROTREMORS, WEAK- AND STRONG-MOTIONS.

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SUMMARY

On October 31st and November 1st 2002 the Basso Molise area (Southern Italy) was struck by two moderate magnitude earthquakes (M = 5.3 and 5.4). The epicentral area showed a high level of damage, attributable both to the high vulnerability of existing buildings and to site effects due to the geo-morphological setting. In order to detect the main cause of the severe building loss, damage and vulnerability distributions were analyzed, together with microtremors and weak motion monitoring, in several municipalities located in the epicentral area (Bonefro, S. Croce di Magliano, S. Giuliano di Puglia and Colletorto). A limited number of strong motion recordings from the most severe aftershocks were also available for Bonefro and S. Giuliano. We initially evaluated the site response by H/V ratios performed on microtremors. The low reliability of the Nakamura method in detecting the absolute amplification level drove us to the adoption of other techniques. With the purpose of understanding the site amplification influence on the damage caused by the main shock, we installed a local network to record weak motions and perform standard spectral ratios with a reference site and single station H/V ratios. Finally, the damage and vulnerability distributions in the building stock were derived from the database of the post-event survey Also the normalized damage was calculated to better understand the separate contribution of vulnerability and site amplification to the actual macroseismic intensity observed in each municipality, and to identify some still open questions.

INTRODUCTION

On October 31st and November 1st, 2002, two earthquakes of magnitude 5.4 and 5.3 hit the area at the border between Molise and Puglia in Southern Italy. The distribution of the observed intensities for the 31/10/02 shock, M=5.4, is shown in Fig. 1, along with the epicenter location and focal

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mechanism of the main shock. The damage pattern qualified the quake as intensity VII MCS (Mercalli-Cancani-Sieberg scale), with one notable exception: the village of San Giuliano di Puglia (VII-IX MCS).

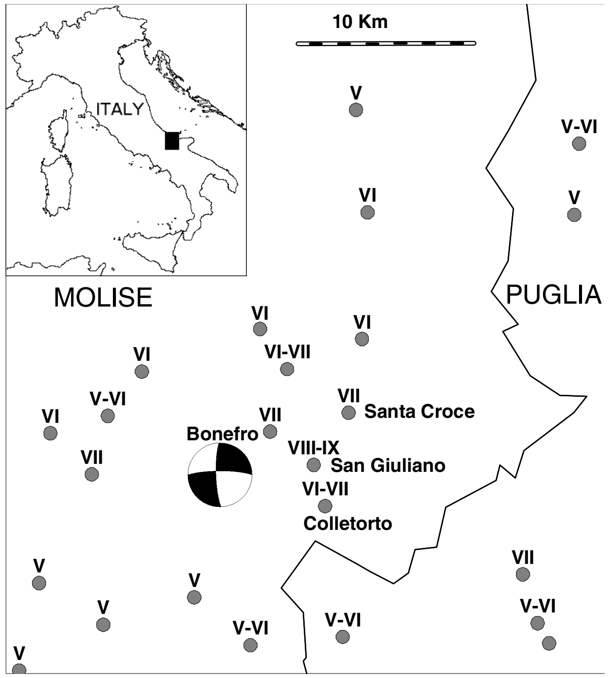

Fig. 1 The distribution of the observed intensities for the 31/10/02 shock (modified from [1])

Inside the same San Giuliano town the damage was varying from moderate to severe, with some total collapses (including unfortunately the primary school) concentrated in a distinct area. A preliminary survey performed in San Giuliano immediately after the sequence by Mucciarelli et al. [1] showed that even if site effects were present, vulnerability should also have played a role to justify the anomalous damage enhancement. A survey on a broader area using microtremor H/V measurements performed by Gallipoli et al. [2] gave an even more puzzling result: damage and H/V values in a frequency band around 2 Hz showed a positive correlation, but the difference in Bonefro, S. Giuliano, S .Croce and Colletorto could not justify the observed difference in MCS intensity. We then decided to carry out a more detailed investigation, trying to separate the contribution of vulnerability and site amplification. We determined Normalized Damage Index for each municipality, weighting the observed damage with the actual vulnerability. The site effects studies were integrated with the results from a temporary seismometric network. Fig. 2 reports the location of noise and weak motion measurement points in the four studied towns.

DAMAGE AND VULNERABILITY

The analysis of damage distribution and of structural characteristics of the building stock is based on the inventory of the data collected using the AeDES survey form for usability and damage of buildings (DPC [3]) after the seismic events of 31.10.02 and 1.11.02. The survey form comprises 9 sections. Beyond data on the damage state, geometrical and qualitative characteristics are reported, such as height, plan and elevation configurations, age, type of vertical and horizontal structures, type of foundation and of roof, retrofitting. Many thousands of buildings were inspected in about 100 municipalities of Molise, mostly in the Campobasso province. In the four studied municipalities, placed in the most affected area, about 4700 buildings were inspected, 700 in S. Giuliano di Puglia, 1590 in S. Croce di Magliano, 1215 in Colletorto, and 1230 in Bonefro. All the four studied municipalities were not classified as seismic zone at the time of the event.

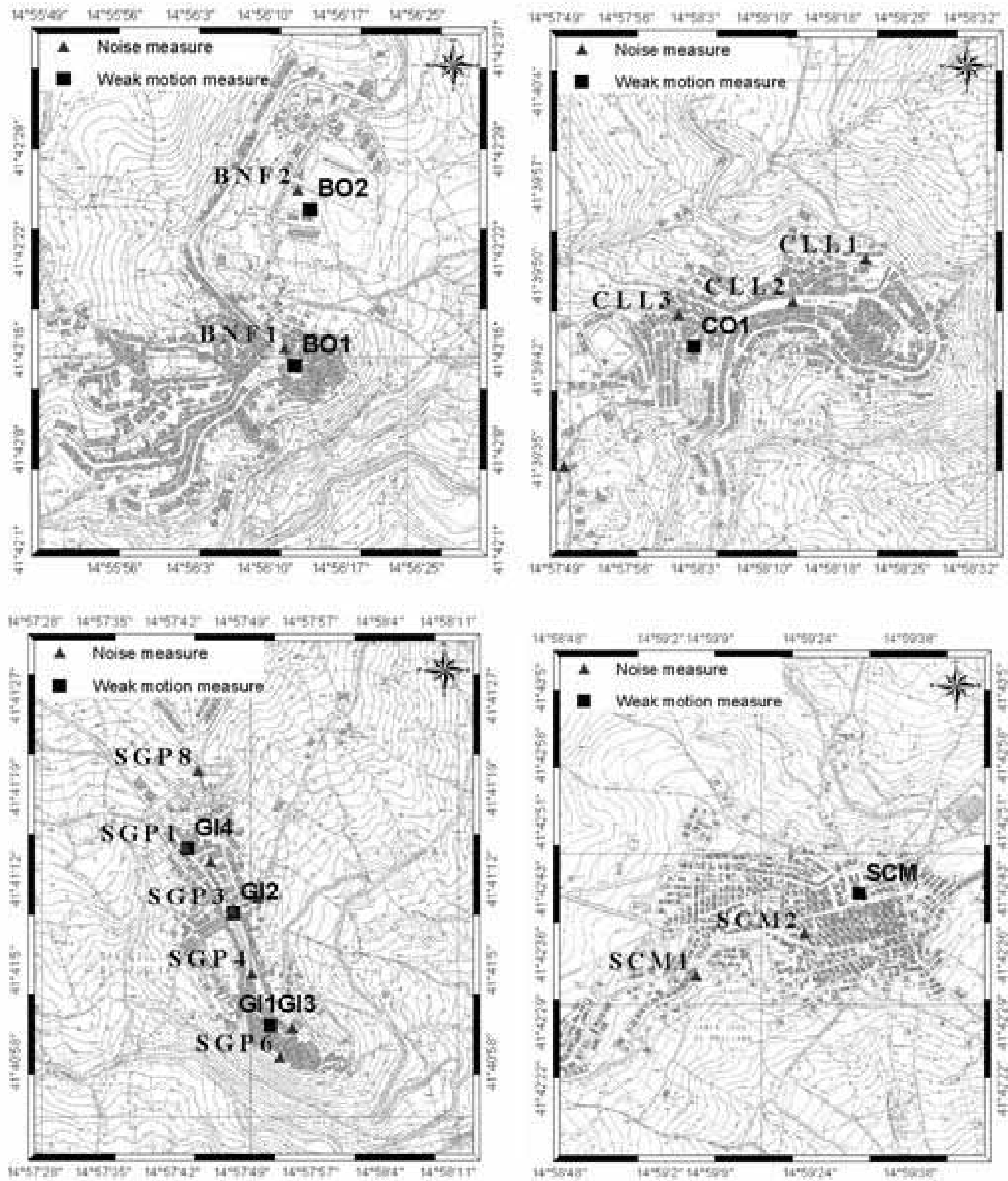

Fig.2 The four studied towns with the location of noise and weak motion measurement points

The age of the buildings suggests a widespread presence of very old structures. In fact, about 50% of the buildings date before the World War II (< 1945), with a higher presence in Bonefro where these buildings are about 65% of the total. The collected data on the vertical structural types show slight differences in the distributions relevant to the four towns under examination. An almost equal fraction (about 75%) of masonry structures is present, whereas the remaining 25% is mainly made of Reinforced Concrete (RC) frame and mixed structures. As far as the quality of masonry structures is concerned, bad (about 50%) prevails on good (about 25%) quality masonry. Horizontal structures of masonry and mixed buildings are typically made up of flexible or semi-rigid floors (e.g. steel beams or wooden beams without or with double layer plank) in S. Giuliano (about 55%), S. Croce (about 45%) and Bonefro (about 65%), whereas in Colletorto the most frequent horizontal structures are vaults (about 40%) and rigid floors (about 30%). RC buildings always have RC rigid floors.

Observed Damage

The distribution of the observed damage has been evaluated using the damage definitions provided by the 1998 European Macroseismic Scale (Gruenthal [4]), where five grades of damage, beyond the null damage, are considered, ranging from 1 (negligible damage) to 5 (collapse). Since in the AeDES form the damage is evaluated in a different way, collecting separately level and extension for each structural component, a correlation between the two different damage scales has been made (Tab. 1). To this purpose, only the damage to vertical structures has been taken into account, always considering the highest damage state, when more than one was reported in the form.

	DAMAGE EXTENSION		
DAMAGE LEVEL	**< 1/3**	**1/3 - 2/3**	**> 2/3**
None	0	0	0
D1	1	1	2
D2-D3	2	3	3
D4-D5	4	4	5

Tab. 1. Correlation between AeDES damage data and EMS98 damage grades.

The distributions of the damage grades for each studied town are reported in Fig. 3, displaying the damage values d_i in the interval 0 –1, (i.e. assuming 1 ≡ 0.2, 2 ≡ 0.4, 3 ≡ 0.6, 4 ≡ 0.8, 5 ≡ 1), so that a comparison with the values of normalized damage reported in the following sections can be made. The distributions show a larger presence of high damage values in S. Giuliano, where about 40% of buildings suffered partial (d_i = 0.8) or total (d_i = 1) collapse. In the other three municipalities less than 10% of the buildings suffered partial or total collapse.

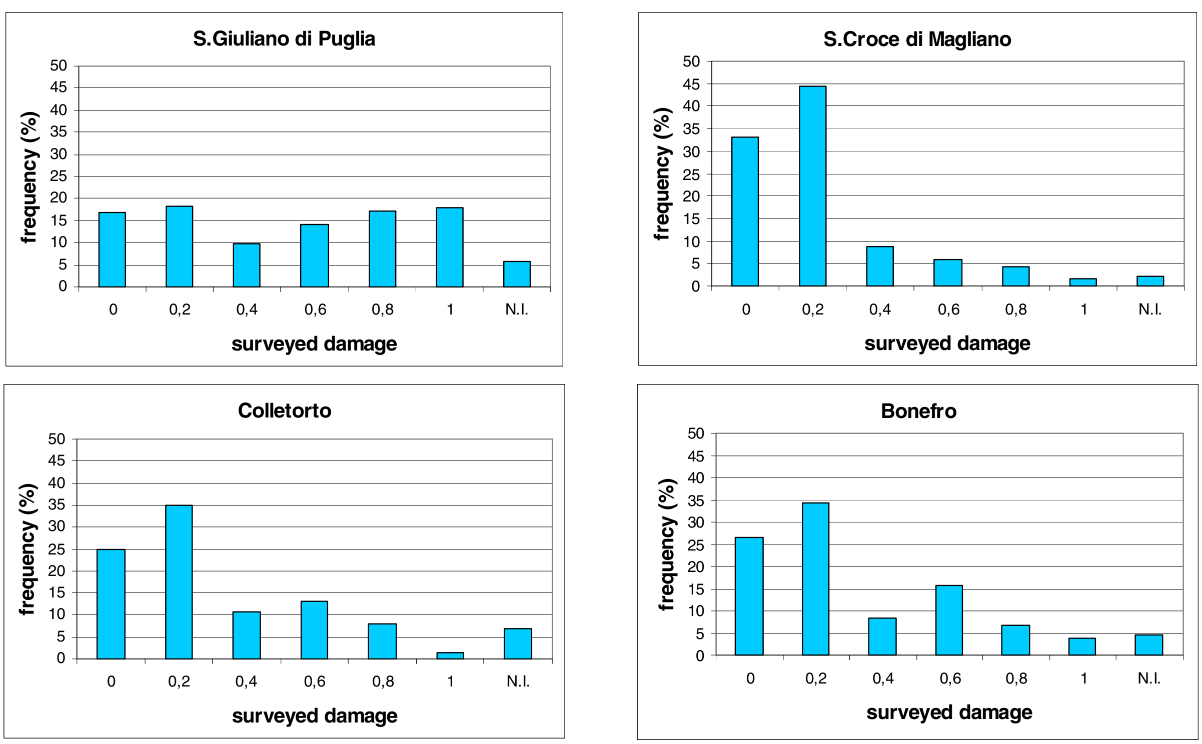

Fig. 3 Distribution of the surveyed damage in the four studied towns (N.I. = Not Identified)

In order to directly compare the damage distributions relevant to each town, a mean damage index (DI_{mean}) is defined following Dolce [5]:

$$DI_{mean} = \Sigma_i (d_i \cdot f_i)$$

where d_i is a generic damage value and f_i is the relevant frequency. DI_{mean} varies betwen 0 and 1, where $DI_{mean} = 0$ means total absence of damage and $DI_{mean} = 1$ means total destruction.
The values of DI_{mean} emphasize the presence of heavy damage in S. Giuliano. For Colletorto and Bonefro, DI_{mean} is almost the same, being equal to 0.27 and 0.29 respectively, whereas it increases up to 0.48 for S. Giuliano. The lowest value, equal to 0.21, is calculated in S. Croce.

Buildings Vulnerability

Seismic vulnerability can be assessed by making use of different techniques (e.g. Corsanego [6], Dolce [7]). The choice depends mainly on the level of information available and on the extension of the area under examination. In the present paper, the vulnerability evaluation is made by using a direct typological technique, i.e. based on data collected during field inspection, which is widely used in Italy. The Damage Probability Matrices set up by Braga [8] after the 1980 Southern Italy earthquake are used. Three classes of vulnerability (high A, medium B and low C), defined according to EMS98 and relevant to structures without any seismic provision, are considered. To each building, a vulnerability class is assigned, taking into account the vertical and the horizontal structures (Tab. 2).

	VERTICAL STRUCTURES				
HORIZONTAL STRUCTURES	MASONRY Bad w/o tie	MASONRY Bad with tie	MASONRY Good w/o tie	MASONRY Good with tie	RC
Vault	**A**	**A**	**A**	**B**	**-**
Flexible floor	**A**	**A**	**B**	**B**	**-**
Semirigid floor	**A**	**A**	**B**	**C**	**-**
Rigid floor	**A**	**B**	**C**	**C**	**C**

Tab. 2 Definition of classes of vulnerability (RC = Reinforced Concrete).

The building stock of the studied towns exhibit globally a high-medium vulnerability, as classes A and B account for about 70% of the buildings (Fig. 4). However, it has to be noted that a larger fraction (about 60%) of buildings with high vulnerability (class A) is present in Colletorto and Bonefro, and the lowest value, in contrast with the observed damage, is relevant to the building stock of S. Giuliano.

Normalized Damage Index

A procedure for damage normalisation, set up by Dolce [9], has been applied to evaluate if the damage to buildings was a consequence of site effects, independently of the building vulnerability. Given the vulnerability class and the actual damage, the procedure normalises the damage of a building by evaluating the damage that a building belonging to a given reference vulnerability class would have undergone at the same site. The graphs to convert the actual damage into normalized damage, assuming class A as the reference vulnerability class, are provided in Dolce [9]. The distributions of the normalized damage in the four municipalities are shown in Fig. 5. Also for the normalized damage, a mean damage index can be computed to obtain a synthetic evaluation of damage distribution. The results are reported in Tab. 3, together with the corresponding values already evaluated considering just the surveyed damage. By comparing the two groups of values, it is clear that the lower damage recorded at S. Croce with respect to Colletorto and Bonefro was mainly due to the somewhat better quality of the buildings, while the higher damage surveyed in S. Giuliano cannot definitely be ascribed to vulnerability.

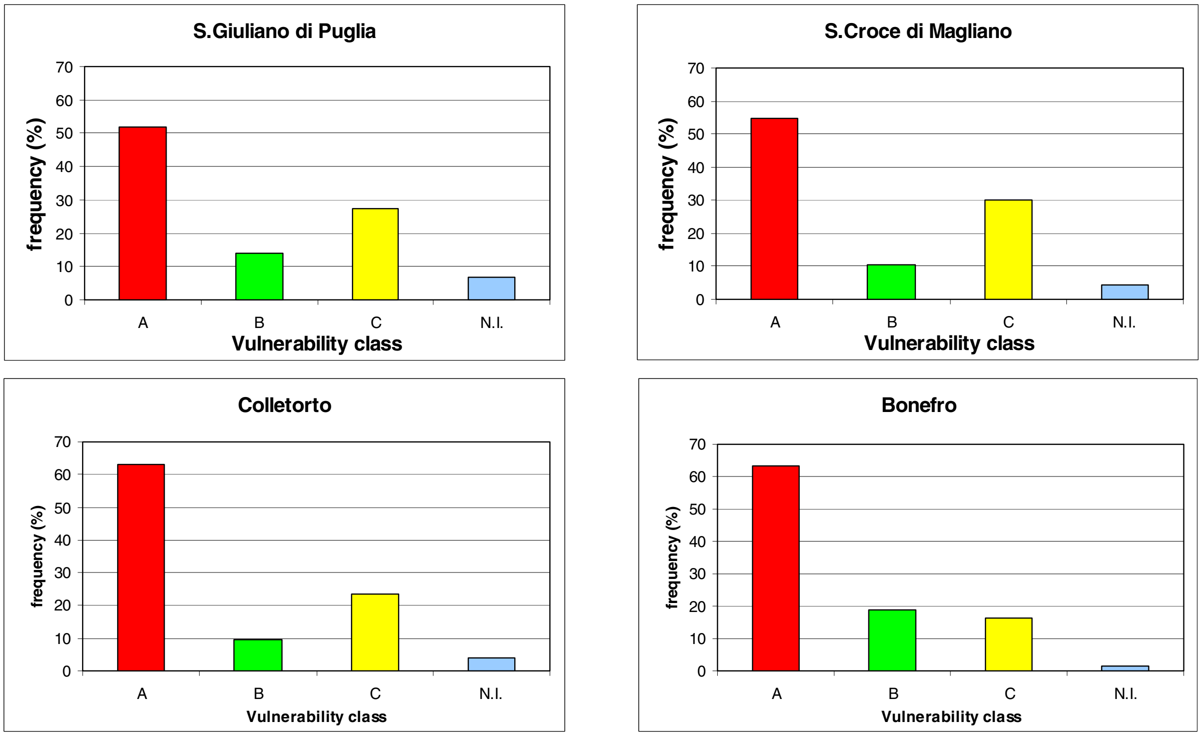

Fig. 4 Distribution of the vulnerability classes in the four studied towns (N.I. = Not Identified)

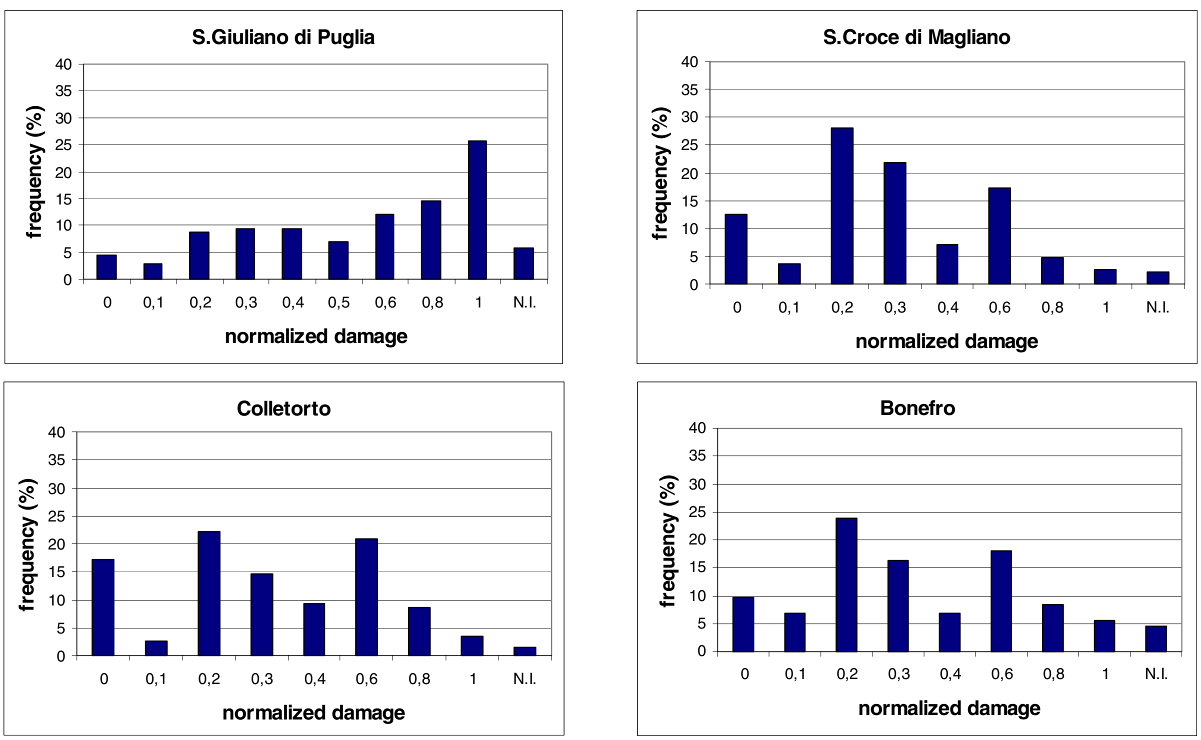

Fig. 5 Distribution of the normalized damage in the four studied towns (N.I. = Not Identified)

	DI_{mean}	
Municipality	Surveyed damage	Normalized damage
S. Giuliano	0.48	0.57
S. Croce	0.21	0.32
Colletorto	0.27	0.35
Bonefro	0.29	0.36

Tab. 3 Values of DI_{mean} for surveyed and normalized damage in the four studied towns

HVNR FROM MICROTREMORS

To record the noise samples we used a compact unit ISMES BNA V2, composed by a Lennartz 3D-Lite tridirectional sensor (1 Hz period), and connected to a 24-bit digital acquisition unit PRAXS-10 and a Pentium 1 personal computer. The sensor has identical characteristics on the three axes; thus for ratios it is possible to consider a reasonable range below the fundamental frequency, as demonstrated in Giampiccolo [10]. We recorded a set of at least five time series of 60-s duration each, sampled at 125 Hz. Five recordings of one minute each are enough to give significant results as recently shown by Albarello [11]. Time histories were corrected for the base line and for anomalous trends, tapered with a cosine function to the first and last 5% of the signal and band-pass filtered from 0.1 to 20 Hertz. Fast Fourier transforms have been applied in order to compute spectra for 25 predefined values of frequency, equally spaced in a logarithmic scale between 0.1 and 20 Hz, selected in order to preserve energy according to Castro [12]. The arithmetic average of all horizontal-to-vertical ratios represents the HVNR site amplification function. The equipment was protected against wind and, in general, we followed all the experimental procedures described in Mucciarell [13]. The total number of measurement points is 53, distributed in all the localities reaching VI degree on EMS-98 scale. Fig. 6 reports a box-and-whisker plot for all the data. For each locality, we put together all the HVNR measurements, for all sites and all the frequency bands between 0.5 and 10 Hz. The line represents the median, the box ranges from the 25 to the 75 percentile, the whiskers extend from 10 to 90 percentile and circles are the outliers. A darker grey shade outlines the four towns studied in this paper. The scattering of the distribution reflects the geo-morphological complexity of the area. The detailed comparison between HVNR at the closest station and other amplification estimates is reported in a later section.

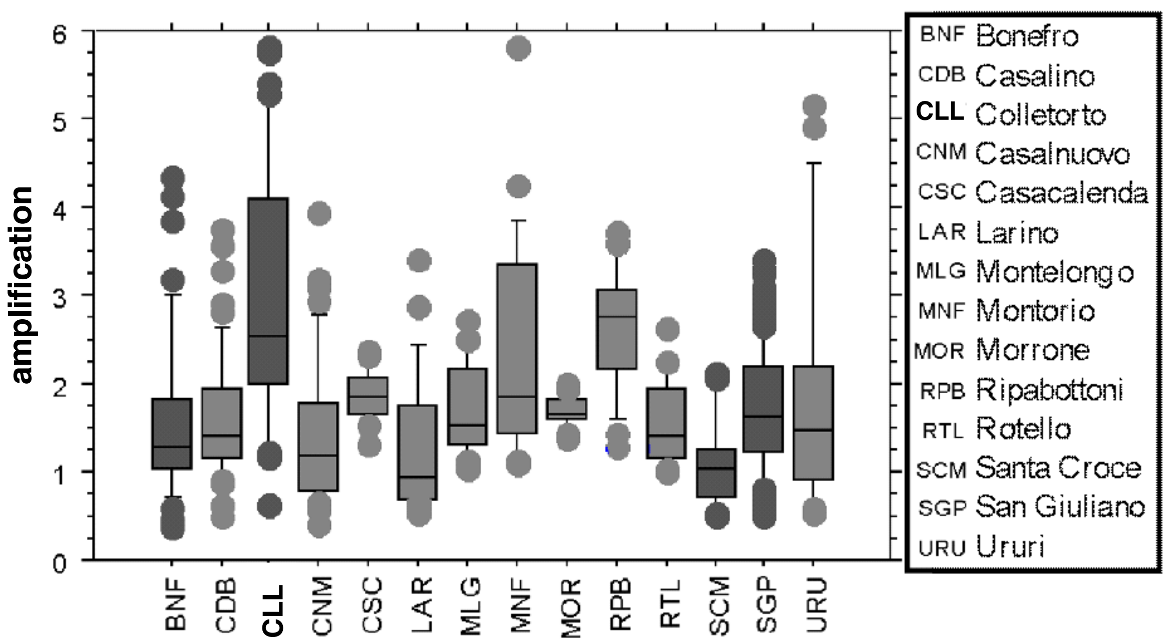

Fig. 6 Box-and-whisker plot of the HVNRs measured in the 14 Molise municipalities (from [2]).

THE TEMPORARY SEISMIC NETWORK

Data Collection and processing

During the period May 27th - November 29th 2003, a temporary seismic network equipped with 5 stations was deployed in the epicentral area of the November-December 2002 Molise sequence. Some of the stations were moved during the operating period to investigate 7 sites. The instrumentation consisted of 5 Mark Products L-4C seismometers with 1Hz natural frequency, coupled with a Lennartz Mars88/FD acquisition system. The sensors had 3 components and recorded by triggering mode at 62.5 sample per second (sample rate of 16 ms). Assuming a coincidence threshold of 2 stations, the initial 9858 recordings, were reduced to a waveforms set of 248 earthquakes. The selection of local events and earthquakes with a signal to noise ratio greater than 3, led to a final data set of 87 events having magnitude ranging from 1.5 to 3.4. We selected the analysis windows starting from the S-waves and ending when the 80% of the energy was reached. This criterion allowed to selected the S-wave train and avoid the contamination of surface waves. A 5% Hanning window taper was applied and the Fourier spectra were calculated and smoothed using a variable frequency band of +/- 25% of the central frequency. The smoothing algorithm preserves the energy of the record.

Horizontal to vertical spectral ratios

We performed the horizontal to vertical spectral ratios (HVSR) for the investigated sites by calculating the average ratio of the horizontal components over the vertical component. Only the station CO1 showed a flat response, being installed on bedrock. The stations BO1, BO2, SCM and GI3 showed slight amplifications in a frequency band variable between 2 and 10 Hz. In particular, BO1, GI3 and SCM were installed on topographic irregularities and can be affected by moderate topographic effects. The station showing the highest amplification is GI4, close to the S. Giuliano school, that exhibits amplitudes larger than 4 between 0.5 and 6 Hz. As HVNR, also HVSR results are plotted and discussed together in the following section.

Reference Station Spectral Ratio and comparison

The standard reference spectral ratios (SSR) were performed by rating the average horizontal components of the selected site over the average horizontal components of the reference site. The main constraint of the analysis is the selection of a reference site, which should be located on plane bedrock. In the investigated area no clear reference site can be identified, as the geologic framework is rather complex [2] and most of the formations are alternation of rock-like layers (calcarenites) and soft layers (clays). In addition, the selective erosion caused the rock-like layers to form ridges and crests of limited extensions, where the inhabited areas were built. Two stations, namely CO1 and GI3, are likely to be reference sites. The HVSR performed on station CO1 gives an almost flat response, confirmed by HVNR (Fig. 8). Moreover, the HVSR of station GI3 is very similar to the horizontal SSR of GI3/CO1 (Fig. 9). This drove us to assume CO1 as reliable reference site. The very similar trends of HVSR and SSR of the SCM and BO1 stations (Fig. 10 and 11), strengthens this hypothesis, although the reference station CO1 is about 6 km far. We could perform no SSR's for the BO2 station for the lack of coincident events (Fig. 12). When performing the SSR with CO1 as reference, the amplification pattern of GI4 station is completely different than the HVSR one. The amplification is even larger and occurs in a different frequency band than HVSR, between 3 and 7 Hz and reaches values of 6 (Fig. 12). The underestimation provided by the HVSR suggests that amplification of the vertical component might occur at GI4. For this purpose, we performed spectral ratios on vertical components too. The result was that the amplification occurs at the resonant frequency of the site, between 3 and 7 Hz (Fig. 13).

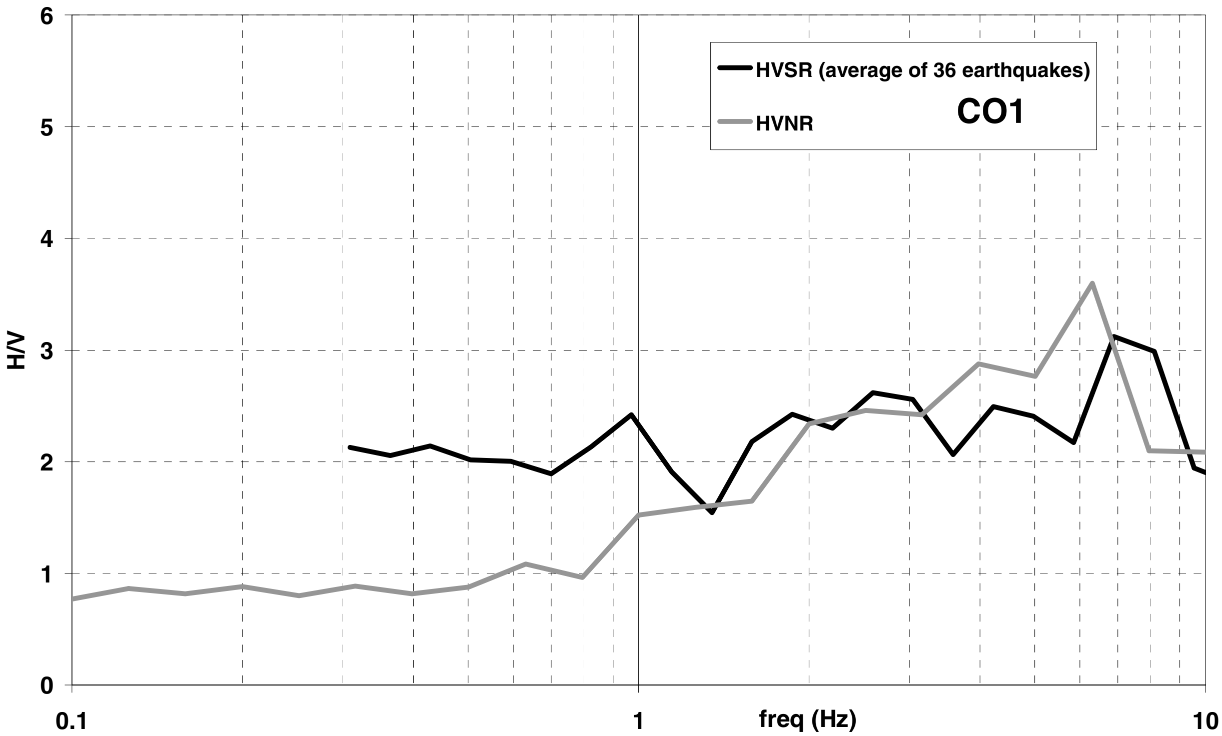

Fig. 8 Comparison between different site amplification estimates at CO1

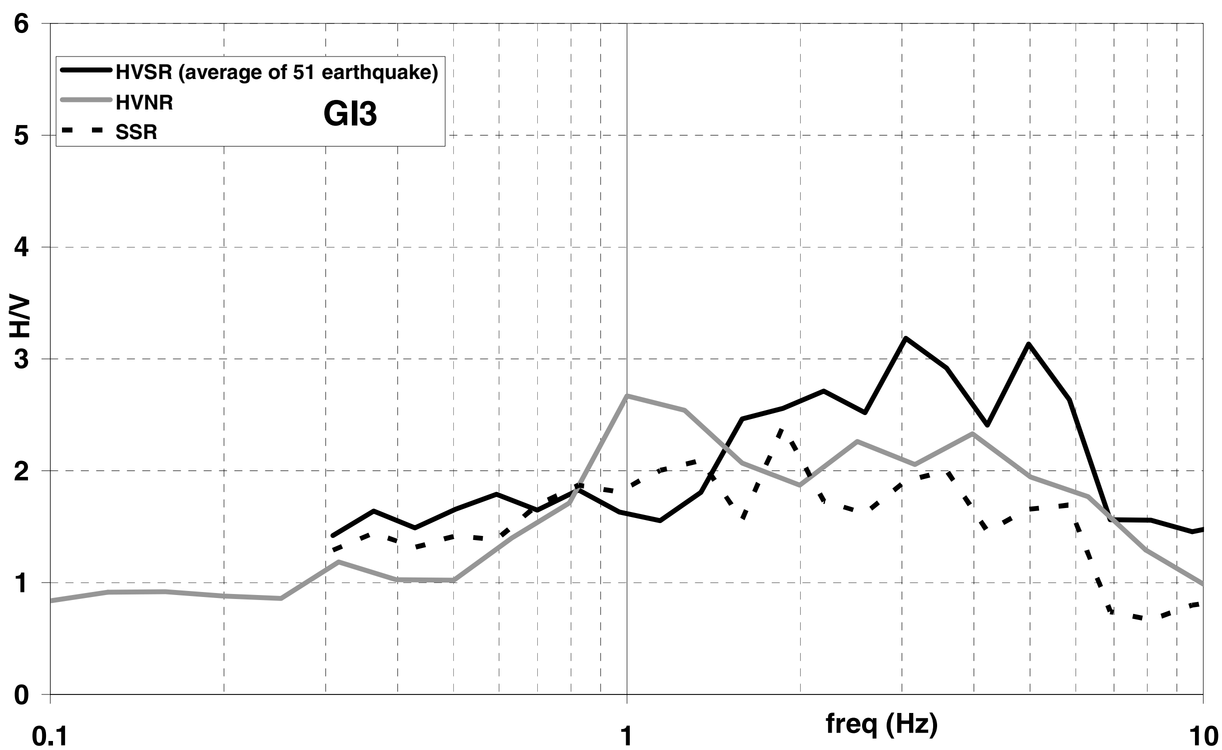

Fig. 9 Comparison between different site amplification estimates at GI3

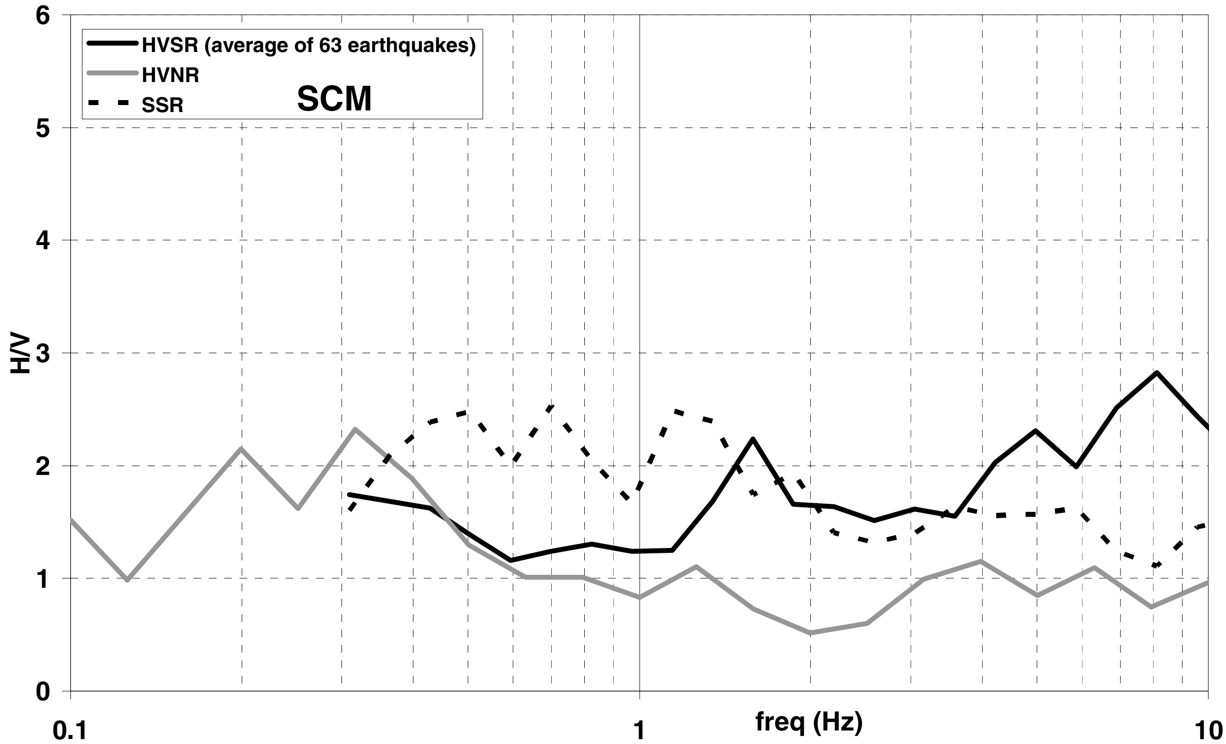

Fig. 10 Comparison between different site amplification estimates at SCM

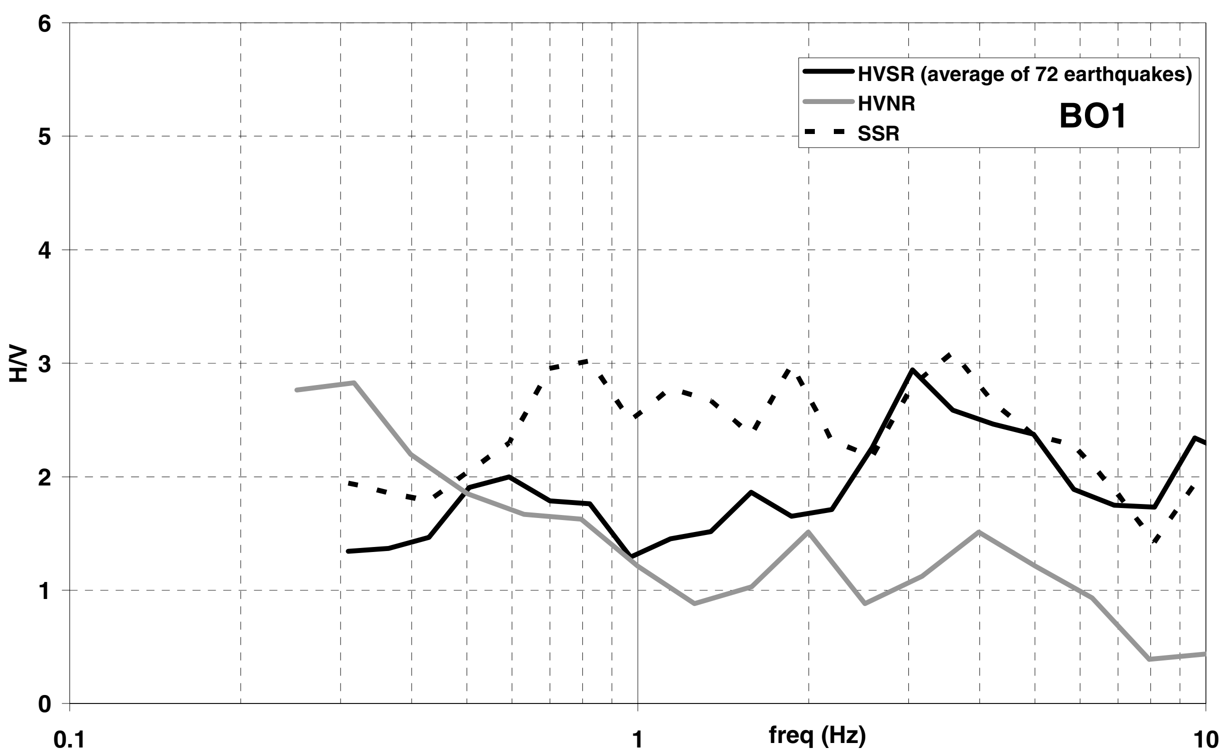

Fig. 11 Comparison between different site amplification estimates at BO1

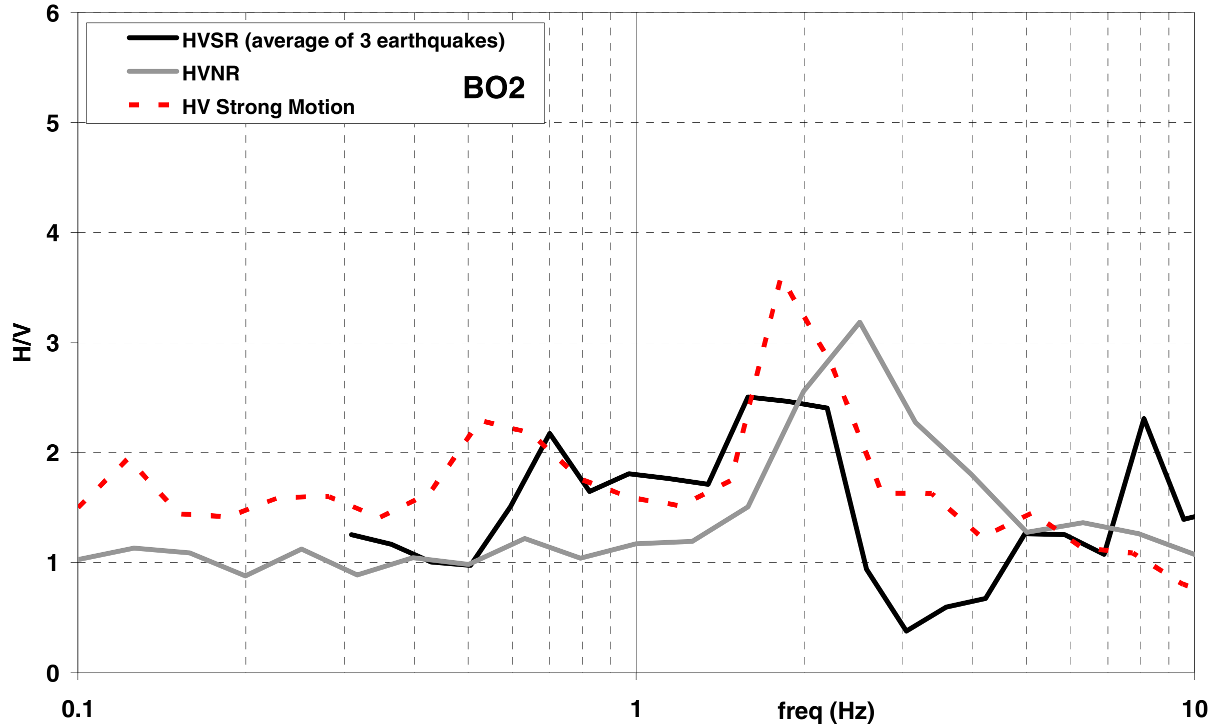

Fig. 12 Comparison between different site amplification estimates at BO2

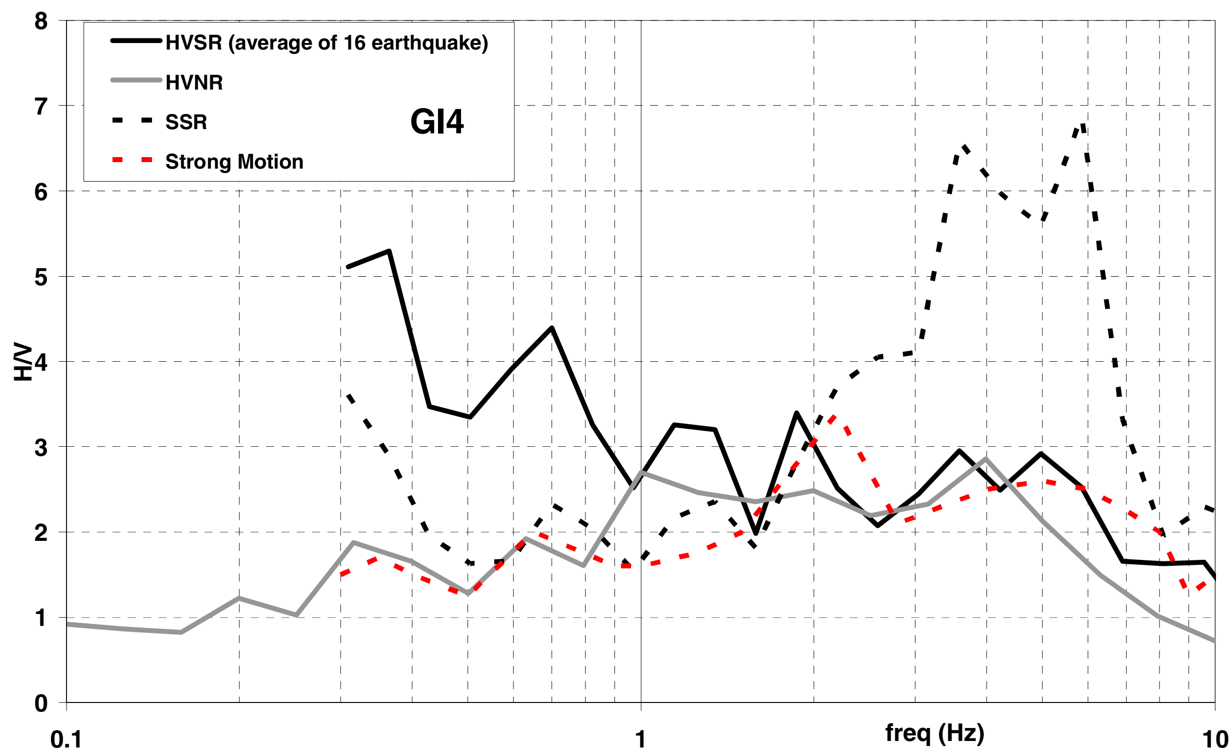

Fig. 13 Comparison between different site amplification estimates at GI4

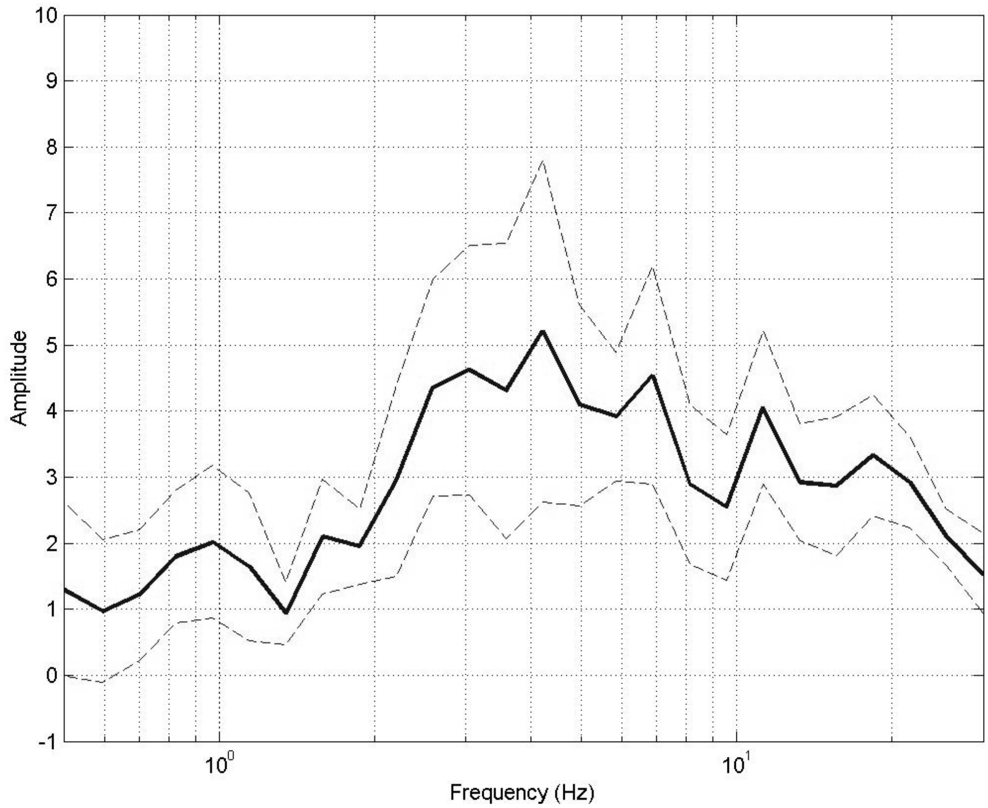

Fig. 14 Vertical SSR amplification between GI4 and CO1

STRONG MOTION DATA

In the immediate aftermath of the earthquake, an accelerometer was installed in San Giuliano, close to GI4 and then in Bonefro close to BO2 (see respectively Mucciarelli[1] and Mucciarelli [14] for more details). It is thus possible to have some strong motion data to analyse and compare with microtremors and weak motion data. The HVSR performed on the available recordings shows on average a pattern similar to microtremor and weak motion (see Figs. 12 and 13). The most interesting results come from the San Giuliano recordings, when separating components and calculating Arias intensity in different frequency bands. The separation into components shows a strong difference between the two (Fig. 15). The EW one, roughly perpendicular to the ridge of San Giuliano (see Fig 2) is much stronger than the NS one. Another clear pattern emerges when time is taken into account (Fig. 16). The band around 2 Hz shows a very strong peak correspondent to the onset of S-waves. The band around 5-6 Hz has a constant amplification through all the accelerograms. This suggests either a strong source/directivity effect or the presence of two distinct site effects. In the band around 6 Hz a 1-d amplification prevails, clearly detectable also in weak-motion. An explanation for this was already given in [1] , invoking dependence from the strong impedance contrast between 15-20 meters of landfill and clays overlying calcarenites. In the 2 Hz band, the strong difference between horizontal components may be attributed to a 2-d effect, whose characteristic is to be prevalent when ground motion increases.

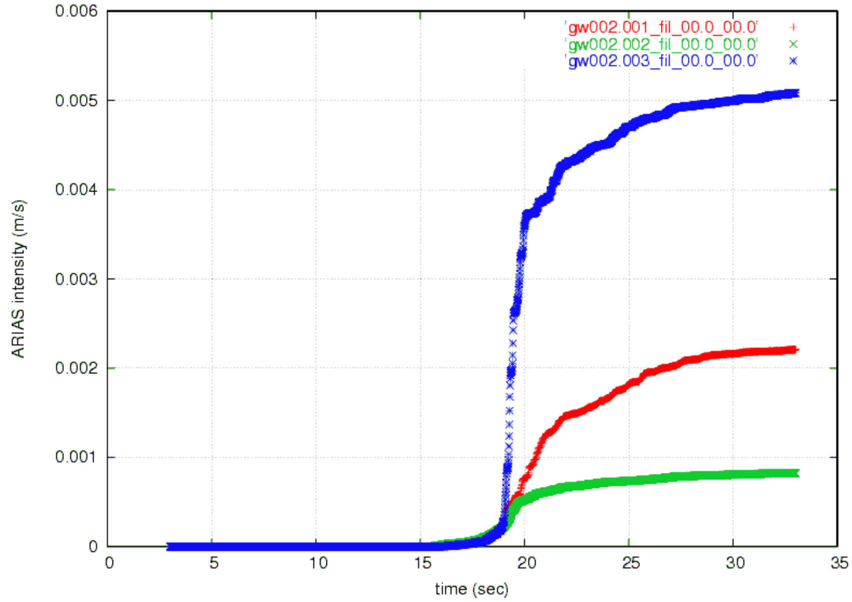

Fig. 15 Difference in Arias intensity for the strong motion recording at GI4 (UP=2, NS=1, EW=3)

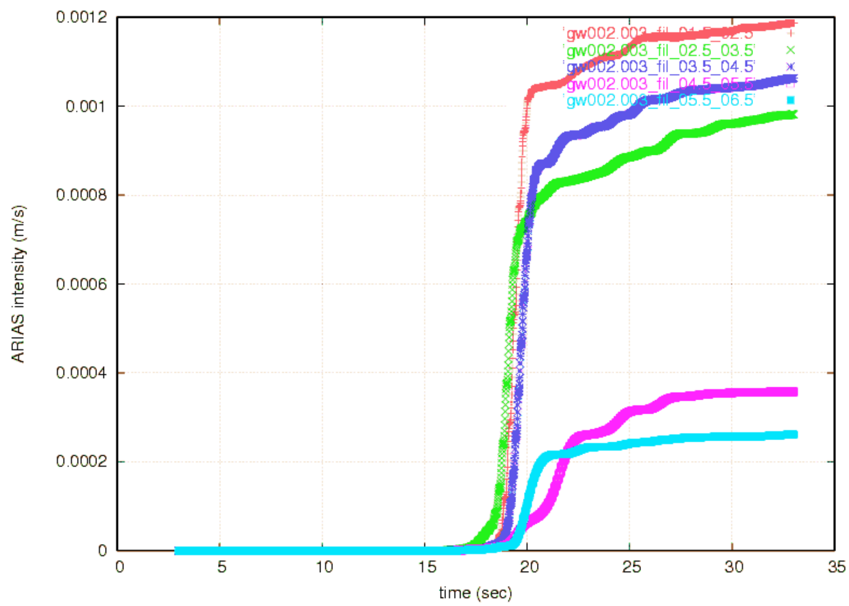

Fig. 16 Arias intensity for different frequency band of strong motion at GI4, EW component (lowest values for 4.5-6.5 Hz range, highest for 1.5-2.5 Hz.

DISCUSSION AND CONCLUSIONS

The analysis of the vulnerability in the four towns reveals that the distribution of buildings vulnerability follows a pattern that does not justify the differences in observed damage. The normalized damage, that de-convolves the effect of vulnerability on the observed damage, shows that the higher damage in San Giuliano cannot be attributed to a local vulnerability higher than the one of the neighboring towns. The comparison among the different techniques used for estimating site amplification reveals an overall agreement. We do not observe strong peaks, with the exception of GI4. This site, inside the most damaged area of the most damaged town, shows the highest HVSR from weak motions. When SSR is considered, GI4 amplification largely exceeds the ones of the other sites. The analysis of the available strong motion data confirms this hint. The possible causes for the observed localized amplification are: 1) the mainshock had a source/directivity effect similar or even exceeding the one observed in strong motion data; 2) 1D effects are not sufficient to explain the observed damage enhancement, and a 2D effect has to be taken into account. 3) Given the strong impedance contrast below GI4 [1], converted waves could play an important role, as suggested by Parolai [15]. The first hypothesis could be tackled analyzing more strong motion data in the neighboring areas, while the second would require 2D modeling.

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